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BULLETIN
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BENTONITE, ATTAPULGITE AND COMMON CLAYS IN WESTERN AUSTRALIA

by P. B. Abeyasinghe



Geological Survey of Western Australia



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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BENTONITE, ATTAPULGITE, AND COMMON CLAYS IN WESTERN AUSTRALIA

**by
P. B. Abeysinghe**

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Micaceous schist in the Wandel Park quarry near Toodyay.

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Bentonite, attapulgite, and common clays in Western Australia

by

P. B. Abeysinghe

Abstract

In Western Australia, potentially economic bentonite deposits are known at Marchagee, Watheroo, Cardabia, and Calwinyardah. The magnesium-rich bentonite in the Marchagee and Watheroo areas is composed mainly of saponite, and is restricted to Quaternary alluvial deposits in claypans. Known deposits in the Watheroo area contain an inferred bentonite resource of about 435 000 t, but the extent of bentonite in the area is likely to be much higher. Nontronite, an iron-rich smectite, is present at Cardabia. Preliminary tests suggest that chemically treated nontronite can be used as a binding agent in iron-ore pellet production. Bentonite, mainly saponite, is associated with crater-lake tuffaceous sediments overlying the Calwinyardah lamproite field. The inferred resource of bentonite in the deposit is estimated at 4.4 Mt. Until now, the exploration target at Calwinyardah has been diamond, and therefore the contained bentonite has not been rigorously tested for quality and possible uses. During 1942–77, Western Australia produced 15 483 t of bentonite valued at \$A117 283. In 1999, Western Australia resumed production of bentonite (358 t during 1999–2000) from deposits at Watheroo.

For most of the 1990s, Australian attapulgite production averaged about 20 000 tpa from the Lake Nerramayne deposit, located 480 km north of Perth and 157 km northeast of Geraldton, Western Australia. However, in 1998–99 production fell below 12 000 t. The Lake Nerramayne attapulgite deposit has a measured resource of 10 Mt and an inferred resource of another 100 Mt. The deposit has formed in playa lakes at the western margin of the Narryer Terrane and approximately 7 km east of the northerly trending Darling Fault. The deposit is currently owned and operated by Hudson Resources Ltd. The main product from the plant is used for pet litter, which is sold in Australia, New Zealand, Japan, and Asia. Other uses include as a pesticide carrier, stockfeed and fertilizer binder, and soil conditioner. The deposit is strategically located near the port of Geraldton, the doorstep to many rapidly developing markets in South East Asia.

Production of construction industry clay in Western Australia for 1999, as reported to the Department of Mineral and Petroleum Resources, was 72 059 t, but the true figure is considered to be in excess of 2.3 Mt. More than 99% of the construction industry clay produced in the State is from the Perth Metropolitan Area. Potential sources of construction industry clay in the Perth Basin are associated with the Guildford, Leederville, Osborne, and Yarragadee Formations, and the Cardup Group. The clay-producing localities in the Perth region include Muchea – Bullsbrook East, the Swan Valley, Armadale–Cardup–Byford–Mundijong, Toodyay, and Gidgegannup. The identified resource in the Perth metropolitan region is estimated at around 68.2 Mt. Other prospective areas of construction industry clay in the State are known in the Perth Basin and numerous localities in the Yilgarn Craton. Test results of clay samples collected from localities around Albany, Ravensthorpe, Kalgoorlie, and Roebourne indicate their suitability for use as structural clay. The brick industry in Western Australia is well established and is dominated by two major companies in the Perth region — Midland Brick Company Pty Ltd, and Metro Brick (owned by Bristle Ltd). Significant production of bricks is also known from regional towns, particularly Geraldton.

KEYWORDS: Western Australia, industrial minerals, industrial mineral resources, Marchagee, Watheroo, Cardabia, Calwinyardah, Lake Nerramayne, Perth, Geraldton, Albany, bentonite, montmorillonite, palygorskite, smectite, sepiolite, bricks, brick clay, brick making, clay deposits, clay pits.

Chapter 1

Introduction

Object and scope

The main objective of this Bulletin is to compile most of the available published and unpublished information on bentonite, attapulgite, and other minor smectite and hormite clays, together with construction industry clays in the State into one publication. The Bulletin is not intended to be an exhaustive study of all the known occurrences, but is a comprehensive summary highlighting the development potential of bentonite, attapulgite, and construction industry clays in Western Australia.

This Bulletin does not include kaolin resources in Western Australia because a separate Bulletin (Abeyasinghe and Fetherston, 1999) on this subject has already been published by the Geological Survey of Western Australia (GSWA).

The economic viability of bentonite and attapulgite depends mainly on the location of major deposits in relation to processing facilities, and major national and international distribution centres. Other factors include availability and price of other competitive minerals, and global production and usage trends. Global trends, as well as some mineralogical and geological aspects of bentonite and attapulgite, are discussed in this Bulletin. Since construction industry clays are very low value commodities, global production trends have very little relevance, and so such trends are not discussed. However, the mode of occurrence, uses, specifications, and local production of construction industry clays are presented in detail.

Sources of information

The sources of information are from both published and unpublished data, supplemented by field inspections. Unpublished information is derived from GSWA records, annual reports, technical files, and statutory exploration reports submitted to the Department of Mineral and

Petroleum Resources (DMPR) by various mining companies. Published information on construction industry clay is restricted to the region around Perth, and therefore, during the current study, more attention was paid to construction-industry clay deposits from regions outside Perth, especially close to regional towns such as Albany, Geraldton, and Karratha. Analytical data for many samples from Bowley (1941) and Gozzard (1987a,b), collected from regions around Perth, are included in this Bulletin.

Some of the major deposits, and others thought to be potentially significant, were visited and sampled by the author. Approximately 115 samples were collected during field trips in July–September 1998 for laboratory testing. Tests on smectite and hormite clays for this publication were limited to mineral identification using X-ray powder diffractometry (XRD), mineral identification and crystallinity studies using scanning electron microscopy (SEM), and chemical analysis using X-ray fluorescence (XRF). Construction-industry clay samples were tested for firing strengths, mineral identification using XRD, and chemical analysis using XRF. SEM and XRD tests were carried out at the Chemistry Centre of Western Australia and firing tests were performed by Midland Brick Company Pty Ltd (subsidiary of Boral Ltd), whereas all other analytical tests were carried out by SGS Australia Pty Ltd, Perth.

Localities of all the samples collected by the author are given in the Appendix 1, and the other localities discussed in this Bulletin are provided in Appendix 2. Photographs of fired products of construction-industry clay samples collected by the author are given in Appendix 3.

More detailed testing of the samples was not done due to the reconnaissance nature of the sampling and the high costs for other tests. However, test results obtained do provide useful guidelines for interested parties to carry out more detailed exploration and evaluation in selected areas.

Abbreviations

\$A	Australian dollars
API	American Petroleum Institute
DMPR	Department of Mineral and Petroleum Resources
E	Exploration Licence
EDXRA	Energy dispersive X-ray analysis
GSWA	Geological Survey of Western Australia
M	Mining Lease
MC	Mineral Claim
ML	Mineral Lease
OCMA	Oil Companies Materials Association
P	Prospecting Licence
PA	Prospecting Area
pp	Private property
SEM	Scanning electron microscope
UK	United Kingdom
USA	United States of America
XRD	X-ray powder diffractometry

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Chapter 2

Bentonite

Definition and mineralogy

Smectite group

Bentonite is an industrial term for some of the minerals in the smectite group (also known as montmorillonite group) of clay minerals (Table 1). Each of the minerals in Table 1 shares a similar structure, although they are chemically distinct. Clay minerals within the smectite group have a 2:1-type layer structure (two tetrahedral sheets are linked to one octahedral sheet; Fig. 1). The tetrahedral cation in the tetrahedral sheet is normally Si, Al, or Fe³⁺. Within the octahedral sheet, the common cations are Mg, Al, Fe²⁺, and Fe³⁺, but other medium-sized cations such as Li, Ni, Cu, and Zn may also be present. The smallest structural unit contains three octahedra. If all three octahedra are occupied (i.e. have octahedral cations at their centres), the sheet is classified as trioctahedral. If only two octahedra are occupied and the third octahedron is vacant, the sheet is classified as dioctahedral (Brindley and Brown, 1980).

Substitution of both the tetrahedral and octahedral cations is common. Substitution of Si⁴⁺ by Al³⁺ in tetrahedral positions, and Al³⁺ or Fe³⁺ by Mg²⁺ or Fe²⁺ in octahedral positions, produces resultant negative charges on the layers that are balanced by exchangeable interlayer cations such as Na⁺, Ca²⁺, and Mg²⁺ ions (Brindley and Brown, 1980). Other interlayer materials include water.

Dioctahedral smectites

Montmorillonite

Montmorillonite is the commonest of the smectite minerals and the name is reserved for dioctahedral Al, Mg smectite where the layer results mainly from the Mg-for-Al substitutions in the octahedral positions (Brindley and Brown, 1980). Depending upon whether sodium or calcium is the dominant exchangeable ion, the variety of montmorillonite may be either sodium or calcium montmorillonite. In industry, terms used to describe sodium montmorillonite include sodium bentonite,

Table 1. Terminology for the principal minerals of the smectite group

<i>Subgroup</i>	<i>Principal mineral</i>	<i>Industrial term</i>	<i>Regional term</i>	<i>Chemical composition (anhydrous)</i>
Dioctahedral	Sodium montmorillonite	Sodium bentonite	Wyoming bentonite (USA)	(Al, Mg) ₂ Si ₄ O ₁₀ (OH) ₂ (Na as exchangeable cation)
		Swelling bentonite	Western bentonite (USA)	
		Sodium-activated bentonite	Bentonite (UK)	
	Calcium montmorillonite	Synthetic bentonite		
		Calcium bentonite	Southern bentonite (USA)	(Al, Mg) ₂ Si ₄ O ₁₀ (OH) ₂ (Ca as exchangeable cation)
		Sub-bentonite	Texas bentonite (USA)	
		Non-swelling bentonite	Fuller's earth (UK)	
	Beidellite			Al ₂ (AlSi ₃ O ₁₀)(OH) ₂
	Nontronite			Fe ₂ (Si ₄ O ₁₀)(OH) ₂
Trioctahedral	Saponite	Magnesium montmorillonite	Armamosite (USA)	Mg ₃ Si ₄ O ₁₀ (OH) ₂
	Hectorite			(Mg, Li) ₃ Si ₄ O ₁₀ (OH) ₂
	Sauconite			(Mg, Zn) ₃ Si ₄ O ₁₀ (OH) ₂

SOURCE: modified from Holmes (1983) and Harben and Kuzwart (1996)

Montmorillonite	$\text{Al}_2[\text{Si}_4\text{O}_{10}](\text{OH})_2 \cdot n\text{H}_2\text{O}$
Beidellite	$\text{Al}_2[\text{AlSi}_3\text{O}_{10}](\text{OH})_2 \cdot n\text{H}_2\text{O}$
Nontronite	$\text{Fe}_2[\text{Si}_4\text{O}_{10}](\text{OH})_2 \cdot n\text{H}_2\text{O}$
Saponite	$\text{Mg}_3[\text{Si}_4\text{O}_{10}](\text{OH})_2 \cdot n\text{H}_2\text{O}$

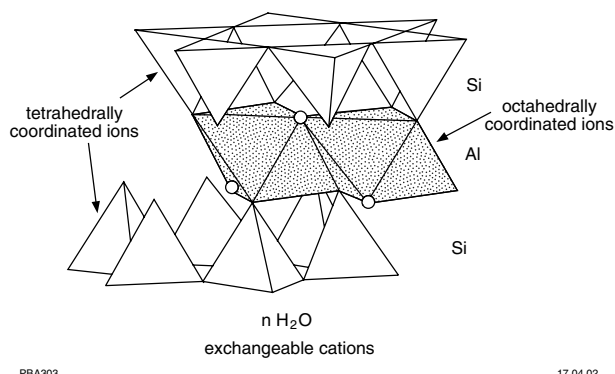


Figure 1. Structure of the smectite mineral group (after Elzea and Murray, 1994)

swelling bentonite, sodium-activated bentonite, and synthetic bentonite. Industrial names used for calcium montmorillonite include calcium bentonite, sub-bentonite, and non-swelling bentonite (Table 1).

Nontronite

Nontronite has layer charges that result principally from Al-for-Si substitutions in the tetrahedral sheets. Nontronite commonly has Fe^{3+} ions in the octahedral sites (Brindley and Brown, 1980).

Beidellite

In a similar way to nontronite, beidellite has layer charges that result principally from Al-for-Si substitutions in the tetrahedral sheets. Beidellite commonly has Al ions in the octahedral sites (Brindley and Brown, 1980).

Trioctahedral smectites

The principal minerals in the trioctahedral subgroup are saponite, hectorite, and sauconite (Table 1).

Saponite

Saponite is a trioctahedral smectite with its layer charges resulting principally from Al-for-Si substitutions. Saponite commonly has Mg^{2+} ions in the octahedral sites. Saponite is a swelling smectite clay with a low cation-exchange capacity and at present is the only smectite of commercial interest in Western Australia.

Hectorite

Hectorite is a trioctahedral smectite with principally octahedral substitutions of Li^+ for Mg^{2+} ions, and is the trioctahedral analogue of montmorillonite (Brindley and Brown, 1980). Hectorite is a high-swelling smectite.

Sauconite

Sauconite is a zinc-bearing trioctahedral smectite, and in a similar manner to saponite the layer charge results principally from Al-for-Si substitutions (Brindley and Brown, 1980).

Other smectites

Other less common smectite varieties include those involving cations such as Cr, Ni, and Cu (Brindley and Brown, 1980).

Bentonite

Knight (1898) first proposed the term bentonite for the clay of the Cretaceous Benton Shale, which is located more than 640 km north of Rock River in Wyoming, USA. The definition of bentonite in the early 20th century was based on this shale's origin (alteration of volcanic ash). The definition widely used at present is that given by Grim (1962), which defines bentonite as a clay consisting essentially of sodium and calcium montmorillonite of the smectite group of clay minerals, regardless of its origin or occurrence. More recently, the term bentonite has been applied by industry to other smectite minerals. For example, saponite is referred to as magnesium bentonite (Table 1).

Bentonite has a wide range of colours including white, yellow, olive green, brown, and blue, and has a characteristic soapy texture and waxy appearance. Weathered sodium bentonite has a distinctive 'popcorn' texture, resulting from the absorption of water that causes swelling expansion during wet periods and contraction during dry summers. Weathered calcium bentonite has an 'alligator skin' texture.

Bentonite is commonly classified based on its swelling capacities when wet or added to water. Sodium-rich bentonite principally has Na^+ on its exchangeable positions, has very high swelling capacities, and forms gel-like masses when added to water. Calcium-rich bentonite, with Ca^{2+} as its exchangeable cation, has much lower swelling capacities than the sodium-rich varieties. Intermediate calcium-sodium bentonite tends to swell moderately and forms a gel of less volume than an equal mass of the sodium type. Chemical analyses of some commercial bentonites are given in Table 2.

In the United States, bentonite may also be classified by geography. Swelling sodium varieties, mainly found in Wyoming and the adjacent states, are known as Wyoming or Western bentonites, and the non-swelling calcium varieties that are most common in the states bordering the Gulf of Mexico are known as Southern or Texas bentonites. In the United Kingdom, sodium bentonite is known simply as bentonite, whereas the calcium varieties are known as fuller's earth.

Fuller's earth

The term 'fuller's earth' was first used in the latter half of the last century for material used in the fulling

Table 2. Chemical analyses of commercial bentonites

	<i>Western USA standard foundry sodium bentonite</i>	<i>Western USA sodium bentonite (pure)</i>	<i>Southern USA foundry calcium bentonite</i>	<i>UK calcium bentonite</i>
	Percentage			
SiO ₂	63.59	61.3 – 64	62.12	55.2
Al ₂ O ₃	21.43	19.8	17.33	13.7
Fe ₂ O ₃	3.78	3.9	5.30	8.1
Na ₂ O	2.70	2.2	0.50	trace
CaO	0.66	0.6	3.68	6.3
MgO	2.03	1.3	3.30	3.3
K ₂ O	0.31	0.4	0.55	0.6
TiO ₂	–	0.1	–	0.7
Trace elements	–	3.2	–	–
Bound water	5.50	7.2	7.22	9.9

SOURCE: Harben (1995a)

(cleansing and thickening) of woollen cloth, and in the decolourizing and purifying of mineral, vegetable, and animal oils. In the first half of this century, this material was extensively used in processing mineral oils, which led to the general application of the term ‘fuller’s earth’ for material used in petroleum processing. The term is now used for clay or other fine-grained earthy materials that are suitable for bleaching and absorbing, and for other uses such as carriers for pesticides and herbicides, but the term has no compositional or mineralogical connotation (Holmes, 1983; Robertson, 1986; Elzea and Murray, 1994).

As previously noted, in the United Kingdom the term fuller’s earth refers to calcium bentonite, whereas in the United States the mineral attapulgite is often referred to as fuller’s earth. Attapulgite (also known as palygorskite) is a hormite-group mineral with a ribbon-like structure, and will be discussed in more detail in a later chapter.

Other minerals

Bentonites contain varying amounts of mineral impurities, depending on the geological environment in which they originated, and on this basis bentonites fall into three categories:

- those formed in volcanic environments;
- those formed in situ as secondary minerals during diagenesis and weathering; and
- those formed as detrital accumulations.

Mineral impurities in bentonites of volcanic origin may include feldspars, biotite, quartz, cristobalite, apatite, zircon, magnetite, amphiboles and, in places, unaltered volcanic glass. Bentonites formed as secondary minerals during diagenesis and weathering may contain various mineral impurities such as poorly sorted silica, zeolite, calcite, selenite, other clay minerals such as kaolinite and illite, and various iron-sulfate minerals. Bentonites formed as detrital accumulations are the least abundant and constitute less than 10% of commercially viable deposits. These detrital minerals include all of the rock-forming minerals found in most sedimentary environments (Elzea and Murray, 1994).

Cation exchange capacity

Cation exchange capacity (CEC) is the ability that minerals have for exchanging cations, and is expressed as milliequivalents per 100 g of clay (meq/100 g). Most bentonites have CECs that range between 60 and 170 meq/100 g (Elzea and Murray, 1994). The most common exchangeable cations in smectite minerals are sodium, calcium, magnesium, hydrogen, and potassium, which are found between the units of tetrahedral and octahedral layers. Water can enter between these layers and the type of cation present controls the amount of water that enters. The amount and type of exchangeable cation influences the clay surface chemistry and charge, which determines how the clay particles will interact in an aqueous suspension (Wolfbauer, 1977; Elzea and Murray, 1994).

Natural bentonite can be treated to enhance certain of its properties, and provide products with a wider range of applications. High-calcium bentonite, which is generally low swelling, may be synthetically sodium exchanged or alkali activated to enhance its swelling characteristics. During alkali activation, water must be present to dissolve the alkali ions so that the exchange process can proceed as far as possible. It is also standard industry practice to chemically treat calcium bentonite with soda ash or other additives to enhance its colloidal properties. This is done where natural sodium bentonite is not available. Organophilic bentonite, which is water repellent (or hydrophobic), is produced when sodium bentonite with a high swelling capacity is coated with polar, long-chain organic molecules. This enables solvents or bonding agents that are made of organic molecules to be interposed between the lamellae of the organophilic bentonite, resulting in thixotropic thickening and a gel structure (O’Driscoll, 1988).

CEC can be measured by a variety of methods. A procedure involving adsorption of methylene blue dye is a favourite method used by the foundry industry. One advantage of this method is that it measures CEC only from smectite minerals and the result is not affected by the presence of other minerals with a high CEC such as zeolites, which can be present in some bentonites. A disadvantage is that measurement by this method is

somewhat subjective and gives results that are lower than the actual CEC of the smectite mineral. Other methods of CEC determination involve displacing all of the exchangeable cations with another index cation (e.g. ammonium or barium ions) and then measuring the index cation to give a total CEC measurement of the individual displaced ions (e.g. Na^+ , K^+ , Ca^{2+} , and Mg^{2+}). These measurements can be done by a combination of atomic absorption spectrophotometry and flame photometry. The result is, however, affected by the presence of other high-CEC minerals such as zeolites, and the presence of small amounts of zeolite can give a misleading result indicating that the bentonite is of a high grade when only a small amount of smectite may be present (Christidis and Scott, 1993).

Mode of occurrence

Bentonite most commonly forms as a result of alteration in situ of volcanic ash or tuff. Less commonly, bentonite can also form due to hydrothermal alteration of volcanic rocks. Bentonite derived from altered volcanic ash can be recognized from:

- Mineralogy — bentonite beds commonly contain euhedral minerals characteristic of volcanic rocks;
- Chemistry — the major element and rare earth chemistry of smectite is consistent with a volcanic precursor; and
- Texture — relict glass shards are pseudomorphically replaced by smectite (observed in thin section and under a scanning electron microscope). The presence of unaltered glass shards in some deposits is the most compelling evidence.

In large, economically viable deposits of bentonite, the parent rock is invariably tuffaceous material rich in volcanic glass. Most bentonite deposits are derived from ash falls, which provide the high surface area necessary for efficient devitrification. Poor to moderate drainage tends to lead to retention of silicon, aluminium, calcium, and magnesium, thus promoting alkalinity and stability of the smectite structure.

Bentonite is typically found as beds in marine and non-marine strata ranging in age from Permian to Pleistocene. The alteration of ash to bentonite is a hydration reaction that involves magnesium, and because of this bentonite is most commonly found in marine strata rich in magnesium. Bentonite also forms from ash when in contact with alkaline lake water or groundwater. Most bentonite is found in beds or lenticular bodies that are conformable and laterally continuous for up to 300 km. These beds range in thickness from several centimetres to tens of metres, and tend to form continuous stratigraphic horizons, layers, or lenses. The contacts of the beds may be variable. They can be sharp at both the top and bottom, gradational with the underlying beds and sharp at the upper contact, or have a sharp contact with the underlying beds and a gradational one at the upper contact. Less commonly, bentonite also forms as irregular-shaped bodies that grade into unaltered host rock; these deposits range from about 0.5 m to more than 10 m in length (Patterson and Murray, 1983; Elzea and Murray, 1994; Harben and Kuzvart, 1996).

Uses

Bentonite comprises loosely tied silica–alumina sheets that can be easily subdivided in aqueous solutions into unit-celled particles about $0.003\ \mu\text{m}$ thick and less than $0.1\ \mu\text{m}$ long. This arrangement of sheets promotes excellent dispersion in water due to the ease of separation and the unbalanced negative electric charges that repel each other in a polar media such as water. Such a property results in a variety of useful characteristics including dilatancy (the ability to swell up to about 15–30 times the original dry bulk volume without agitation), viscosity (resistance to flow), and thixotropy or gelling strength (Harben, 1995a).

Drilling mud

Bentonite is one of the most efficient materials used for drilling mud in those instances where the rocks penetrated contain only freshwater. It was first used as drilling mud in the late 1920s or early 1930s. Bentonite is used in high-chloride and hard-water environments. The role of bentonite in drilling fluids is to build an impervious coating on the wall of the hole, to increase the viscosity to about 15 centipoise to aid the removal of rock cuttings, and to provide thixotropic properties so that cuttings do not settle when movement of the drilling column ceases temporarily. The most critical specifications for bentonite used for drilling mud are the suspension properties, wet screen analysis, and moisture as shipped.

Suspension properties

Suspension properties are determined by viscosity, yield point, and filtrate tests. Determination of the viscosity and yield point involves preparation of a suspension consisting of 22.5 g of bentonite in $350\ \text{cm}^3$ of distilled water. The suspension is aged and then the viscosity determined and the yield point calculated from dial readings at 300 and 600 rpm using a direct-reading viscometer, according to procedure and equipment requirements outlined in the American Petroleum Institute (API) specifications (American Petroleum Institute, 1969). The filtrate test is another important test for suspension requirements. This test is a measure of the volume of water lost from the prepared suspension when it is tested in a pressurized filter press according to procedures outlined in the API specifications. The specifications for the above tests for bentonite in drilling muds are given in Table 3.

Wet screen analysis

Wet screen analysis (grit test) is a measure of the material in bentonite mud that is coarser than a 200 mesh ($75\ \mu\text{m}$) USA series sieve. The test involves mixing 10 g of bentonite in $350\ \text{cm}^3$ of water containing 0.2 g dispersing agent and then stirring, ageing, and washing the material through a sieve with a specified spray system outlined by the API specification. The residue on the sieve is then dried, weighed, and its percentage of the original bentonite is determined (Elzea and Murray, 1994; Harben and

Table 3. Specifications for bentonite in drilling mud

<i>Requirement</i>	<i>API bentonite</i>	<i>OCMA bentonite</i>
Suspension properties		
Viscometer dial reading @ 600 rpm (centipoise)	30	30
Yield point/plastic viscosity ratio	3	6
Filtrate volume, cm ³ , max.	15.0	16.0
Residue >75 µm (200 mesh US series) max.	4.0 wt%	2.5 wt%
Moisture, max.	10.0 wt%	13.0 wt%

SOURCE: Harben (1995a)

NOTE: API American Petroleum Institute
OCMA Oil Companies Materials Association

Kuzvart, 1996). The specifications for residue in drilling muds are shown in Table 3.

Moisture

The maximum moisture content is 10.0 wt% for API specification bentonite, and 13.0 wt% for Oil Companies Materials Association (OCMA) bentonite.

Iron ore pelletizing

Bentonite has been used since the late 1950s as a binding agent in the production of iron ore pellets and this continues to be a major use. Natural or sodium-exchanged bentonites are very effective at producing pellets with high mechanical strength and good thermal-shock resistance. Typical amounts of bentonite added are 7–10 kg/t of pellets, although the amount can be as low as 4–5 kg/t.

Specifications for bentonite used for pelletizing taconite-type iron ore have not been standardized, and its use in pelletizing varies with individual requirements and preferences. Some pelletizing plants use crude bentonite and mill it on-site, whereas others prefer to purchase processed ore. However, bentonite is not a perfect binding material as it contaminates the iron ore by adding unwanted silica to the blast furnace burden and increasing the required flux and coke. Nevertheless, bentonite remains the most widely used pellet binder despite many years of research into alternatives. Some pelletizing plants use alternative inorganic binders, such as dolomite and hydrated lime, where economics or chemical processes or both make them attractive, but such use is not widespread. The large number of variables that influence pellet characteristics complicates the testing of bentonite alternatives and makes comparisons difficult (Kendall, 1996).

However, a number of alternatives to the blast furnace iron-making route, such as direct reduction of iron ore, have emerged over the last two decades and these do not use pellets. These technologies constitute only a small proportion of the global iron-making capacity. According to Kendall (1996), the total world iron-ore pellet production in 1995 was 198.3 Mt and will increase to about 204 Mt in 2005.

Foundry sand

The foundry industry can be loosely divided into ferrous (cast iron and steels) and non-ferrous. Sand moulding processes are predominant within the ferrous sector, with green sand the most widely used mould material. The composition of a typical foundry-sand mix for high-pressure moulding would be 86–89% green sand, 5–7% bentonite, 2.5 – 3.5% water, 0.5% starch, and possibly up to 3% coal dust or a similar substitute to improve surface finish. Typical foundry requirements for sodium bentonite are shown in Table 4. Green-sand moulding is also commonly used in non-ferrous castings, but this sector has a larger number of alternative casting methods and a greater use of other binding systems.

The foundry sand industry has evolved considerably over the last two decades, with the replacement of straightforward bentonite usage by foundry additive blends. In addition to bentonite, the green-sand moulding formulations commonly contain materials such as seacoal, seacoal replacements, cellulose, starch, and pitch or other carbon sources.

The application of sodium and calcium bentonites as a binder in green-sand foundry moulds for metal casting is probably the largest single use for bentonite (Kendall, 1996). The role of bentonite is essentially to bind the sand grains together during the moulding and casting cycles. It also maintains structural integrity of the mould during

Table 4. Typical foundry requirements for sodium bentonite

Moisture	6–12%
pH	≥8.2
CaO	<0.70%
Liquid limit	600–850
Green compressive strength	>58 kPa
Green deformation	2.5%
Green shear strength	17 kPa
Green tensile strength	10 kPa
Dry compressive strength	656 kPa
Methylene blue capacity	100 meq/100 g ^(a)

SOURCE: Kendall (1996)

NOTE: The above specifications can vary widely depending on factors such as the metal being cast, the size and shape of casting, and the sand system in use

(a) Millequivalents per 100 g of clay

Table 5. Comparison of bentonites in green-sand moulding

<i>Sodium bentonite</i>	<i>Calcium bentonite</i>
Primary sand-binding agent	Primary sand-binding agent
Increases dry compression strength	Increases green compression strength
Increases hot compression strength	Lower hot retained strength; aids shakeout
Gives rapid bond development	Requires less pressure to make uniformly compacted moulds
Enhances mouldable moisture range	Can reduce mechanical penetration
Enhances durability	Imparts excellent flowability
Allows development of fine detail	–

SOURCE: Kendall (1996)

metal pouring and solidification, and will break down easily on shakeout, thus easing the removal of the casting. The proportion of sodium and calcium bentonites used varies depending on the desired mould properties, the metal being cast, and the size of casting. However, in volume terms the use of natural sodium bentonite is dominant. Generally sodium bentonite can be used in higher temperature castings than calcium bentonite, as it is more stable at higher temperatures. The primary foundry applications of sodium bentonite are in casting steel, ductile and malleable iron, medium to heavy grey iron, and, to a lesser extent, a range of non-ferrous metals. Tables 5 and 6 show some comparisons of sodium and calcium bentonites in foundry usage.

Absorbents

Bentonite clays have high adsorption (the ability to attract and hold ions or molecules of gas or liquid) and absorption (the ability to assimilate or incorporate materials) properties, and are highly hygroscopic. The clays will adsorb many times their own weight in liquid, and granules tend to bind together when wet. These properties are useful in a number of applications such as pet litter,

foundry sand, industrial absorbents, sealants, and bleaching oils.

Pet litter

The main requirements for pet litter are for high absorbency; suitable bulk density; clean, well-sorted, dust-free litter; odour control; moisture absorption; colour; and long life (Kendall, 1996). In addition, granules should be rounded, should not stick to the fur of pets, and must be of the correct size distribution. Different types of clay satisfy these qualities. Sodium and calcium bentonites compete with other absorbent clays such as sepiolite and attapulgite. ‘Clumping pet litter’ (also known as scoopable cat litter) was developed in the USA towards the end of the 1980s using microgranular (1–2 mm) blends of sodium bentonite, calcium bentonite, and attapulgite. The clay in clumping pet litter, on exposure to liquid, bonds and expands to form a clump that is unlikely to break apart and will resist scratching and sifting by cats. The clumps of cat urine and excrement are simply scooped out, thus leaving the unaffected pet litter for further use (O’Driscoll, 1992; Landis and Gaylord, 1999). In recent years, the market for scoopable pet litter has grown and that for traditional (non-clumping) pet litter has been steady. Between 1992 and 1994, the demand for bentonite in the USA for pet litter more than trebled, rising from 148 300 to 455 000 t. In 1996, the market had an annual growth of around 5% in the USA and 7% in Europe. Bentonite consumption for pet litter in Europe is around 19.5% of the total bentonite market (Baxter, 1997).

Industrial absorbents

Absorbent clays are widely used to control different kinds of spillages in many industrial situations. The main requirements of industrial absorbents are adequate mechanical strength, hardness, and abrasion resistance; chemical stability; non-flammability; and a high liquid-absorption capacity. Bentonite can be calcined to improve its mechanical strength when wet. Sodium and calcium bentonites are commonly used, but compete with other absorbent clays such as sepiolite and attapulgite (Kendall, 1996).

Table 6. Advantages and disadvantages of foundry bentonites

<i>Bentonite type</i>	<i>Advantages</i>	<i>Disadvantages</i>
Sodium	Good green strength, with high hot and dry strengths Best with hot sand Highest wet tensile strength Highest durability	Least flowable and most difficult to mull
Calcium	Highest green strength Mulls quickly Good shakeout Good flowability	Poor draw Least durable

SOURCE: Morrison (1999)

Table 7. Containment applications of sodium bentonite

<i>Containment type</i>	<i>Application</i>
Freshwater containment	Ornamental ponds and lakes, wetlands, golf courses, balancing ponds, reservoirs, canals
Wastewater containment	Sewage lagoons, reed beds, leachate and industrial-effluent lagoons
Landfill containment	Basal seals, caps, cut-off walls, gas barriers
Contaminated land	Caps, cut-off walls
Secondary containment	Tank farms, leach pads
Groundwater containment	Borehole sealants
Nuclear-waste containment	Underground repositories

SOURCE: Kendall (1996)

Containment (impermeable layers and liners)

Bentonite-based liners are increasingly used to provide hydraulic seals or barriers in a wide range of civil engineering applications such as the construction of dams, canals, reservoirs, settling ponds, and trenches (Table 7). The role of bentonite in other civil engineering applications is shown in Table 8.

When used as a containment liner, the bentonite platelets (0.2 – 2 µm in length) form a very effective fluid barrier resulting in a low-permeability seal. The high water absorption and resultant swelling contribute to the sealing characteristics of the clay by occupying void spaces. The uptake of free water can also help stabilize waste. Low-permeability layers are widely used to prevent leachate and gas escape from waste dumps.

In landfill containment, bentonite has been used for many years to enrich the soil and to form low-permeability layers at the base of landfill sites. For soil enrichment, bentonite (typically milled to minus 75 µm in size) is either mixed into the soil in situ (rotovation mixing) or the soil is excavated, mixed with bentonite, and then reapplied. The disadvantages of mixing in situ are that the resulting layer may not be homogeneous and more bentonite is required. Commonly, mixing in situ requires 7–8% bentonite compared with 5–6% for pre-mixing. The soil-enriched layer is normally 30 cm thick following compaction and may be used in conjunction with a plastic layer.

In recent times, a new market has emerged in the form of geosynthetic-clay (geo-clay) or geo-composite liners in which bentonite is combined with plastic or textile layers. Most geo-clay liners essentially comprise a thin layer of

Table 8. The role of bentonite in civil engineering applications

<i>Application</i>	<i>Role of bentonite</i>	<i>Details</i>
Diaphragm, cut-off, and retaining-wall construction	To support excavations until concrete pouring; to penetrate soil walls and create an impermeable membrane	3–10% sodium bentonite slurry stabilizes and imparts cohesiveness to ground walls
Bored piling, caisson sinking	Prevents cave-in; lubricates cutting tools and pile casings/caissons	As above, but milled bentonite can also be added directly to soil during auger boring to form a slurry with groundwater
Pipejacking	Lubrication; seals joints	
Cement/concrete additives	Increases workability; reduces bleeding of mixes	3% bentonite will increase workability and allow greater pumping distances
Grouting	Consolidation and stabilization or sealing of ground	Water-based bentonite grouts can be combined with cement or sodium silicate to vary setting times
Tunnelling	Face support and stabilization when tunnelling in difficult ground conditions; lubricates cutting bits; solids removal	3–5% sodium bentonite slurry maintained at pressure at the cutting face in front of a tunnelling machine supports the tunnel face. Excavated material transported to the surface in the bentonite slurry
Electrical earthing	Bentonite grout earths buried cables	Provides safety medium in case of cable fracture
Solids transportation	Enhances lubricity; prevents settling on standing	Additions of up to 3% sodium bentonite

SOURCE: Kendall (1996)

Table 9. Specifications for a typical geo-clay liner

Primary backing	Non-woven polypropylene or high-density polyethylene
Cover fabric	Woven polypropylene or polyester
Bentonite requirement	4.8 – 5.0 kg/m ²
Montmorillonite content	80–90%
Bentonite particle size	20–50 mesh
Thickness (unswollen)	6–10 mm
Permeability coefficient	2×10^{-10} cm/sec

SOURCE: Kendall (1996)

bentonite sandwiched between synthetic fabrics. These fabrics include woven and non-woven polypropylene (Harries-Rees, 1993; Kendall, 1996), and high-density polyethylene (HDPE). The uppermost layer is permeable to enable the encapsulated bentonite to swell, producing an impermeable, self-sealing flexible layer. The specifications of a typical geo-clay liner are shown in Table 9.

The bentonite within the liner can also be tailored to the application through chemical treatment. In some applications, there may be aggressive attack from certain species such as sulfates or chlorides that will cause a partial collapse of the bentonite swell. Such collapse can be avoided by treating bentonite with a polymer such as anionic polyacrylamide that will lock swelled clay particles together.

One containment application that may grow over the next few years is in high-level nuclear-waste repositories. The impermeable and self-sealing nature of sodium bentonite is ideally suited for isolating canisters of waste from groundwater (Kendall, 1996).

Animal feed

Bentonite has long been used as a binding agent in the production of pelletized feeds. In addition to its role as a binding agent, it improves material flow and reduces die adhesion and friction during pelletization. It can also impart a number of medicinal or nutrient-related benefits, such as slowing the passage of feed through the gut and thus maximizing nutrient uptake.

In 1992, an innovative producer in Pakistan designed an edible grade of bentonite called ‘repotentiated bentonite (RB)’. Its efficacy and performance has been authenticated from extensive field and institute-level biological trials in Pakistan. During these trials, scientists observed that the inclusion of 1% RB in basal feed to broiler chicken feed could result in an extra 32% weight gain. They also noted an increase in edible meat percentages, with better bone-to-meat ratios. Results also revealed that the addition of 1.5% RB to feed for layer hens increased egg production by 15%. The egg size increased by 10% and the eggs had stronger shells (Saeed, 1996).

In addition to improving feed efficiency, bentonite has significant effects on milk yield from cattle. In dairy cattle farming, a supplement of around 300 g/day per head of cattle of sodium bentonite increased milk yield by 10%

and also increased milk content and protein yields. It also increased the solids content of the dung. In feeds including wheat, bentonite is useful in counteracting the risk of acidosis and will help animals adapt to high-grain and rapidly fermentable feeds used in fattening yards. Sodium bentonite has also been shown to reduce the incidence of scouring in poultry and pigs.

Furthermore, the absorptive properties of bentonite can also be tailored to give additional benefits to livestock. Bentonite will readily bind to natural toxins such as aflatoxin and mycotoxin, thus preventing their uptake in the gut, and can help suppress high blood-urea levels, thereby reducing the effects of excessive soluble nitrogen on cow fertility (Kendall, 1996).

Bleaching oil

Most vegetable, animal, and fish oils require refining to remove impurities such as phosphatides, gums, trace metals, and free fatty acids that may produce oxidation products leading to degradation and short shelf life of the final product. Bleaching clay adsorbs many of these products and also reduces the red, yellow, and green colouration, produced by compounds such as carotene, carotenoids, xanthophyll, and chlorophyll, to more acceptable levels. A number of characteristics determine the efficiency of material used as a bleaching clay. These characteristics are adsorption capacity, acid properties, catalytic properties, ion-exchange capacity, and particle-size distribution (Santaren, 1993).

Detergent

Bentonite is used in the production of detergents, principally as an antidepositing and softening agent. This application is widespread in Latin America, and white sodium and calcium bentonites are almost exclusively used. Mexico has plentiful reserves of both these bentonites. However, actual properties and functions of bentonite in this application are closely guarded secrets, but in general the average physical properties that determine the specifications are apparently fineness, viscosity, flocculation, and brightness (Nebergall, 1988; Table 10).

Other uses of white bentonite are in pharmaceuticals, cosmetics, toiletries, and other uses such as surface coatings, electrical ceramics, catalytic carriers, and refractories (O’Driscoll, 1988; Russell, 1991).

Table 10. Typical properties of export-grade bentonite from Mexico for use in detergents

<i>Property</i>	<i>Sodium bentonite</i>	<i>Calcium bentonite</i>
Fann viscosity (centipoise)	18	4
Flocculation	no	yes
Fineness (<200 mesh)	90%	90%
Brightness	82	87

SOURCE: Nebergall (1998)

Exploration and evaluation

The first step in bentonite exploration is to identify geologically favourable target areas that are likely to contain bentonite deposits. For example, bentonite often forms as a result of the subaqueous alteration of volcanic tuff, especially ash, or volcanoclastic sediments derived from them. Another useful feature is that many bentonite deposits in the world are associated with Cretaceous and Tertiary marine strata.

After the identification of target areas, a reconnaissance field program is commonly conducted to establish whether any bentonite deposits are present. The characteristic 'popcorn' texture is a simple guide for its identification. A good quality bentonite should be compact, soft and soapy to the feel, and it is slippery when wet. The colour is commonly dark green or grey when buried under thick overburden, becoming yellowish green or yellow when weathered and near the surface. However, the nature of the parent rock and the history of alteration affect the colour. After preliminary identification of the deposit, additional work involving mapping and drilling should be carried out to estimate the resources available.

Factors such as the amount of overburden, the distance to processing plants or markets, available transportation, and the available resource have to be considered before capital is invested in evaluation and extensive testing of the deposit.

Laboratory testing

A thorough mineralogical investigation of a bentonite deposit is very important, as the behaviour of bentonite in industrial processes is entirely dependent on the structure of the smectite mineral, and on the other mineral phases present. X-ray diffraction is the most important method used for identification of the minerals. This method is rapid and identifies any impurities present. X-ray diffraction results may be complemented by other techniques such as thermal analysis and infra-red spectroscopy. Differential thermal analysis (comparison of the effects of heating of the sample with an inert material) coupled with thermogravimetry (weight loss on heating) can be used to obtain information about the dehydroxylation and heat decomposition of the bentonite. Such information is useful in assessing the likely behaviour of the clay in foundry sands and iron-ore

pelletizing applications. Infra-red spectroscopy helps in recognizing the type of smectite present. Electron-beam techniques such as scanning electron microscopy can be used to obtain additional information about the textural relationships between smectite and its associated impurities. The identification of such impurities is important. For example, impurities such as cristobalite, which is present in the form of opal (smaller in size than 2 µm) in some bentonite, can form intimate intergrowths with smectite 'flakes' and affect the rheological and binding properties of the bentonite. The reason for this is that the rheological and binding properties of bentonite depend on the interaction between the individual smectite flakes and stacks of crystals (Christidis and Scott, 1993).

Quantitative chemical analysis is not useful in assessing the technical properties of the clay. However, a knowledge of the chemical composition, including the composition of the exchangeable ions, is useful for identifying or confirming whether the type of bentonite present is sodic, calcic, or another variety.

Quality and grade

In the evaluation of many mineral deposits, the terms 'grade' and 'quality' are synonymous and express the concentration of the useful chemical element or mineral in the raw material. However, this does not apply to bentonite deposits because its performance in various industrial applications does not depend only on the absolute quantity of smectite present. In the case of bentonite, quality refers to the performance of the material in its different applications, whether in its natural or modified form, whereas grade refers to the smectite content of the bentonite.

Quality

The quality of bentonite can be assessed by a combination of three main criteria (Christidis and Scott, 1993). These criteria are the sodium carbonate exchange, a swelling test, and the liquid limit of the material.

Sodium carbonate exchange is the amount of sodium carbonate required by a bentonite to attain optimum properties, and is relevant to bentonite in which the exchangeable cations are dominantly calcium or magnesium. These bentonites have inferior properties for most applications unless they are sodium exchanged. The swelling test is a measure of the swelling efficiency of the raw material in distilled water in terms of a gel volume obtained from a known amount of clay. The liquid limit is the minimum moisture content required for fluidity in a clay and water mixture. It is a measure of the bonding efficiency of the clay and is a routine test for bentonite in the foundry industry.

Quality can be affected by secondary processes that can result in a lowering of the bentonite gel pH or the formation of smectite with different lattice dimensions. The latter effect can be caused either by different substitutions in the alumina part of the alumina-silica structure or by oxidation or reduction of iron.

Grade

The grade of a bentonite-bearing clay increases with increasing smectite content, and can be assessed by measurement of the CEC or the surface area, or both. Assessment of grade by CEC measurement is the preferred method in industry, and smectites have a high CEC relative to other clay minerals. The range of CEC values for most commercial bentonites is 60–150 meq/100 g, with higher grade varieties generally in excess of 100 meq/100 g. The surface area is determined by adsorption of ethylene glycol monoethyl ether (EGME). For pure smectites, the theoretical EGME adsorption value is of the order of 800 m²/g.

The procedures outlined above for assessing bentonite are appropriate for preliminary evaluation of a bentonite deposit using samples collected from surface exposures, trenches, and drillcore. The tests are not specific to any one industry, but provide data on the overall properties of the clay from which potential uses can be established. Further tests are required to assess the material for specific applications.

Mining and processing

Mining

Bentonite is commonly mined using highly selective openpit methods. Many deposits in the USA are mined by stripping methods (e.g. Wyoming). However, bentonite is also mined by underground methods in a number of countries (e.g. the Combe Hay district in the UK; Beatty, Nevada in the USA; and Choushen and Linan in China).

In openpit mines, bulldozers and scrapers or pans are most commonly used in removing overburden. In a typical pit, the overburden is removed in panels, the clay is mined by loading trucks with a dragline or endloaders, and then the overburden from an adjacent panel is shifted to the mined-out area. The thickness of overburden removed is variable. For example, most Wyoming-type bentonite deposits in the USA have less than 9 m of overburden, and many Chinese deposits have an overburden of less than 5 m. Some deposits in the southern USA have overburden depths as great as 30 m (Zhu, 1985; Elzea and Murray, 1994). Generally, the rock material in the overburden is soft and can be loaded directly by self-propelled or pushed scrapers, although in some places loosening of the material by bulldozers or rippers may be required before loading.

In many bentonite deposits, selective mining is required due to the variable physical properties of the clay. Bentonite from a single pit or bed may be separated into three stockpiles, each with different physical properties. These separate stockpiles can then be blended or used separately to prepare bentonite suitable for different uses. In some places, blending of bentonite is done while it is dumped on stockpiles using earth-moving or cultivating equipment.

Processing

Beneficiation and processing of bentonite typically involve crushing, drying, grinding, and packaging. In most plants, the raw clay is passed through some type of clay ‘slicer’, before drying, to break up the large chunks to sizes below 20 mm. Soft bentonite does not need to be crushed.

The average water content of soft bentonite is approximately 30%, and that of hard bentonite is approximately 18%. The water content of bentonite is reduced to about 8% in the drying process. Drying can be done using a fluid-bed dryer, where the temperature varies with the intended use of the bentonite. The temperature in dryers is likely to be approximately 800°C at the inlet, 100–200°C at the outlet, and 400–500°C in the main drying zone. Some countries (e.g. China) reduce the water content of soft bentonite to approximately 15% by natural drying, then the material is further dried by hot air to bring down the water content to 8–12% for milling (Zhu, 1985; Elzea and Murray, 1994).

The dried bentonite is ground and sized in several ways. In some plants, rods in rotary dryers do much of the grinding. However, most of the powdered product is ground with roll and hammer mills or other pulverizers, followed by screening (Fig. 2). Most bentonite is ground to approximately 90% finer than 200 mesh (75 µm).

Several types of packaging are used for transportation of bentonite. Multiwalled paper bags (some with plastic liners) are most commonly used for transportation of other than bulk shipments. Fibre drums are used for speciality products sold in small quantities. With applications that require lengthy periods in storage or involve repeated handling, bentonite has to be stored in metal drums, usually of 45 kg capacity. Most of the granules sold for pet litter are packed in 4.5 – 13.6 kg paper bags.

The transportation method depends on the end-use and the location of markets. Processed bentonite may be transported by rail in bulk hopper cars, but boxcars and bulk trucks can also be used. Bentonite is commonly pelletized and bagged for shipment by either rail or truck. Ore-carrier ships, with bentonite as the only cargo, are used for overseas shipments in the USA. Bentonite transported in this way is semi-crude and only partly dried at the point of origin, making it possible to load and unload by bulk-handling equipment. However, the bentonite has to be further dried and ground before usage (Elzea and Murray, 1994).

Production and market trends

Production

Data on global bentonite production is not readily available, and that which exist appear to be approximate due to the confusion of nomenclature. Available production figures indicate that annual global production of bentonite is approximately 8–9 Mt (Table 11). However, total annual global production is likely to be much higher, as China is known to be a major world producer and is

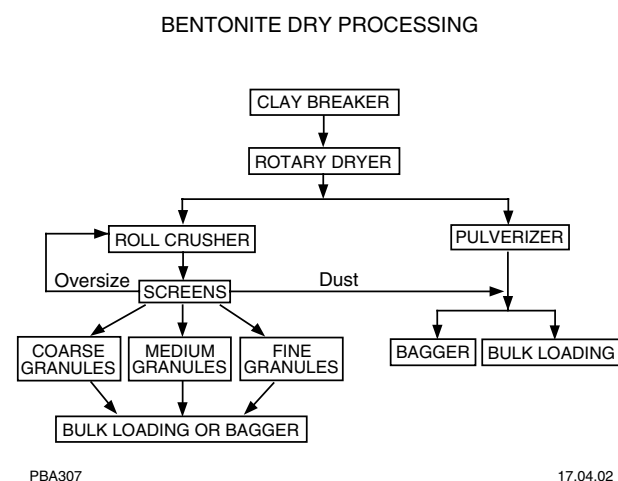


Figure 2. Flow sheet for the processing of bentonite (after Elzea and Murray, 1994)

not included in this total. It is estimated that China produced 1.4 Mt in 1994, but exact production figures on an annual basis are not available. The USA is the world's largest producer of bentonite, with production of around 4 Mt of bentonite in 1997. Other major producers of bentonite in excess of 450 000 t per annum include China, Greece, Germany, Italy, Turkey, and Japan.

USA

Bentonite in the USA is found mainly in Upper Cretaceous and Tertiary rocks. The most important localities for high-swelling or sodium bentonite (also known as Western or Wyoming bentonite) are Wyoming and Montana, and the

western border of South Dakota. The important areas for low-swelling or calcium bentonite are Mississippi, Texas, California, Colorado, and Arizona.

Wyoming bentonite (Western bentonite)

Major deposits of Wyoming bentonite are present in two districts centred on the state of Wyoming. The first of these is the northern Black Hills district of northeast Wyoming and western South Dakota, centred on the town of Colony. The Black Hills district is the oldest sodium-bentonite mining district in the world, and produces high-quality sodium bentonite mainly for the foundry and drilling mud industries, and to a lesser extent for civil engineering applications and cat litter. In this district, bentonite is mined from five discrete bentonite horizons in the Lower Cretaceous Newcastle Sandstone and Mowry Shale, and the overlying Upper Cretaceous Bell Fourche and Pierre Shales. In general, the thickness of the bentonite horizons in these formations averages 1–2 m and is up to 4 m in places (Harben and Kuzvart, 1996).

Wyoming bentonite is also mined in the Hardin District. These deposits are found northwards from Thermopolis and Kaycee in the Big Horn Mountain region of central Wyoming to Cody, Lovell, Malta, and Glasgow in Montana. In the Hardin District, sodium bentonite beds are found in a 1500 m-thick sequence of Lower to Upper Cretaceous marine strata. The Upper Cretaceous sequence consists of the Soap Creek bentonite in the Belle Fourche shale. The bentonite horizons in this sequence range in thickness from 4 m to more than 10 m. Other bentonite-producing formations include the Cody and Bearpaw Shales. End-uses for bentonite from the above regions include absorbents, animal feed, drilling fluids, foundry sand binders, wine clarification, iron ore pelletizing, and environmental and construction applications.

Table 11. World production of bentonite (thousand tonnes)^(a)

Country	1990	1991	1992	1993	1994	1995	1996	1997
United States of America	3 530	3 487	3 001	2 916	3 343	3 881	3 740	4 020
Greece	602	610	610	689	698	1 115	974	950
Turkey	100	126	126	464	524	508	482	519
Italy	232	408	153	332	392	402	472	513
Germany	586	592	590	481	483	529	491	511
Japan	558	563	543	525	492	486	469	496
Spain	153	152	152	152	152	152	151	150
Argentina	109	110	100	99	99	99	135	130
Mexico	147	147	138	97	102	93	70	112
Iran	52	41	49	86	85	86	84	85
South Africa	67	66	45	51	73	72	48	33
Romania	15	15	122	122	102	102	44	27
Former USSR	2 743	2 438	2 032	1 626	1 321	1 321	–	–
Zimbabwe	102	102	84	84	172	173	–	–
Brazil	183	132	133	115	142	142	110	–
Cyprus	83	60	60	53	48	51	–	–
Others	383	461	242	197	257	261	1 110	1 244
Total	9 645	9 511	8 180	8 088	8 495	9 018	8 380	8 790

SOURCE: Harben and Kuzvart (1996); Hatjilazaridou et al. (1998); Reuther Ernst-Ulrich (1998); Maranzana (1998); British Geological Survey (1999)

NOTE: (a) Does not include Chinese annual production (estimated at 1.4 Mt in 1994)

The origin of the Wyoming bentonite is related to the ejection of massive quantities of pyroclastic material from volcanic centres in the Rocky Mountains during the Cretaceous. Vast thicknesses of rhyolitic ash were repeatedly deposited as volcanogenic sediments in the sea to the east of the mountain range. Subsequent compaction and alteration of this material have produced some of the richest accumulations of sodium bentonite in the world.

Companies producing Wyoming bentonite include American Colloid Co., M.I. Drilling Fluids Co., Bentonite Corporation, Black Hills Bentonite Co., Wyo-Ben Inc., and Bentonite Performance Minerals (Harben and Kuzvart, 1996; Keegan, 1998).

Calcium bentonite (Southern bentonite)

Most calcium bentonite is mined in Mississippi, Alabama, and Texas, with other producing deposits located in Missouri, Illinois, and Tennessee. Bentonite from these regions is primarily for use in foundry moulding sands, as a refining agent in oils and fats, as a rheological additive, and in a variety of speciality applications. This area is the second largest production area of bentonite in the USA.

Bentonite deposits are found throughout the Gulf Coast region and have formed in Cretaceous to Middle Tertiary beds. In Mississippi, commercial deposits of calcium bentonite formed in the Upper Cretaceous Eutaw and Ripley Formations and the Tertiary Vicksburg Formation. The latter formation is also a source of bentonite in Alabama. In Texas, extensive bentonite deposits formed in the Tertiary Jackson and Gueydan Formations. Some of these clays are treated to produce organophillic clays for use as rheological additives in liquid organic systems such as paint, ink, grease, and cosmetics. Untreated calcium bentonite mined in Texas has a major market for use as a rheological additive for ceramic glazes, as a plasticizer in whiteware, and as a plasticizer and binder in plastic refractory materials. Texas bentonite also has a growing market in water treatment (Elzea and Murray, 1994; Harben and Kuzvart, 1996).

Principal producers of calcium bentonite include Harshaw-Filtrol, and American Colloid Co. (Mississippi); Southern Clay Products Inc. and Milwhite Co. (Texas); and Absorbent Clay Products Inc. and Aimcor (Tennessee).

Other deposits

A number of small, but significant deposits are mined in other areas of the USA. Sodium bentonite, used primarily for the preparation of livestock feed (and also used in cat litter), is mined from the Miocene Chalk Hills Formation southwest of Boise, in Idaho. Bentonite is also mined from deposits in California, western Nevada, and Arizona. In California, a deposit made up largely of hectorite is situated near Hector, about 55 km east of Barstow, and has been mined since 1931. Hectorite is used in applications where special properties such as high viscosity, gel strength, temperature stability, and colour are required. Most of the applications of hectorite require highly customized blends that have been developed over a long

period of time in close conjunction with customers (Pulliam-Fitzgerald and Kendall, 1996). In Nevada, the most important bentonite deposits are in the Amargosa Valley, a desert basin with an area of 1550 km² that is situated east of Death Valley. In this area, bentonite, saponite, sepiolite, and hectorite are present in nearly flat-lying beds, probably of Pleistocene age. The main bentonite-producing area (mainly calcium bentonite) in Arizona is around Sanders and Cheto, in Apache County. Sodium bentonite, used in the civil engineering and drilling mud industries, is mined near Adrian, in Oregon. Several small deposits of sodium and calcium bentonite located in San Pele County are mined primarily for civil engineering applications.

Greece

Greece produces approximately 0.95 Mtpa of bentonite (Table 11), and ranks as the second largest producer in the world (from available production figures). Both natural calcium bentonite and sodium-exchanged calcium bentonite are produced for a variety of uses such as iron ore pelletizing (37%), foundries (33%), civil engineering (19%), cat litter (6%), and drilling mud (5%). Most of the products are exported to Western Europe, North America, and some countries of the former USSR.

The major production is from the island of Milos, with periodic production from the nearby island of Kimolos. The bentonite on Milos contains predominantly calcium montmorillonite (>80%). The deposits have formed in recent geological times in a marine environment as a result of hydrothermal alteration of acid volcanic rocks and associated tuffs. Subsequent hydrothermal alteration has modified the mineralogy and physical properties of these bentonites to varying degrees. Impurities include quartz, feldspar, unaltered volcanic glass, and kaolin.

The major producers of bentonite in Greece are Silver & Baryte Ores Mining Co. SA and Mykobar Mining Co. SA. These two companies produce more than 80% of the total output from Milos, and both companies use their own installations for the activation of bentonite with soda ash. Silver & Baryte Ores Mining extracts bentonite from several openpits on Milos — the largest one being the Aggeria mine. The reserves in the Aggeria mine are estimated to exceed 20 Mt (Elzea and Murray, 1994; Harben and Kuzvart, 1996; Hatjilazaridou et. al., 1998).

Former USSR

In 1995, the former USSR countries produced over 1.3 Mt of bentonite (more recent figures are not available; Table 11). The main deposits in the former USSR are located in the following countries: Crimea (Kurtsev deposit), the Transcarpathian region (Pyzhev and Gorbsk deposits), Azerbaijan (the Khaular deposit of Cretaceous age), Georgia (Gumbri and Askani deposits), Turkmenistan (Oglanly deposit), Uzbekistan (Azkamar deposit), Ukraine (1.5 – 8 m-thick Miocene beds at Cherkassy), and Kazakhstan where bentonite of Palaeocene age formed by the alteration of hydromica (Harben and Kuzvart, 1996).

China

Bentonite production figures from China are not readily available, but according to Wen Lu (1998) 1.4 Mt was produced in 1994. Both sodium and calcium bentonite are produced from Jurassic, Cretaceous, and Tertiary beds that are present in various parts of China.

The Heishen mine in the Liaoning Province is the largest openpit bentonite mine in China, and has an annual production capacity of 200 000 t. Bentonite in this deposit has formed as a hydrothermal alteration product of obsidian and tuff that is sandwiched between overlying rhyolite and underlying andesite. The thickness of the bentonite beds ranges from a few metres to tens of metres.

Linan mine, located in the Zhejiang Province, is the largest underground bentonite mine in China. The mine has an annual production of approximately 27 000 t of sodium bentonite, 27 000 t of sodium–calcium bentonite, and 5000 t of activated calcium bentonite. The commercially important bentonite beds, ranging in thickness from 1.7 to 5 m, are present about 174 m below the surface, located between dark-grey calcareous shales above and calcareous and sandy shales below (Zhu, 1985; Harben and Kuzvart, 1996; Baxter, 1997).

Germany

Germany produces approximately 0.5 Mtpa of bentonite of several grades (Table 11). These include acid-activated bentonite, which is a high-quality decolourizing product, and sodium-exchanged bentonite sold primarily for oil-well drilling and foundry applications. Other expanding markets include cat litter and oil sealants.

Calcium bentonite is mined from deposits in Bavaria, where it is present in marine marls and tuffaceous sands in the Upper Miocene Molasse. The production localities in Bavaria are mostly around Moosburg, Mainburg, and Landshut, and many bentonite beds in Bavaria have no commercial value due to the presence of high proportions of illite and kaolinite. The main producer is Sud Chemie, which has mining and processing operations around Moosburg. The other significant producers include Erbsloh Geisenheim GmbH & Co. and Marx Bergbau GmbH & Co. (O'Driscoll, 1992; Elzea and Murray, 1994; Harben and Kuzvart, 1996).

Turkey

Turkey produces approximately 0.5 Mtpa of bentonite (Table 11). Most of the production is from Cretaceous beds in the Ankara region. The types of bentonites produced in Turkey include white bentonite (bentonite with a range of off-white hues), sodium bentonite, and calcium bentonite. White bentonite deposits are found in Unye, Kutahya–Basoran, and Balikesir. The most important sodium bentonite deposits, along with some sodium–calcium bentonite deposits, are found at Tokat Re Sadiye, 450 km east of Ankara, and Cankiri Kursunlu, just north of Ankara.

Samas Sanayi Madenleri AS produces bentonite that ranges in composition from sodium–calcium to calcium bentonite from deposits around Tokat Re Sadiye. This company has a grinding plant in Re Sadiye that produces oil-well drilling, foundry, and iron-ore pelletizing grades. The sodium bentonite deposits at Cankiri are mined by Emko Bentonit Ticaret ve Sanayi AS, and are used mainly in the domestic market by the iron and steel industry as a binding material in foundry sand. The calcium bentonite deposit at Unye is mined by Kayac Industrial Raw Materials and Marketing Co. Ltd, which also operates a sodium bentonite mine at Fatsa (Ozdemir and Sezer, 1987; Elzea and Murray, 1994; Harben and Kuzvart, 1996; Ciullo, 1996).

Japan

In recent years, Japan has produced over 0.46 Mt of bentonite annually (Table 11). Sodium bentonite and an unusual 'acid-clay' are the two major types mined in Japan. Most of the Japanese bentonite production is from Yamagata, Niigata, and Gunma Prefectures on Honsu, the main island. An excellent swelling bentonite in Yamagata Prefecture is thought to have formed from zeolites derived from chemical alteration of volcanic ash in a marine environment. The bentonite beds (1–2 m thick) in this area are part of a series of Miocene tuffaceous strata intercalated with hard shales. To the south, in Niigata Prefecture, bentonite deposits are found within the Miocene Nanatani (Awase) Member. Economically significant deposits are also found at Kanto and Teikoku, around Mikawa. The Kanto deposit has formed by hydrothermal alteration of rhyolite, forming an aggregate of very fine fibrous or lamellar montmorillonite and cristobalite. The Teikoku deposit is massive and has formed by hydrothermal alteration of a rhyolitic tuff. In Gunma Prefecture, bentonite deposits are present in a zone 24 km long and 2 km wide, and are associated with tuffaceous beds intercalated with Tertiary marine sediments. Bentonite that has formed from Miocene–Pliocene tuffs is found on the northern island of Hokkaido. The 'acid-clay' deposits are found in the Yamagata and Niigata Prefectures.

The main producing companies are Kunimine Industries Co. Ltd and Hojun Kogyo Co. The main company producing 'acid-clay' is Mizusawa Industrial Chemicals Ltd (Elzea and Murray, 1994; Harben and Kuzvart, 1996).

Italy

In 1997, Italy produced 0.513 Mt of bentonite (Table 11), and most of this comes from the island of Sardinia, with processing plants located on the mainland. On Sardinia there are large calcium bentonite deposits that have been formed by the hydrothermal alteration of trachytes and trachytic tuffs. One deposit at Uri, on Sardinia, comprises a succession of lenticular beds of bentonite 1–2 m thick within a trachyte–andesite. White bentonite, formed through the hydrothermal alteration of volcanic ash during the Miocene–Pliocene, is mined from a locality at S'Aliderru in northwestern Sardinia.

More than 50% of the bentonite production is controlled by Laviosa Chimica Mineraria SpA, which produces from areas around Pedra de Fogu and Puntenuova on Sardinia. The processing plants for this company are located at Oristano on Sardinia and at Livorno, south of Pisa. The second largest producer of bentonite in Italy is Sud Chemie Italia SpA, which has both its mine and plant at Giba in the Cagliari district of Sardinia. Caffaro SpA produces acid-activated montmorillonite from the deposits on Sardinia (Elzea and Murray, 1994; Harben and Kuzvart, 1996).

Spain

Spain produces approximately 0.15 Mtpa of bentonite (Table 11). Calcium bentonite is mined in Madrid and Almeria. The deposits in Almeria have been formed by hydrothermal alteration of rhyolites and andesites. Spain produces many grades of bentonite from natural, acid-activated, and sodium-exchanged bentonite varieties. The grades include those for use in drilling mud, foundry, civil engineering, animal feed, wine clarification, oil bleaching, and ceramic applications, and other speciality applications such as carbonless copy paper.

Australia

Large deposits of bentonite are known in Queensland and in New South Wales, and the current production in Australia is mostly from these two States, with a small output from Western Australia. Victoria has not produced any bentonite in recent times, but has produced it in the past.

Queensland

Queensland produces approximately 60 000 t of bentonite annually, and the production during 1996–97 was 57 753 t valued at \$A5.6 million. The known bentonite deposits in Queensland are present in the Cretaceous Orallo Formation in the Miles district, the Tertiary volcanic rocks in the Upper Yarraman district, the Walloon Coal Measures in the Rosewood–Walloon district, the Black Alley Shale in central Queensland near Springsure, and the Petrie Formation in the Brisbane area.

Most of the production of bentonite in Queensland comes from the Upper Orallo Formation in the Miles district, about 350 km west of Brisbane. This formation contains high-quality sodium bentonite horizons near the surface. The largest and oldest bentonite mine in the Miles district is at Gurulmundi, located about 30 km north of Miles. The deposit, now owned by Unimin, has resources of 12 Mt, of which over 3 Mt is premium-grade bentonite. The bentonite from this mine is used in a number of applications such as an additive in stockfeed, foundry moulds, the manufacture of refractory linings and ceramics, civil engineering, for cleansing wines, as an additive in drilling muds, and for horticulture. Another mine located approximately 6 km northwest of Gurulmundi has a proven reserve of 2 Mt of bentonite, with a further 10 Mt of probable reserves. Bentonite from this mine is used in stockfeed, cat litter, and as an oil absorbent. A deposit containing proven reserves of 0.4 –

0.5 Mt of bentonite is mined 5 km southwest of Miles, and is sold for use in stockfeed, medicines, cat litter, and for sealing dams.

Bentonite in altered Tertiary alkali–acid volcanic ash is mined at Meandu Creek in the Upper Yarraman district, located approximately 130 km northwest of Brisbane. This deposit has formed from altered volcanic ash that was deposited in a lacustrine environment. In the Rosewood–Walloon district, located approximately 50 km southwest of Brisbane, bentonite is mined as a byproduct from two coal mines. In these mines, bentonite is found in the upper coal sequence of the Walloon Coal Measures. Significant bentonite deposits are also known in a number of other localities in Queensland, and these include deposits in the Black Alley Shale at Mantuan Downs, southwest of Springsure, and the Petrie Formation in the Brisbane area (Carmichael, 1995; Keeling, 1997).

New South Wales

The annual production of bentonite in New South Wales averages approximately 10 700 t, and is from a deposit at Cressfield, owned by Unimin. The company also owns the bentonite operation at Gurulmundi in Queensland and aims to have combined production capacity of 100 000 tpa from operations in Queensland and New South Wales. The bentonite at the Cressfield mine is the calcium variety, but is treated to produce a sodium variety for foundry and civil engineering applications. A large deposit of high-purity sodium–magnesium bentonite is known at Arumpo, 80 km northeast of Mildura. The deposit was discovered in 1978 by CRA (now Rio Tinto) and is currently held by Arumpo Bentonite (a subsidiary of MultiEmedia.Com), and according to an announcement by the Australian Stock Exchange released in October 1999, MultiEmedia.Com has sold Arumpo Bentonite to Sunraysia Bus Lines). The deposit is large by world standards and has been intersected in 50 drillholes within an area of 8 km². The main seam is flat to gently dipping, with an average thickness of 5 m, and has a clay–sand overburden averaging 14.6 m thickness. Drilling indicates a strike length of 6 km and a width in excess of 1 km. The deposit is estimated to contain an indicated resource of 70 Mt of bentonite. The material is currently supplied to pet litter markets, but work is continuing to produce material suitable for other applications such as in civil engineering (Browns Creek Gold NL, 1993).

Victoria

In Victoria, there has been no production of bentonite in recent years, but 7064 t was produced during 1979–89 from the Greenwald deposit, 4 km southwest of Greenwald, which is located approximately 40 km northwest of Portland. In this deposit, calcium bentonite has formed at the top of a sequence of limestone and marl (known as the Middle Miocene Gambier Limestone), and is overlain by weathered Newer Volcanics basalt and minor quartz–mica silt, which occurs as a 12–35 m-thick overburden. The bentonite bed is 0.3 – 6.0 m thick, extends over an area of approximately 2 km², and is exposed at the edges of the plateau where erosion has removed the overlying basalt. Drilling has outlined measured resources

Table 12. Bentonite production in Western Australia (tonnes)

<i>Year</i>	<i>Marchagee</i>	<i>Woodanilling</i>	<i>Gunyidi</i>	<i>Watheroo</i>	<i>Total</i>
1942	16	—	—	—	16
1943	162	—	—	—	162
1944	430	—	—	—	430
1945	51	—	—	—	51
1946	63	—	—	—	63
1947	45	—	—	—	45
1948	273	—	—	—	273
1949	152	—	—	—	152
1950	216	—	—	—	216
1951	456	—	—	—	456
1952	595	—	—	—	595
1953	221	—	—	—	221
1954	1 140	—	—	—	1 140
1955	657	—	—	—	657
1956	1 426	—	—	—	1 426
1957	754	—	—	—	754
1958	38	—	—	—	38
1959	135	—	—	—	135
1960	388	—	—	—	388
1961	596	—	—	—	596
1962	493	—	—	—	493
1963	1 216	—	—	—	1 216
1964	478	—	209	—	687
1965	428	—	508	—	936
1966	376	—	196	—	573
1967	114	—	—	—	114
1968	38	—	—	—	38
1969	255	—	4	—	259
1970	99	18	—	—	117
1971	20	—	—	—	20
1972	165	—	—	—	165
1973	290	—	544	—	833
1974	328	—	241	—	569
1975	685	—	253	—	938
1976	564	—	—	—	564
1977	147	—	—	—	147
1999 ^(a)	—	—	—	358	358
Total	13 511	18	1 954	358	15 841

NOTE: (a) Financial year (1999–2000)

Marchagee: MC 258H, 282H, 283H, 259H, 288H, 290H, 294H, 295H, 437H, 438H, 439H, 456H, 484H, 537H, and 1042–1045H;
Woodanilling: MC 1720H; Gunyidi: MC 907H, 1070H, and 1055H

of 2.5 Mt of bentonite at 10% moisture. In addition, indicated resources are estimated at 3.3 Mt and inferred resources at 2.4 Mt (both at 10% moisture). The other significant deposit of bentonite in Victoria is at Gellibrand, located on the northern flanks of the Otway Ranges, 28 km south of Colac. The bentonite in this deposit is interbedded with Lower Cretaceous Otway Group sediments containing arkose, mudstone, and shale. The main bentonite layer is 7.3 – 8.3 m thick and has a proven strike length of 300 m. Depending on the parameters set for the recovery of the bentonite, the deposit is estimated to contain measured resources of 28 000 – 170 000 t and indicated resources of 57 000 – 340 000 t (McHaffie and Buckley, 1995).

Western Australia

Western Australia produced 15 483 t of bentonite valued at \$A117 285 during 1942–77, and from 1999 the State

resumed production (358 t during 1999–2000) from deposits at Watheroo (Tables 12 and 13). The production has been erratic, with the highest annual production of 1426 t recorded in 1956. The main production areas (Table 12) were Marchagee (13 511 t) and Gunyidi (1954 t), which are located not very far from each other. In 1999, Watheroo Minerals commenced production of small quantities of bentonite (saponite) from the Watheroo deposits, located in the Marchagee area. These and other deposits in Western Australia are discussed in the section on **Bentonite in Western Australia**.

Market trends

The prices of bentonite are dependent on the source and quality of the raw material and not on the type of application. Commonly, the prices are lowest for natural crude bentonite varieties, followed by sodium-exchanged

Table 13. Value of bentonite production in Western Australia (\$A)

<i>Year</i>	<i>Marchagee</i>	<i>Woodanilling</i>	<i>Gunyidi</i>	<i>Watheroo</i>	<i>Total</i>
1942	66	—	—	—	66
1943	674	—	—	—	674
1944	2 151	—	—	—	2 151
1945	240	—	—	—	240
1946	372	—	—	—	372
1947	269	—	—	—	269
1948	1 613	—	—	—	1 613
1949	900	—	—	—	900
1950	1 198	—	—	—	1 198
1951	2 695	—	—	—	2 695
1952	4 072	—	—	—	4 072
1953	1 481	—	—	—	1 481
1954	8 222	—	—	—	8 222
1955	5 183	—	—	—	5 183
1956	11 316	—	—	—	11 316
1957	5 963	—	—	—	5 963
1958	306	—	—	—	306
1959	1 064	—	—	—	1 064
1960	3 066	—	—	—	3 066
1961	3 197	—	—	—	3 197
1962	2 425	—	—	—	2 425
1963	7 749	—	—	—	7 749
1964	2 442	—	700	—	3 142
1965	2 137	—	1 500	—	3 637
1966	2 003	—	579	—	2 582
1967	896	—	—	—	896
1968	302	—	—	—	302
1969	1 540	—	12	—	1 552
1970	630	144	—	—	774
1971	120	—	—	—	120
1972	2 322	—	—	—	2 322
1973	3 663	—	8 045	—	11 708
1974	4 314	—	3 555	—	7 869
1975	9 436	—	2 177	—	11 613
1976	5 076	—	—	—	5 076
1977	1 470	—	—	—	1 470
1999 ^(a)	—	—	—	24 970	24 970
Total	100 573	144	16 568	24 970	142 255

NOTE: (a) Financial year (1999–2000)

Marchagee: MC 258H, 282H, 283H, 259H, 288H, 290H, 294H, 295H, 437H, 438H, 439H, 456H, 484H, 537H, and 1042–1045H;
Woodanilling: MC 1720H; Gunyidi: MC 907H, 1070H, and 1055H

bentonite, natural sodium bentonite, acid-activated bentonite, and organo-clays. Acid-activated bentonite fetches a higher price because of its improved properties and the cost of processing. The prices of some bentonite products are given in Figure 3, which shows that the 1999 price of Wyoming foundry-grade bentonite (with 85% at -200 mesh) is much higher (approximately \$A350 per tonne) than the Wyoming crude bentonite (approximately \$A65 per tonne). The prices show an upward trend from 1996.

Resurgence in the oil-well drilling sector has boosted demand for bentonite and this is expected to continue. The use of bentonite in foundry moulding has also performed well. The increasingly competitive markets and rising raw-material costs have resulted in a considerable shake-up in the world's bentonite-producing companies.

Bentonite in Western Australia

There are bentonite deposits of economic significance in the Marchagee, Watheroo, Cardabia, and Calwynyardah regions in Western Australia (Fig. 4). The Marchagee and Watheroo deposits are in Quaternary lacustrine sediments overlying the Moora Group (Fig. 5). The deposits are located at 10–15 km southwest of Marchagee (Lakes A and E) and approximately 12 km northeast of Watheroo (Lake B; Figs 6 and 7). The Cardabia deposits are found in clay-rich horizons within Lower Cretaceous siltstones in the Carnarvon Basin (Fig. 8). At Calwynyardah, bentonite deposits are present in tuffaceous crater-lake sediments developed at the top of a Lower Miocene lamproite pipe (Jaques et al., 1984). Here, the

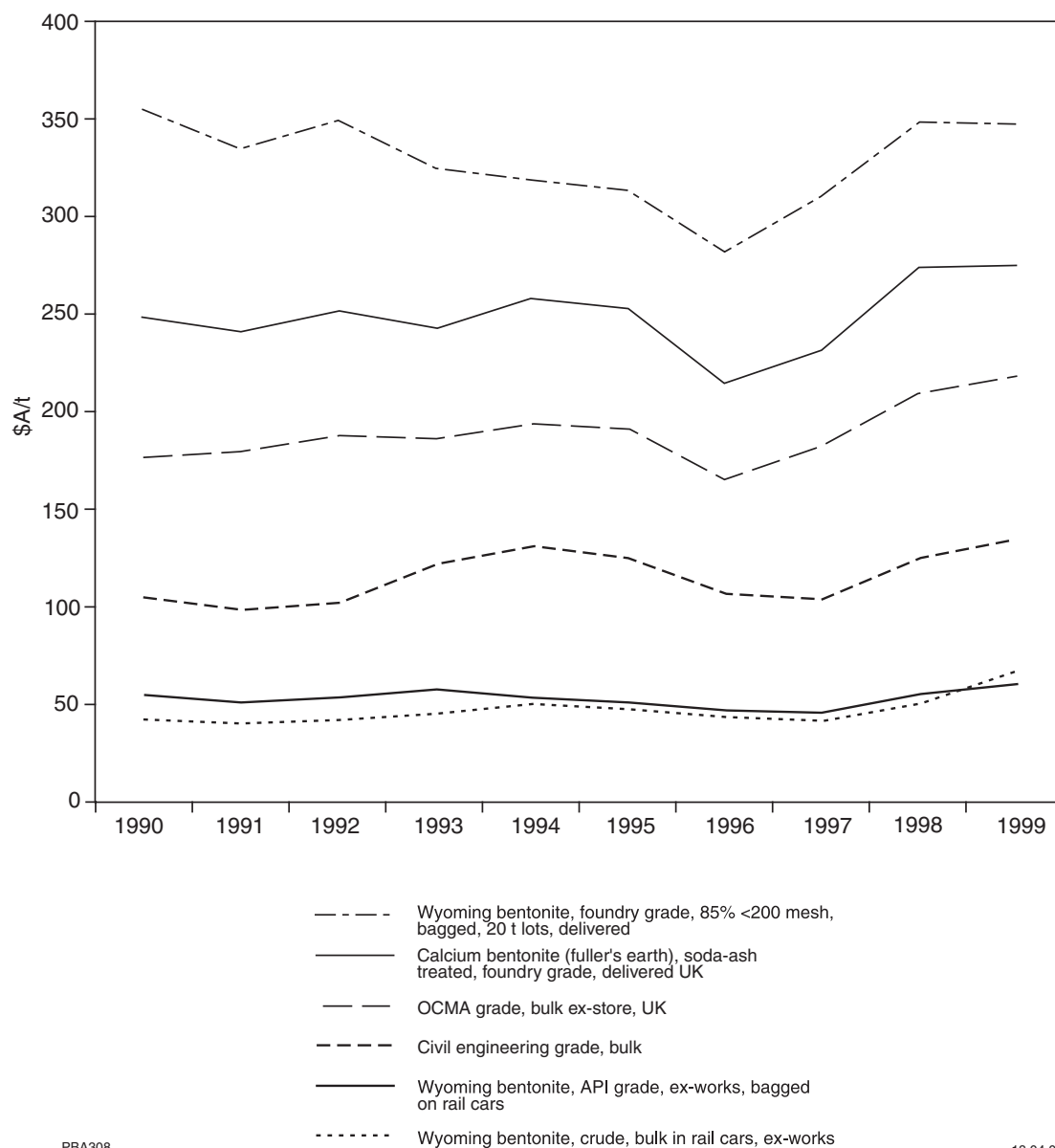


Figure 3. The price of different grades of bentonite (adjusted to 1999 dollars; after Cameron, 1998a)

host rocks are Phanerozoic sedimentary rocks of the Lennard Shelf, on the northern margin of the Canning Basin (Fig. 9).

The variety of smectite present in most of the known bentonite deposits in Western Australia is the magnesium-rich variety, saponite. High-grade sodium-rich bentonite, similar to that in Wyoming, USA, has not yet been found.

Western Australia has resumed production of bentonite (358 t during 1999–2000) from deposits at Watheroo. In the past, the State has produced 15 483 t of bentonite valued at \$A177 283 during 1942–77, mostly from deposits in the Marchagee region (Tables 12 and 13).

Deposits in the Marchagee–Watheroo area

Geological setting

The Proterozoic Moora Group forms part of the poorly exposed Pinjarra Orogen along the western margin of the Yilgarn Craton (Fig. 5). The rocks in the Moora Group consist of the Billeranga and Coomberdale Subgroups, and have been described by Logan and Chase (1961), Playford et al., (1976), Carter and Lipple (1982), Baxter and Lipple (1985), and Myers (1990a). The Billeranga Subgroup unconformably overlies the Archaean basement and is

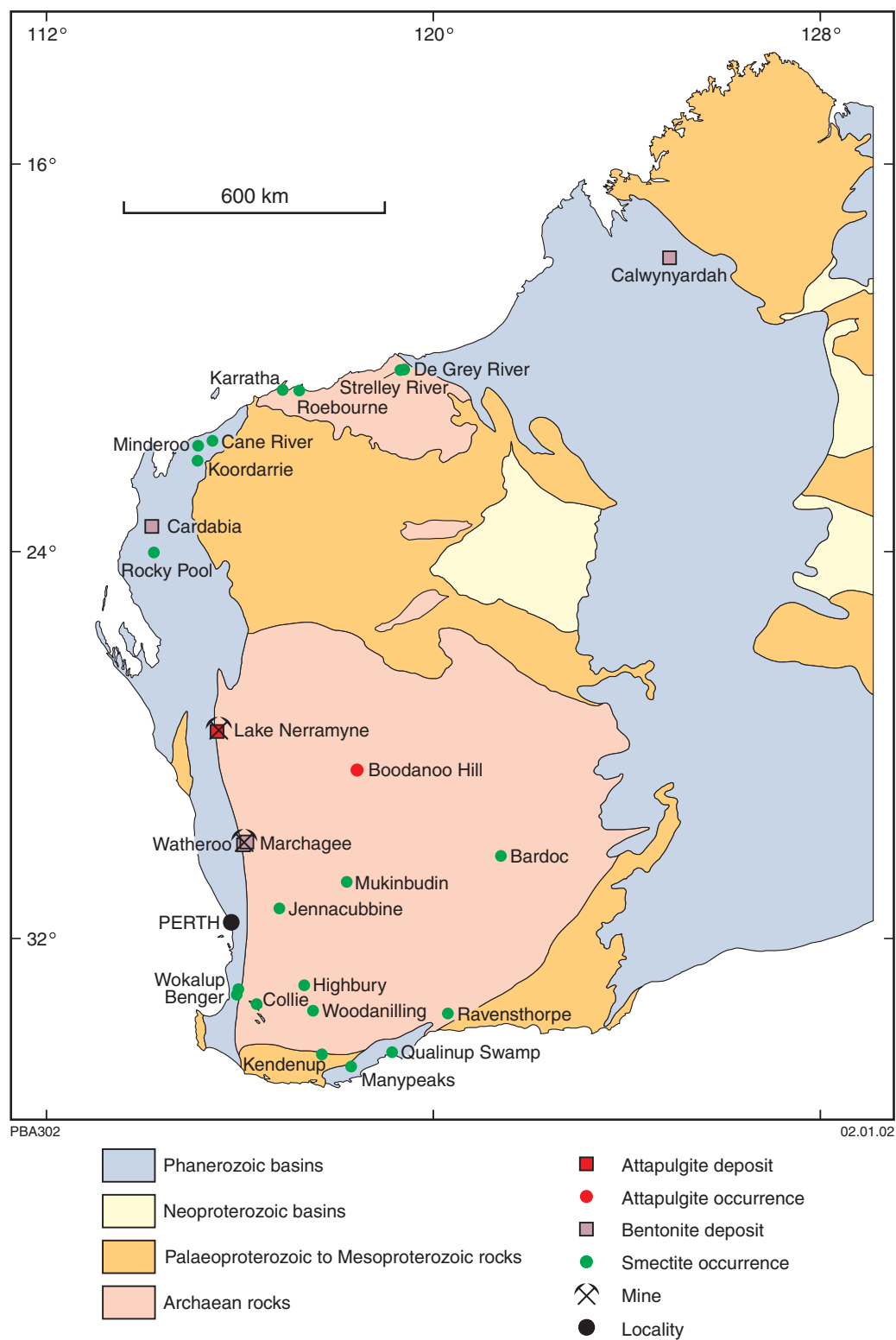


Figure 4. Bentonite and attapulgite clay occurrences in Western Australia

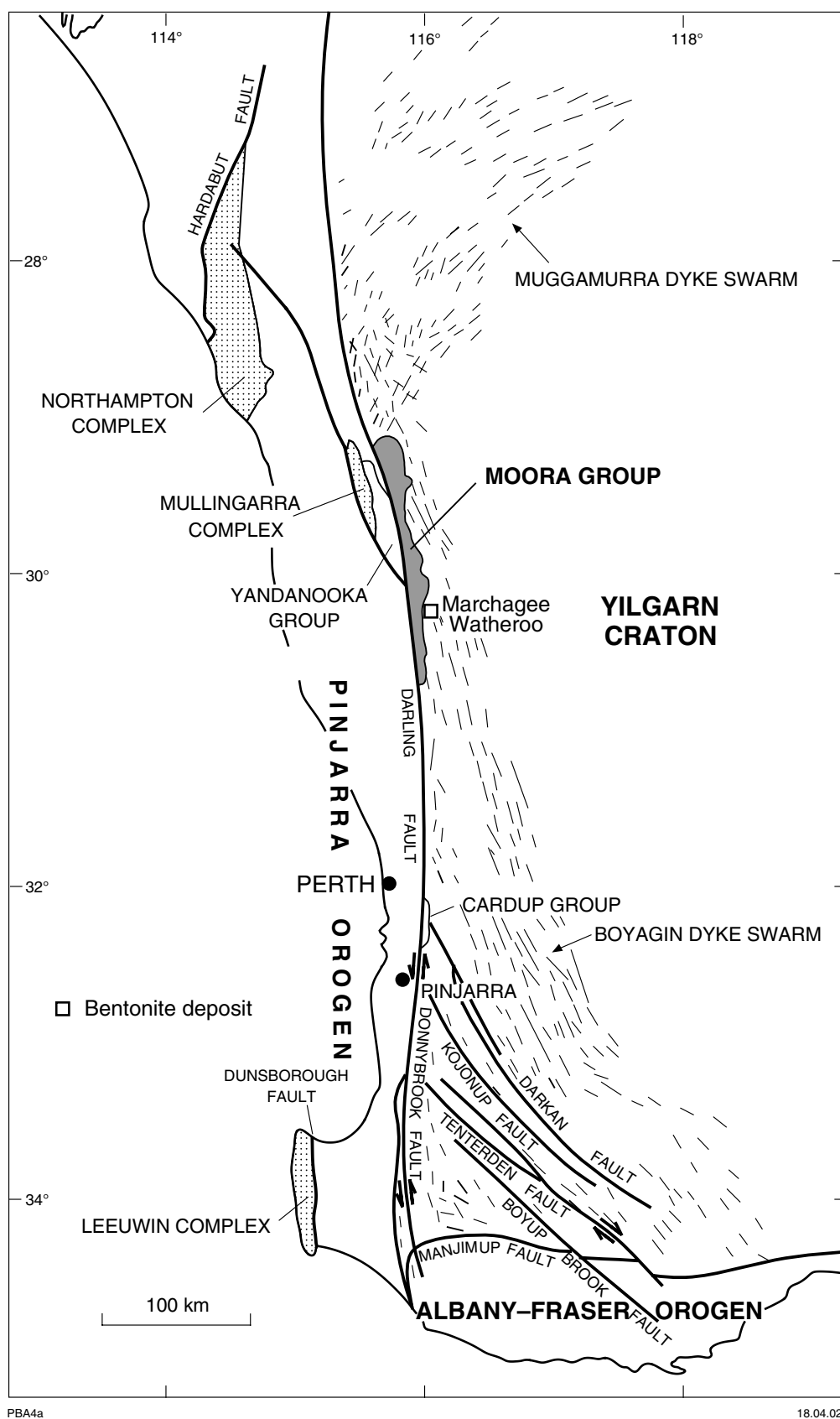


Figure 5. Map of the southwestern portion of the State, showing the location of the Moora Group (after Myers, 1990a)

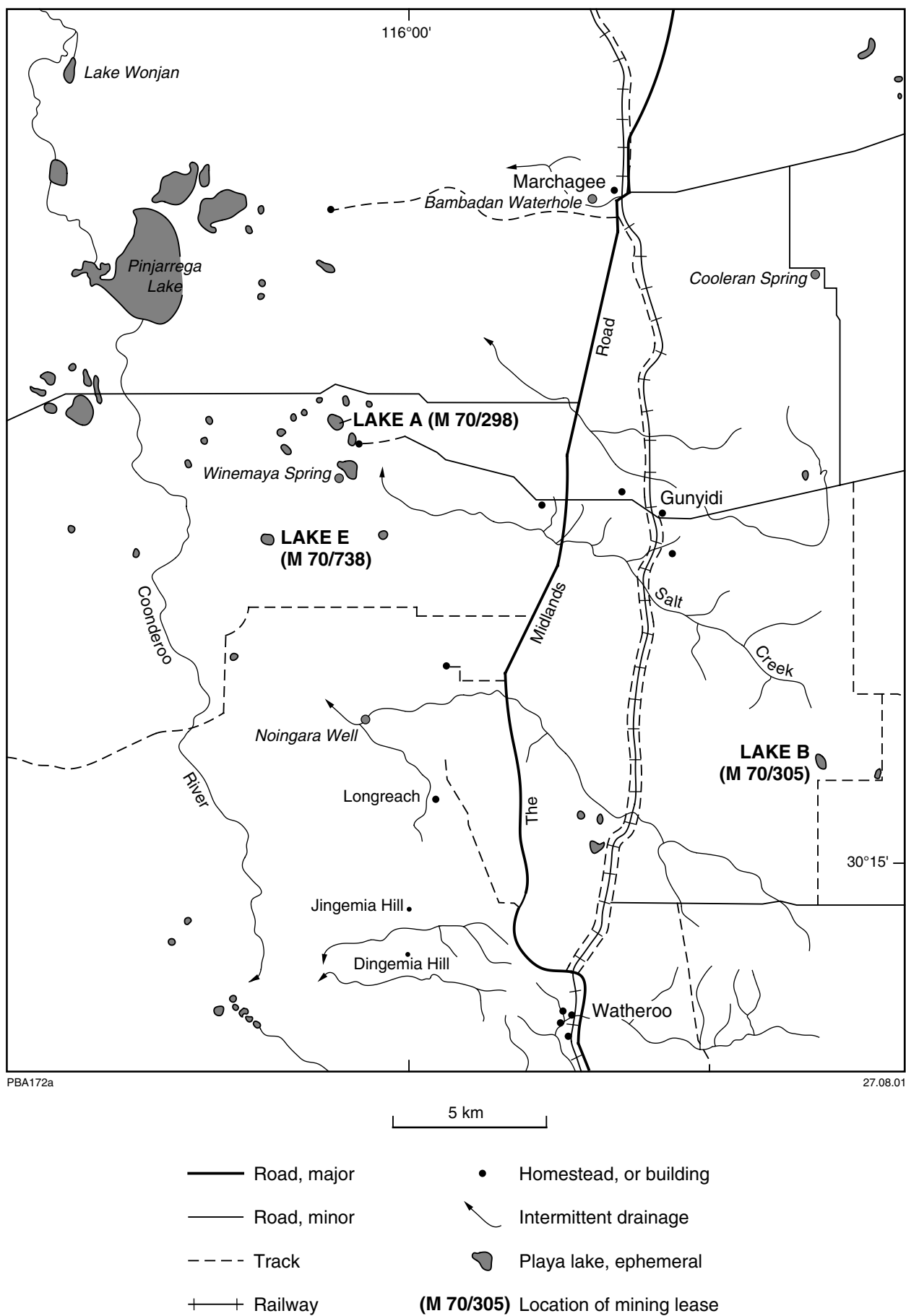


Figure 6. Location of saponite playa Lakes A, B, and E in the Marchagee-Watheroo area (after Fetherston et al., 1999)

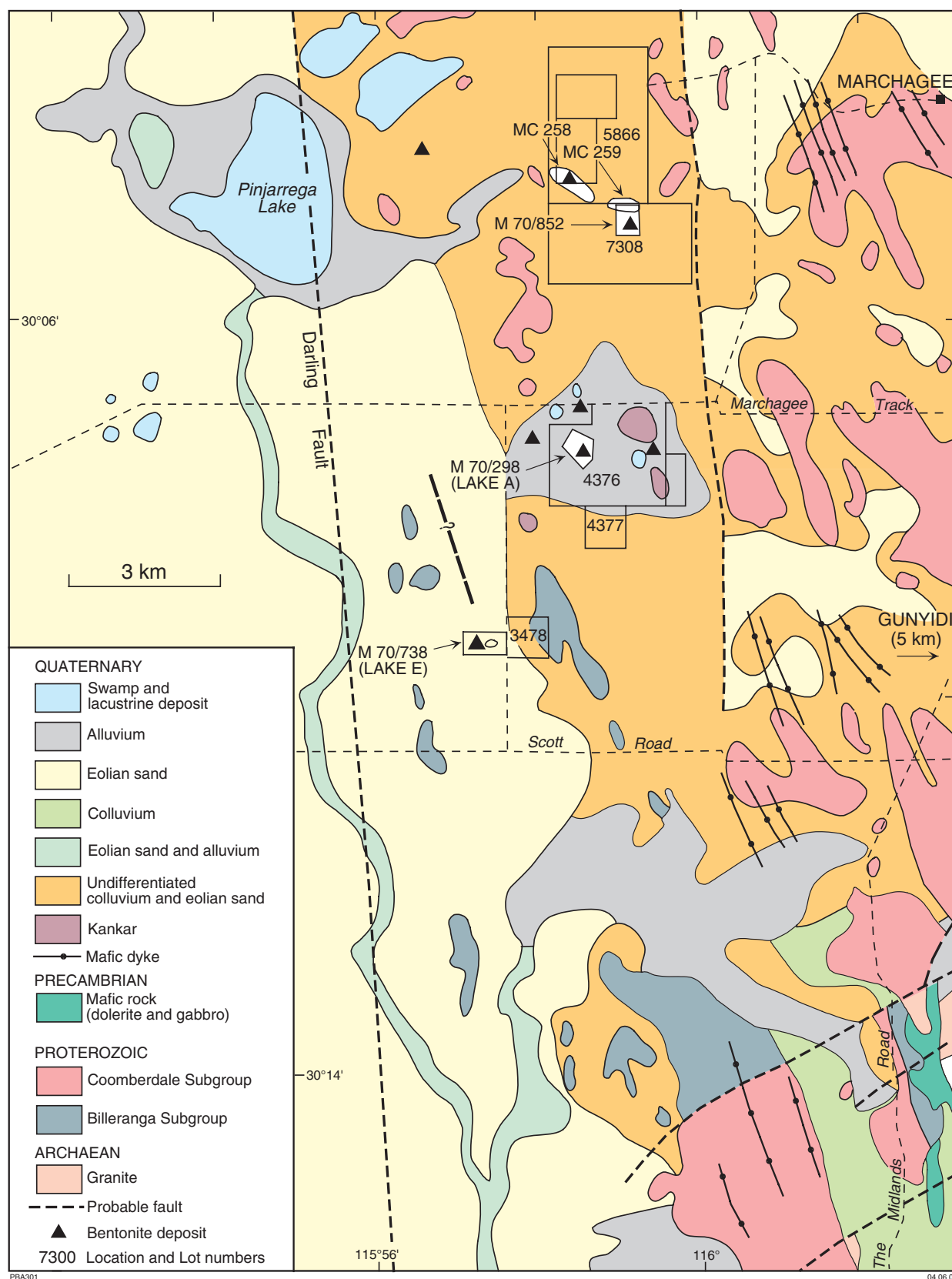


Figure 7. Geology of the area around the Marchagee–Gunyidi bentonite deposits

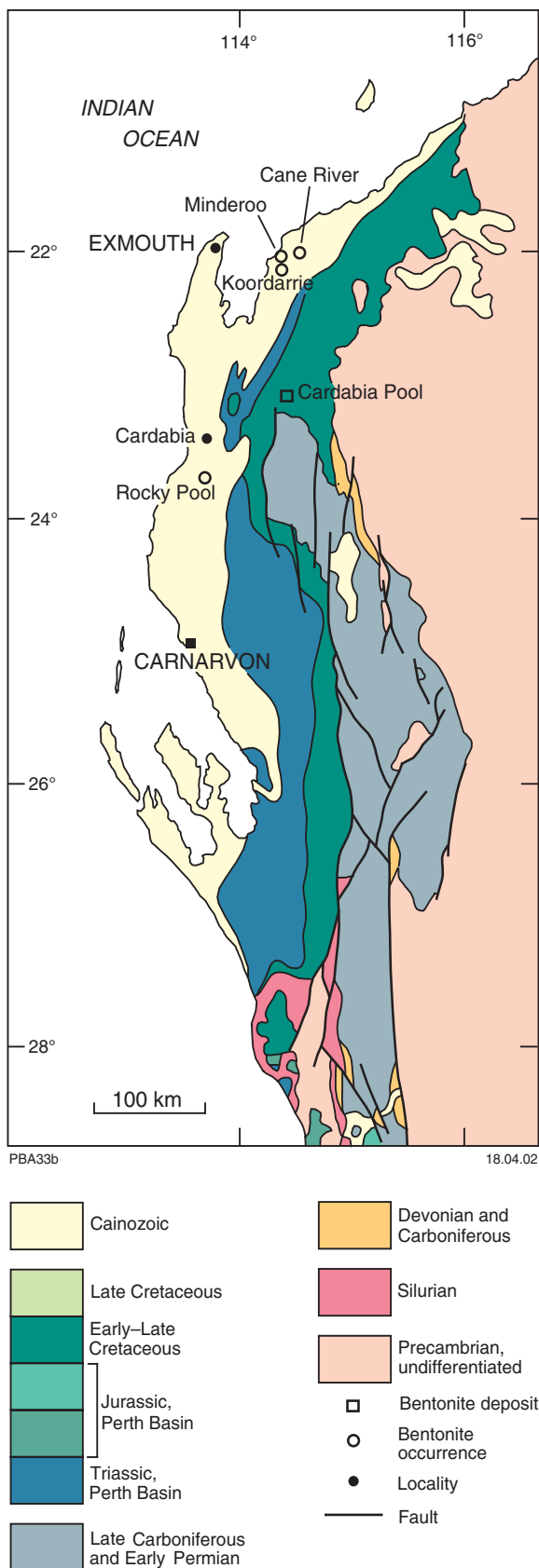


Figure 8. Geology of the Carnarvon Basin (after Hocking et al., 1987)

itself unconformably overlain by the Coomberdale Subgroup.

The Billeranga Subgroup (Table 14) comprises sandstone, siltstone, basalt, and tuff ranging in thickness from 100 to 400 m. These rocks have been deposited on an irregular, locally rugged surface of the Archaean basement. The sedimentary rocks in the subgroup contain stromatolites, and the volcanic rocks have given poorly defined Rb–Sr isochrons of about 1000 Ma (Compston and Arriens, 1968) and 1390 ± 140 Ma (Giddings, 1976). Rocks of the Billeranga Subgroup are gently folded and the cleavage is weakly to moderately developed, but close to the Darling Fault the folds are increasingly compressed, with steeply bedding dips of approximately 80° being recorded. The Coomberdale Subgroup has not undergone significant deformation and metamorphism, except for contact metamorphism adjacent to dolerite dykes. Weak to moderate cleavage and minor concentric folding have developed in the shales and siltstones.

The unconformably overlying Coomberdale Subgroup is 1500 m thick and is exposed over a width of 4–15 km extending northwards for over 200 km from Mount Lamb to near Jacobs Ladder. The units within the Coomberdale Subgroup are the basal Mokadine Formation, Winemaya Quartzite, and Campbell Sandstone overlain by the Noingara Siltstone, Noondine Chert (generally regarded as a silicified carbonate rock), Jingemia Dolomite, and Coomberdale Chert. Although this subgroup contains stromatolites at many localities, their precise age is unknown.

Marchagee–Watheroo deposits

The bentonite deposits overlying the Moora Group are developed in Cainozoic beds located in the Marchagee and Watheroo areas. The Marchagee deposits are in lake beds west of the dolomite-bearing formations of the Coomberdale Subgroup, whereas deposits in the Watheroo area are found east of these dolomite-bearing formations (Figs 6 and 7). In all the above bentonite deposits, a common feature appears to be the presence of Billeranga Subgroup strata containing tuffaceous rocks and dolomite-rich rocks. Tuffaceous rocks could have been reworked and altered to form bentonite, and dolomitic rocks can act as a source of magnesium for the generation of magnesium-rich smectite (saponite).

These deposits have been described by Miles and Stephens (1950), Graham (1952), de la Hunty (1954a,b), McLaughlin (1986), and Fetherston et al. (1999). They are located mostly in Cainozoic lake beds approximately 8–15 km west and southwest of Marchagee, and 12 km northeast of Watheroo. Since 1960, a number of companies have shown interest in these deposits, but none appear to have found a substantial high-grade resource suitable for relatively large-scale mining. However, some deposits have been fairly extensively tested to evaluate their quality.

During 1965, Cliff International carried out investigations for bentonite in an area 13 km west of Marchagee and approximately 2–3 km east of Pinjarrega Lake. In

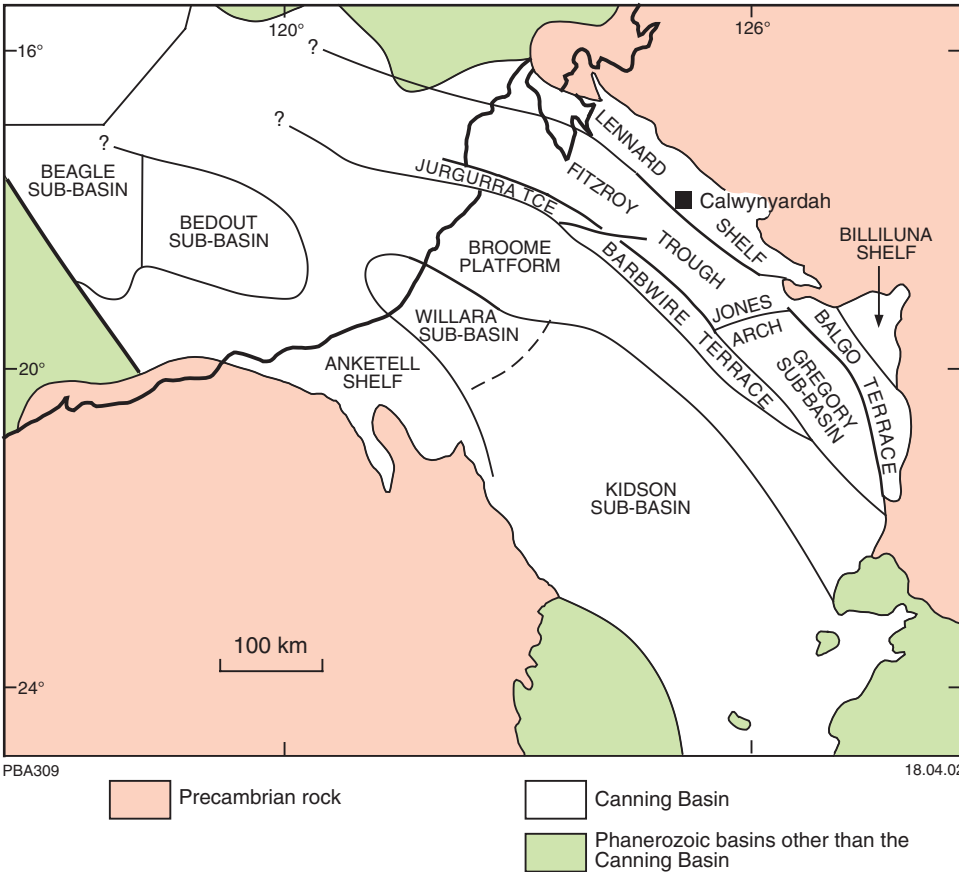


Figure 9. Subdivisions of the Canning Basin (after Middleton, 1990)

Table 14. Stratigraphy of the Moora Group

<i>Subgroup</i>	<i>Formation</i>	<i>Previous nomenclature</i>	
	<i>MOORA 1:250 000 sheet</i>	<i>PERENJORI 1:250 000 sheet</i>	
Coomberdale		Coomberdale Chert	Dudawa Beds
		Jingemia Dolomite	
	Noondine Chert	Noondine Chert	
	Noingara Siltstone	Noingara Siltstone	
	Winemaya Quartzite	Campbell Sandstone	
	Mokadine Formation	Mokadine Formation	
~~~~~ Unconformity or disconformity ~~~~~			
<b>Billeranga</b>		Oxley Chert	Billeranga Beds Billeranga Group
		Morawa Lavas	
	Dalaroo Siltstone	Dalaroo Siltstone	
	Capalcarra Sandstone	Neereno Sandstone	
~~~~~ Unconformity ~~~~~			
ARCHAEAN BASEMENT			

SOURCE: modified from Baxter and Lipple (1985)

1995, Australian Industrial Crystal explored the same general area for bentonite. Mining Lease 70/852 (Fig. 7) in this area is currently held by Australian Mineral Products for its bentonite potential. In the past, bentonite has been produced from a number of deposits in small mineral claims located east of Pinjarrega Lake (Locations 5866 and 7308), and south of Marchagee Track (Lots 4376, 4377, west of 3478; Fig. 7; Adair, 1967; Sillcock, 1997).

Watheroo Minerals owns three major deposits of saponite, identified as Lake A (M 70/298) and Lake E (M 70/738) in the areas southwest of Marchagee, and Lake B (M 70/305) in an area northeast of Watheroo (Figs 6 and 7). These deposits were first owned by Kestrel Mining, which changed its name to Western Minerals NL in early 1992. In 1994, Western Minerals acquired 100% ownership of Bentonite (Australia) Ltd and subsequently changed the name to Greatlake Pty Ltd. The ownership then changed to Watheroo Minerals Pty Ltd.

Geology

The geological units around the bentonite deposits are summarized below:

Age	Unit or rock type
Quaternary	Swamp and lacustrine deposits — peat, clay, and sand
	Alluvium — clay (dolomitic, gypsiferous, and bentonitic), silt, and sand
	Eolian sand
	Colluvium — quartz sand and soil
	Eolian sand — quartz sand and alluvium
	Kankar
?Precambrian	Mafic dykes (dolerite, gabbro)
Proterozoic	Coomberdale Subgroup
	Billeranga Subgroup
Archaean	Granitoid basement rocks

The Quaternary alluvial, colluvial, and kankar units have probably been derived mostly from the Proterozoic Coomberdale Subgroup rocks, which are the predominant older rocks in the area (Fig. 7). These rocks contain numerous dolomitic formations. Other possible source materials for the Quaternary units in the area, for example the eolian sand, include siltstone and sandstone of the Billeranga Subgroup. However, basalt and tuff of the Billeranga Subgroup are not exposed in the surrounding area of bentonite-bearing clays. Both Coomberdale and Billeranga Subgroup rocks are extensively intruded by numerous doleritic and gabbroic dykes.

Occurrences

Bentonite occurrences are restricted to the Quaternary alluvial deposits in a number of claypans located between 8 and 15 km west of Marchagee (Fig. 7). Miles and Stephens (1950) described two important deposits located between Locations 5866 and 7308. These localities are approximately within and around the current Mining Lease 70/852 (Fig. 7). The largest of these two deposits

Table 15. Chemical analyses of the Marchagee saponitic bentonite

Sample	Simpson (1952)		Graham (1952)
	1	2	
	Percentage		
SiO ₂	59.6	45.32	41.79
Al ₂ O ₃	4.29	5.53	5.35
Fe ₂ O ₃	1.45	1.87	2.96
FeO	0.18	0.28	0.16
MgO	14.21	20.03	21.12
CaO	2.77	4.55	4.84
Na ₂ O	2.58	0.75	0.52
K ₂ O	0.42	0.31	0.28
MnO	trace	0.11	0.08
TiO ₂	0.34	0.38	0.28
P ₂ O ₅	0.00	0.00	—
SO ₃	0.27	0.25	0.04
H ₂ O	7.03	10.03	12.60
H ₂ O ⁺	5.32	7.09	6.61
CO ₂	2.21	3.54	3.19
Total	100.67	100.04	99.82

(located at the southwestern corner of Location 5866) consists of a long, narrow, irregular-shaped claypan extending in an approximately northwesterly direction. The thickness of the bentonite horizon ranges from 0.6 to 0.9 m, and within this horizon high-grade bentonite of greyish colour is confined to a 22–25 cm-thick layer at the surface. Underlying this high-grade surface layer is a layer of gypsiferous clay (13–23 cm thick), which in turn is underlain by a layer of approximately 38 cm-thick lower grade light-brown bentonite. All three layers contain small fragments of limestone. X-ray studies have revealed that the top layer is essentially composed of saponite (magnesium smectite; Miles and Stephens, 1950; Graham, 1952). The chemical composition of the top layer indicates that the less than 2 µm fraction contains 41.79% SiO₂, 5.35% Al₂O₃, and 21.12% MgO (Graham, 1952; Table 15). Simpson (1952) also determined similar compositions from samples at Location 5866. The investigations by de la Hunty (1954a,b) of clay beds northeast of Pinjarrega Lake (Mineral Claims 452 and 456) indicated very low grade bentonite.

McLaughlin (1986) suggested that the origin of the saponitic bentonite in this region is quite different to conventional bentonite types, and that this saponitic bentonite formed as a precipitate from magnesium-rich solutions derived from the Proterozoic sedimentary dolomitic rocks of the Noondine Chert within the Coomberdale Subgroup. However, the presence of tuff in the Billeranga Subgroup is an important factor. In favourable geological environments, tuff can alter to bentonite, which could be modified to saponitic bentonite due the presence of dolomitic rocks in the region. Most of the known bentonite deposits in the Marchagee–Watheroo belt are found close to and west of a probable fault zone, which is likely to be related to secondary splay faults or fractures (Fig. 7). These possible faults or fractures could act as pathways for fluids that may alter

the tuff to form bentonite. It is also interesting to note that some of the occurrences (especially the deposits on Lot 5866) have preferential trends along a northwesterly direction, suggesting some structural control. Based on these observations, the Billeranga Subgroup with its tuff beds, which are close to fault structures in the area, could be a potential target for discovering bentonite. However, much more work, especially drilling, is required to support these observations.

Exploration by Cliff International

Cliff International carried out investigations of bentonite deposits in lake beds east of Pinjarrega Lake, 13 km west of Marchagee, with the aim of identifying bentonite material similar to Wyoming bentonite for use as pellet-binding material for the Robe River iron ore. The testing of the clay indicated that the material was not typical sodium montmorillonite, but was close to saponite in composition, with 34.64% SiO₂, 2.54% Al₂O₃, 14.46% CaO, 19.18% MgO, 1.2% FeO, and 25.19% loss on ignition (LOI). The initial tests for binding applications indicated that the binder may impart sufficient wet and dried strength to the pellets of Robe River iron ore to eliminating the use of Wyoming bentonite. However, the likelihood of obtaining consistent-quality material from this deposit was considered doubtful due to contamination of the clay with siliceous sand and silt washed into the lake during the rainy season. Furthermore, the use of this material was considered prohibitive due to heavy transportation costs from Marchagee to the Robe River district (Adair, 1967).

Australian Industrial Crystal

Exploration by Australian Industrial Crystal in the same general area indicated the presence of saponite in a number of lake beds. Sillcock (1996) suggested that the lakes containing saponite are volcanic pipes that intruded granites of the Yilgarn Craton and were emplaced along a major shear parallel to the Darling Fault. Subsequent weathering during the ?Cainozoic, aided by the movement of groundwater through these volcanic rocks (kimberlite or lamproite pipes), resulted in the formation of fine saponitic clay. Furthermore, Sillcock (1997) suggested that the area was then inundated by the sea during the ?Cainozoic, thus resulting in the formation of the overlying carbonate and gypsum beds. On this basis, he suggested that the area is prospective for diamond. He did not support this theory with any technical information such as chemical analyses, or isotopic or geochronological data, and there is no available information on any deep drilling done in the area. Although this contradicts McLaughlin's (1986) theory that the saponite formed due to precipitation from magnesium-rich solutions, it matches the known model that applies to the Calwinyardah lamproite pipes in the Canning Basin, which will be discussed later.

Krama Pty Ltd and M. Sillcock

Mining Lease 70/852 (Fig. 7), currently held by Australian Mineral Products, has been explored by Krama and M. Sillcock for its saponite potential. The lease can be

accessed by a graded gravel road (Fennell Road) and then along farm tracks. Saponite in this lease contains varying amounts of carbonate, gypsum, and silicate mineral impurities, but is of a high enough grade for a number of end-uses, including binding, dam sealing, cat litter, agriculture and horticulture, and as a general absorbent for industrial spillages. Krama and M. Sillcock processed some of the material using a mobile screening plant to estimate the suitability of the material for cat litter (Sillcock, 1995). Due to the relatively small tonnage available within the mining lease, investment in upgrading the plant was not recommended (Sillcock, 1997).

Watheroo Minerals

The three saponite deposits designated Lake A, Lake B, and Lake E are currently owned by Watheroo Minerals (Figs 6 and 7). The previous owners, Kestrel Mining, Western Minerals, Bentonite (Australia), and Greatlake, as well as the current owners, have explored these deposits at various times during 1986–98.

During 1994–95, 13 398 t of saponitic bentonite were extracted from Lake A, but were not reported to DMPR. Mining was done by scraping the surface into windrows using a grader (Longley, 1994; Milne, 1995). Mining of the deposit is relatively easy during the dry season. Watheroo Minerals, the new owners of the Watheroo bentonite deposit, resumed mining in 1999 (Fig. 10; Tables 12 and 13).

Lake A

Lake A is an oval-shaped claypan surrounded by low calcrete and calcareous banks. The surface of the pan consists of grey desiccated clay. The area was explored by 23 reverse-circulation aircore drillholes drilled on a 100 × 100 m grid to a depth of less than 2.5 m.

This is the largest deposit of the three lakes and contains an indicated clay resource of 390 000 t. The saponitic bentonite is commonly pale grey to beige, and is found from the surface to a depth of about 1.8 m. The material grades into calcrete after 1.8 m, with lesser amounts of saponitic bentonite. A representative sample from the saponite-rich layer contained about 50% saponite, 32% calcite, 15% dolomite, 2% quartz, and 1% halite. (Longley, 1993; Hewitt, G., Watheroo Minerals, 2001, written. comm.).

Lake B

Lake B is a relatively small claypan surrounded by dunes of eolian sand and soil, with local float of dolerite or gabbro. The area was not drilled due to difficulties in moving heavy vehicles on the soft ground. However, the area was explored by trenching to a maximum depth of 3 m. A total of 14 sites were excavated at 50–100 m spacings. The saponitic bentonite appears to be a product of incipient alteration of subcropping dolerite. The thickness of the saponitic bentonite is variable over short distances. A thin (0.2 m) gypsiferous layer containing organic material, presumably having no commercial value, extends right across the claypan.



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Figure 10. Watheroo saponitic bentonite stockpiles (courtesy of Watheroo Minerals Pty Ltd)

The inferred resource of saponitic bentonite in Lake B is 60 000 t within a depth of about 1–2 m of the surface, and is relatively small. A high-grade sample from this location contained 94% saponite, 4% halite, 1% quartz, and 1% gypsum. Mining of this deposit is more difficult due to a shallow watertable that remains at a high level even during the summer months (Longley, 1993; Hewitt, G., 2001, written comm.).

Lake E

Lake E is an irregularly shaped claypan with margins containing low dunes of eolian sand, which in places, especially along the southern shore, appear to have been reworked and washed out over the saponitic clay. The area was explored by 41 reverse-circulation aircore drillholes totalling 94.5 m, drilled on a 50 × 50 m grid. The top 0.5 m consists of thick, gypsum-bearing, partly desiccated saponitic clay, followed by 2.0 – 2.5 m of thick, light grey-brown, highly plastic saponitic bentonite that gradually changes to a calcareous, pale-brown, less plastic saponitic bentonite at depth. Below this is a layer of friable calcrete and clay or clayey sands.

The deposit is estimated to contain a measured resource of 70 000 t. The overburden contains two layers: one with low amounts of halite and high amounts of quartz, and the other with 20–30% gypsum. The high-grade zone is 0.5 – 1.5 m below the surface, has a thickness of about 2.0 – 2.5 m, and contains 90% saponite, 6% quartz, 2% dolomite, and 2% halite. The material below the high-quality layer becomes increasingly dolomitic (Longley, 1993; Hewitt, G., 2001, written comm.).

Quality and grade

The Watheroo saponitic bentonite can be divided into four types: calcareous saponite, variable-grade saponite, gypsum-rich saponite, and highly plastic saponite. Impurities within the saponitic bentonite include calcite, dolomite, quartz, gypsum, and halite. The hormite clay sepiolite was identified in some of the samples (Fetherston et al., 1999).

Chemical analyses of samples from Lakes A, B, and E are given in Table 16. Analyses from the Lake A deposits indicate that the material is a Ca–Mg bentonite, and those from Lakes B and E are Mg bentonite. Laboratory test results for the Watheroo Lake E samples are given in Table 17.

Tests by Rosewyn Associates for Western Minerals indicated that the Watheroo saponite exhibited high-swelling properties in water that were comparable with commercially available smectites. However, the Watheroo saponite exhibited less favourable rheological properties.

Uses of Watheroo saponitic bentonite

High-quality drilling mud

High-quality drilling mud is characterized by a high mud-making rate, low water loss, and a small yield point. The general specifications for drilling mud are given in Table 3.

Watheroo saponitic bentonite was tested to determine whether the quality could be upgraded to meet industry specifications with the use of various chemicals and polymers (Fetherston et al., 1999). Initial tests revealed

Table 16. Chemical analyses of the Watheroo saponite

Locality GSWA no.	Lake E 132201	Lake E 132202	Lake E 132203	Lake E 132204	Lake E 117886	Lake E 117887	Lake E C3	Lake B 132205	Lake B 11788	Lake A 117889	Lake A 132206	Lake A 132207
Percentage												
SiO ₂	49.54	58.53	51.21	50.17	51.2	47.8	51.61	49.74	52.07	27.3	25.81	25.84
Al ₂ O ₃	4.96	5.34	4.98	4.81	4.70	4.69	5.48	3.40	3.57	2.86	2.42	2.48
Fe ₂ O ₃	1.95	2.57	2.17	2.00	1.88	1.92	1.91	1.76	1.79	0.98	0.98	0.95
MgO	21.98	18.22	18.74	21.45	16.50	19.70	23.83	20.72	22.20	17.20	18.27	18.06
CaO	0.96	0.08	<0.01	0.01	0.17	0.13	0.38	0.16	0.28	18.90	19.96	19.70
Na ₂ O	4.04	1.90	4.76	4.43	3.09	4.15	4.33	3.76	4.27	1.15	0.63	0.77
K ₂ O	0.35	0.50	0.43	0.33	0.37	0.28	0.41	0.29	0.25	0.22	0.08	0.08
MnO	0.06	0.07	0.07	0.07	0.04	0.05	0.049	0.04	0.04	0.01	0.03	0.02
TiO ₂	0.35	0.41	0.38	0.35	0.36	.35	0.41	0.22	0.24	0.18	0.17	0.17
P ₂ O ₅	0.03	0.04	0.05	0.03	0.31	0.027	0.046	0.04	0.049	0.032	0.05	0.05
Li ₂ O	—	—	—	—	—	—	0.0037	—	—	—	—	—
F	—	—	—	—	—	—	0.0563	—	—	—	—	—
SO ₃	—	—	—	—	0.24	0.83	0.22	—	0.41	0.31	—	—
BaO	—	—	—	—	0.01	0.01	—	—	0.01	0.01	—	—
LOI	16.01	11.16	15.29	14.73	21.0	20.3	10.39	18.13	14.4	31.3	30.63	30.41
Total	100.22	98.81	98.08	98.38	99.87	100.237	99.125	98.25	99.579	100.452	99.02	98.52
Parts per million												
Ba	118	119	97	84	—	—	—	52	—	—	55	56
B	147	72	154	87	—	—	—	<10	—	—	<10	<10
Ag	<0.05	<0.05	<0.05	<0.05	<1	<1	—	<0.05	<1	<1	<0.05	<0.05
As	12	7.4	8	11	<1	5	—	7.4	6	<1	3.2	3.6
Bi	0.2	0.2	0.2	0.2	<5	<5	—	0.1	<5	<5	<0.1	<0.1
Cd	<0.1	<0.1	<0.1	<0.1	<1	<1	—	<0.1	<1	<1	<0.1	<0.1
Ce	38	31	29	28	<1	<1	—	15	33	41	11	14
Cr	19	24	13	14	35	20	—	14	26	17	8	7
Cu	20	20	11	11	15	14	—	6	11	8	2	<2
Ga	7.2	8	7.7	4.6	10	10	—	5.1	11	<10	3.2	3.7
La	21	25	22	17	28	30	—	19	30	<10	11	12
Li	20	28	30	26	43	38	—	6	19	15	8.7	7.3
Mo	0.9	0.7	0.8	0.8	1	2	—	0.5	2	3	0.3	0.3
Nb	13	7.6	7.4	4	7	10	—	4	6	4	2.7	3
Ni	9	9	9	10	18	20	—	7	16	18	<2	<2
Pb	7.9	9.4	9.8	8.7	14	16	—	6	14	20	5.9	4.8
Rb	9.5	14	12	6.4	14	14	—	5.7	11	6	2.9	3.6
Sn	0.8	0.9	1.1	0.7	<10	<10	—	0.5	<10	<10	0.9	1.8
Sr	19	15	15	13	19	22	—	26	38	194	184	208
Th	1.78	6.1	4.5	3.1	10	7	—	1.59	8	8	0.93	1.95
U	4.4	1.38	11	4.1	3	7	—	1.63	4	6	4.1	4
S	0.26	<0.01	0.39	0.15	—	—	—	0.23	—	—	0.04	<0.01
W	1.2	1	0.9	1	—	—	—	0.5	—	—	0.4	0.4
Y	8	9	8	7	—	—	—	12	—	—	4	4
Zn	47	40	27	26	31	32	—	15	24	18	12	11
Zr	65	87	72	62	—	—	—	45	—	—	30	29

SOURCE: Fetherston et al. (1999)

Table 17. Laboratory test results for saponitic clay samples from Watheroo (Lake E)

Absorption of methylene blue (meq/100 g) ^(a)	105.20
Cation exchange capacity (meq/100 g)	
Total CEC	110
Exchangeable sodium	56.6
Exchangeable potassium	1.8
Exchangeable calcium	6.6
Exchangeable magnesium	37.9
Volume of colloid (ml/15 g)	100
Maximum decolourization value (in 2.5% sulfuric acid)	111.72
Wet pressure strength (10 ⁴ pascals)	5.78
Thermal tensile strength (10 ² pascals)	8.4

SOURCE: Fetherston et al. (1999)

NOTE: (a) milliequivalents per 100 g of clay

Table 18. Standard bentonite tests on Watheroo saponitic clay from Lake E

Sample no.	1	2	3	4	5	6
Saponite (g)	22.5	22.275	22.1	21.845	21.6	21.375
Na ₂ CO ₃ (g)	0	0.225	0.45	0.675	0.90	1.125
Viscometer dial reading						
at 600 rpm (centipoise)	28	36	38	38.5	31	26
at 300 rpm (centipoise)	23	29.5	33	35	27.5	22.5
Apparent viscosity (centipoise)	14	18	19	19.25	15.5	13
Plastic viscosity (PV) (centipoise)	5	6.5	5	3.5	3.5	3.5
Yield Point (YP) (pounds/100 ft ²)	18	23	28	32	24	19
YP/PV ratio	3.6	3.5	5.6	9.1	6.8	5.4
Filtrate volume (water loss, cm ³)	25	25.5	25.5	24.6	24.8	25.4
Mud-making value (m ³ /t)	12.1	—	—	18.8	—	—

SOURCE: Fetherston et al. (1999)

Table 19. Test results for Watheroo saponitic clay from Lake E after fluid-loss modification by the addition of polymers

Sample no.	1	2	3	4	5	6	7	8
Saponite (g)	21.725	21.7	21.5	21.25	21.5	21.25	21.7	21.65
Water (ml)	350	350	350	350	350	350	350	350
Na ₂ CO ₃ (g)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
PAC ^(a) (g)	—	—	—	—	—	—	0.05	0.1
CMC ^(b) (g)	—	—	—	—	0.25	0.5	—	—
Starch (g)	—	—	0.25	0.5	—	—	—	—
AP-137 polymer (g)	0.25	0.05	—	—	—	—	—	—
Viscometer dial readings ^(c)								
at 600 rpm	28	26	62	73	27	32	35	39
300 rpm	22	20	55	67	21	27	30	35
200 rpm	20	19	51	63	19	24	28	33
100 rpm	18	17	49	56	17	23	25	30
6 rpm	23	24	35	42	15	22	25	31
3 rpm	23	22	33	39	15	23	24	31
Plastic viscosity (PV) ^(c)	6	6	7	6	6	5	5	4
Yield point (YP) (pounds/100 ft ²)	16	14	48	61	15	22	25	31
YP/PV ratio	2.7	2.3	6.9	10.2	2.5	4.4	5.5	7.8
Filtrate volume (water loss, cm ³)	24.0	28.0	21	19	19	19	18	18

SOURCE: Fetherston et al. (1999)

NOTE: (a) polyacrylamide polymer
(b) sodium carboxymethyl cellulose polymer
(c) values in centipoise

Table 20. Test results for Watheroo saponitic clay from Lake E after the addition of polymers and an inert solid

Sample no.	1	2	3	4
Saponite (g)	20.525	19.4	20.4	20.1
Water (ml)	350	350	350	350
Na ₂ CO ₃ (g)	0.75	0.75	0.75	2.0
AP-189 (g)	0.05	0.05	0.05	—
PAC ^(a) (g)	0.05	0.05	0.05	—
Barite (g)	1.125	2.25	1.25	—
Chinese proprietary polymer (g)	—	—	—	0.4
Viscometer dial readings ^(b)				
at 600 rpm	56	58	58	40
300 rpm	45	42	45	35
200 rpm	41	38	40	—
100 rpm	37	36	37	—
Viscometer dial readings ^(b) (gel formation)	32–34	32–35	32–35	37–47
Apparent viscosity ^(b)	28	29	29	20
Plastic viscosity (PV) ^(b)	11	16	13	5
Yield point (YP) (pounds/100 ft ²)	34	26	32	30
YP/PV ratio	3.09	1.63	2.46	6.0
Water loss (cm ³)	14.5	16.5	15.0	12

SOURCE: Fetherston et al. (1999)

NOTE: (a) polyacrylamide polymer
(b) values in centipoise

that the mud-making capacity of the raw saponitic bentonite at Watheroo is 12.1 m³/t (Table 18). When 0.675 g of sodium carbonate was added, the value increased to 18.8 m³/t, with a yield point (YP) of 32 pounds/100 ft². This indicated that the mud-making rate of the saponitic bentonite was well above the industry specification of greater than 16 m³/t, but the water loss of 24.6 cm³ was too high since values usually range from 13.5 to 16 cm³.

In an attempt to reduce the water loss of the Watheroo saponitic bentonite to an acceptable level for use as a drilling mud, relief agents in the form of various polymers were added. When varying quantities of starch, and sodium carboxymethyl cellulose (CMC) and polyacrylamide polymers, were added to test samples 4 to 8 (Table 19), the water loss was significantly reduced to 18–19 cm³, but was still above the acceptable limit. The addition of AP-137 polymer in samples 1 and 2 had no effect on water loss. Table 20 shows the results obtained when a second attempt was made to further reduce water loss. An unspecified Chinese proprietary polymer was added to the saponite mud containing sodium carbonate as the only other additive (sample 4). In this instance, water loss was reduced to 12 cm³, which is within acceptable limits. However, the yield point of 30 pounds/100 ft² and the YP/PV ratio of 6.0 were still above the limits specified for drilling mud. The addition of AP-189 polymer, sodium carbonate, and barite (as an inert solid) to samples 1, 2, and 3 (Table 20) improved the mud-making rate, yield value, and the YP/PV ratio to meet the required specifications for a high-quality drilling mud. Water losses of 14.5, 15.0, and 12 cm³ for samples 1, 3, and 4 respectively were just within specified limits, whereas the water loss of 16.5 cm³ for sample 2 was only marginally higher.

These tests demonstrate that minor adjustments to the selection of polymers, combined with the addition of an inert solid, can adjust the water-loss factor and other essential specifications to within acceptable limits for high-quality muds used in saltwater drilling operations.

Geotechnical clay

Lake A saponitic bentonite contains 88% material finer than 1 mm, and it was found that the impermeability of many soil types could be improved substantially by adding small amounts of this fine material. Such improved soils can be used as a remedial treatment for leaking farm dams, and also to create impervious barriers underneath structures such as rubbish dumps, sewage ponds, and tailings dams (Longley, 1994). For example, Watheroo saponitic bentonite has been used as a sealant during the construction of three large dams in coarse sandy soils at Dandaragan in Western Australia (Figs 11a,b). Application of Watheroo saponitic bentonite during the construction phase of a dam was found to be cost efficient. The current owner of the Watheroo deposits is looking at promoting the material for use as a geotechnical clay, mainly for use in landfill sites, water run-offs, compensating basins, settling ponds, and tailings dams (Hewitt, G., 2001, written comm.).

Industrial and domestic adsorbent

The adsorption ability of the clay mineral saponite is much greater than that of other clay minerals. Together with other favourable mechanical properties, granular saponite can be used as an adsorbent for water and oil. Saponite also has the ability to adsorb moisture and organic liquids, although the initial rate of adsorption is much lower than that of silica gel and activated bauxite. If the saponite is

a)



PBA343

20.12.01

b)



PBA344

19.04.02

**Figure 11. a) A dam site before the application of saponitic bentonite (courtesy of Watheroo Minerals Pty Ltd);
b) The dam site after the application of saponitic bentonite (courtesy of Watheroo Minerals Pty Ltd)**

Table 21. Industry specifications for adsorbents

Granularity	1–5 mm
Ammonium adsorption	>11 g/kg
Water adsorption	100–110 wt%
Brightness	72–82%
Screening	95% passing 300 mesh

SOURCE: Fetherston et al. (1999)

activated by heating, the adsorption ability will be enhanced without any obvious loss of surface area. The industry specifications for adsorbents are given in Table 21. The high-swelling properties of saponite from Watheroo are indicative of its potential for use as an adsorbent. Lake A saponitic bentonite is already used in the manufacture of cat litter (Longley, 1994; Hewitt, G., 2001, written comm.).

Watheroo saponitic bentonite has also been used in some environmental applications such as in the lining of effluent ponds. An example is the use of this saponitic bentonite in the lining of an effluent pond at Muresk Institute of Agriculture in Western Australia (Hewitt, G., 2001, written comm.).

Further testing of the Watheroo saponite for use as a contaminant adsorbent is continuing. The results of batch adsorption tests indicate that Watheroo saponite has a much higher adsorption for copper and zinc (as much as nine times) than basaltic clay and bentonite from other parts of Australia (Richards, 1999; Hewitt, G., 2001, written comm.).

Stockfeed

In recent times, a significant use of Watheroo saponitic bentonite has been for stockfeed. The company supplies saponitic bentonite to stockfeed manufacturers for inclusion in different size pellets for use in cattle, sheep, and pig feed rations. In addition to its role as a binding agent, it has beneficial effects on ration consumption and production performance. Its primary use is to prevent acidosis syndrome in animals because of its ability to act as a buffer (Hewitt, G., 2001, written comm.).

Decolourant

Bentonite is widely used internationally as a decolourant for mineral and vegetable oils, and animal fat. The bleaching properties of saponitic bentonite are due to its high surface area and chemical adsorption properties. When saponite is activated under low-acidic conditions (in a 2.0 – 2.5% H₂SO₄ solution), the decolourization ability is greatly enhanced. Tests by Rosewyn Associates (1993) suggest that Watheroo saponitic bentonite could be acid activated to produce a bleaching agent for use in refining and clarifying products for the food and industrial oil industries. However, to be commercially viable the saponite clay would have to match or better the decolourant properties of the attapulgite clay presently mined at Lake Nerramyne in the Geraldton region. Decolourant specifications are given in Table 22.

Soil conditioner

Lake A saponitic bentonite has been found to be useful for improving the properties of acidic and sandy soils. For example, black sandy soils on the eastern side of the Perth coastal plain have very poor water and plant-nutrient retention capacity, and it has been found that the addition of 2% Lake A saponitic bentonite has substantially improved the phosphorus retention and the wettability of this soil. However, the water retention properties are less markedly improved (Longley, 1994).

The current owner, Watheroo Minerals, is conducting research to improve the use of Watheroo saponitic bentonite as a soil conditioner and the tests carried out so far have yielded positive results (Hewitt, G., 2001, written comm.).

Paper industry

Lake E saponitic bentonite has been found to be effective as a drainage or retention aid in the manufacture of paper. Tests indicate that the saponite clay, combined with a polymer, is able to flocculate fine fibres and filler particles, thus ensuring their retention in the paper. Other tests suggest that the saponite clay could be used as a retention aid in pitch control and de-inking processes (Rosewyn Associates, 1993; Longley, 1994).

Other applications

Other applications that are being considered for the Watheroo saponitic bentonite are its usage in foundry sands, possibly in the automotive industry in South East Asia, and also in the pelletizing of iron ore from deposits in the Pilbara region and the more recently proposed iron-ore projects of Kingstream Steel Ltd and Mount Gibson Iron Ltd.

Another application, in its infancy, is its use as an earthing agent in the construction industry. Watheroo Minerals has produced an anode mix (saponitic bentonite and gypsum) at the request of local industry and is awaiting test results (Hewitt, G., 2001, written comm.).

Table 22. Decolourant specifications for saponitic clay

	NKH (Japanese)	No. 105 (American)
Specific surface area (m ² /g)	200–300	300
Free acid (mg KOH/g)	2	4.8
Particle size (% passing)		
100 mesh	85–95	100
200 mesh	85–95	95
300 mesh	85–95	78
Moisture (wt%)	12–15	15
Bulk density (kg/L)	–	0.672
Filtration velocity (ml/minute)	–	38
Oil adsorption (wt%)	–	35

SOURCE: Fetherston et al. (1999)

Deposits in the Carnarvon Basin

The Carnarvon Basin has an onshore width ranging from about 50 to 300 km, and extends for a distance of approximately 1000 km from Geraldton to Karratha along the western and northwestern coastline of Western Australia (Fig. 8). Sedimentation in the Carnarvon Basin occurred from the Silurian to the Holocene. A detailed description of the geology of the Carnarvon Basin has been given by Hocking et al. (1987).

The most important geological units for the occurrence of bentonite in the Carnarvon Basin are the Gearle Siltstone and Muderong Shale of the Cretaceous Winning Group.

In the Carnarvon Basin, there are known smectite deposits and occurrences at Cardabia, Koordarie, Minderoo, Cane River, and Rocky Pool.

Previous exploration

Exploration for bentonite in the Carnarvon Basin has concentrated mostly around Cardabia Creek. In this area, the active companies have been Garrick Agnew Pty Ltd, International Nickel Australia, and Hofmann GmbH (Sofoulis, 1951; Graham, 1952; Rohde, 1992a,b).

Occurrences of smectite clays were discovered by Western Mining Corporation, during a uranium exploration program, at Koordarie and Cane River (Reeve, 1979a,b). Another occurrence is at Rocky Pool, where smectite clay was discovered during a drilling program for a dam site investigation (Hancock, 1969). Recently, a smectite clay occurrence was located at Minderoo (Fig. 8).

Geological setting

The Cretaceous Winning Group is the most significant geological unit for bentonite in the Carnarvon Basin. The Winning Group comprises the Birdrong Sandstone, Muderong Shale, Windalia Radiolarite, Gearle Siltstone, Alinga Formation, and Haycock Marl. These units were deposited during a major transgression that began in the Neocomian and continued through the Cretaceous. The following descriptions are summarized from Hocking et al. (1987) and Hocking (1990).

The Birdrong Sandstone is at the base of the Winning Group, unconformably overlying older sedimentary rocks except where the Wogatti Sandstone or Nanutarra Formation are present. The Birdrong Sandstone has two main facies in outcrop. The principal facies is a fine- to coarse-grained, moderately well-sorted, relatively featureless quartz sandstone. The second facies is small- to medium-scale, cross-bedded, fine to very coarse grained sandstone, locally silty and pebbly, and poorly to moderately sorted. The Birdrong Sandstone is mostly between 20 and 30 m thick, and extends from the Murchison River in the south to drillhole Hampton 1 in the north (Hocking et al., 1987). The type section is on the western side of the Kennedy Range, about 1 km south of Birdrong Spring.

The Muderong Shale, which overlies the Birdrong Sandstone, is very similar to the Windalia Radiolarite in lithology, but is generally readily distinguished because of its distinctive outcrop patterns. Although the unit is named the Muderong Shale, it is dominantly an argillaceous siltstone and fine-grained sandstone.

The Windalia Radiolarite conformably overlies the Birdrong Sandstone or Muderong Shale and grades laterally into the Nanutarra Formation, which is a Lower Cretaceous clayey to sandy siliciclastic sequence that has been recognized along the eastern margin of the northern Carnarvon Basin, but has not been classified as a unit within the Winning Group (Hocking and van de Graaff, 1978). The Windalia Radiolarite is conformably overlain by the Gearle Siltstone, the Alinga Formation, or the Haycock Marl. It commonly has a porcellanized cherty appearance due to secondary opaline silicification, and exhibits Liesegang banding. The colour is dominantly white, but locally varies from yellow to red, purple, and brown. This silicified material is known locally as 'mookaite' and is mined and sold as a semi-precious stone.

The Haycock Marl is a more calcareous lateral equivalent of the Gearle Siltstone in the Dampier Sub-basin and is conformable between the Windalia Radiolarite and Toolonga Calcilutite, which is an Upper Cretaceous unit. The Haycock Marl consists of two units of argillaceous calcilutite and marl, separated by a thin, laterally persistent claystone horizon.

The Gearle Siltstone, conformably overlying the Windalia Radiolarite, is a silty and clayey sequence with appreciable radiolarian siltstone. It is conformably overlain by the Toolonga Calcilutite, and grades laterally into the Alinga Formation in the Southern Carnarvon Basin, and the Haycock Marl in the Dampier Sub-basin. The type section is in C-Y Creek in the Giralia Anticline, but does not extend down to the base of the formation. The greatest penetrated thickness of the Gearle Siltstone is over 700 m in the vicinity of the Spar 1 and Tryal Rocks 1 drillholes on the North West Shelf, but towards the eastern margin of the basin it gradually thins. In the Giralia Range, the thickness of the Gearle Siltstone is 120–170 m and declines to about 90 m west of Kennedy Range. The Gearle Siltstone is poorly exposed except in dams. In outcrop, the Gearle Siltstone mostly consists of weathered soil. The exposures in dams are dark grey to black, with a sulfurous odour. Greenish and brownish tints result from the presence of glauconite and carbonaceous material respectively. The clayey horizons in the formation are bentonitic, whereas the siltstone horizons are commonly pyritic and glauconitic, but are micaceous if the clay content is low. In the Giralia Anticline, radiolarian siltstones are found near the top and base of the Gearle Siltstone. Primary bedded barite and gypsum are present in outcrop, and botryoidal barite nodules with a central crystalline gypsum core have formed near the top of the formation. These nodules also commonly contain marcasite. A possible bentonitic tuffaceous sandstone is present on the eastern side of the anticline near Black Dam (Fig. 12; Harrison, 1979; Hocking et al., 1987).

The Birdrong Sandstone was deposited at the onset of a period of transgression, and in the wake of this

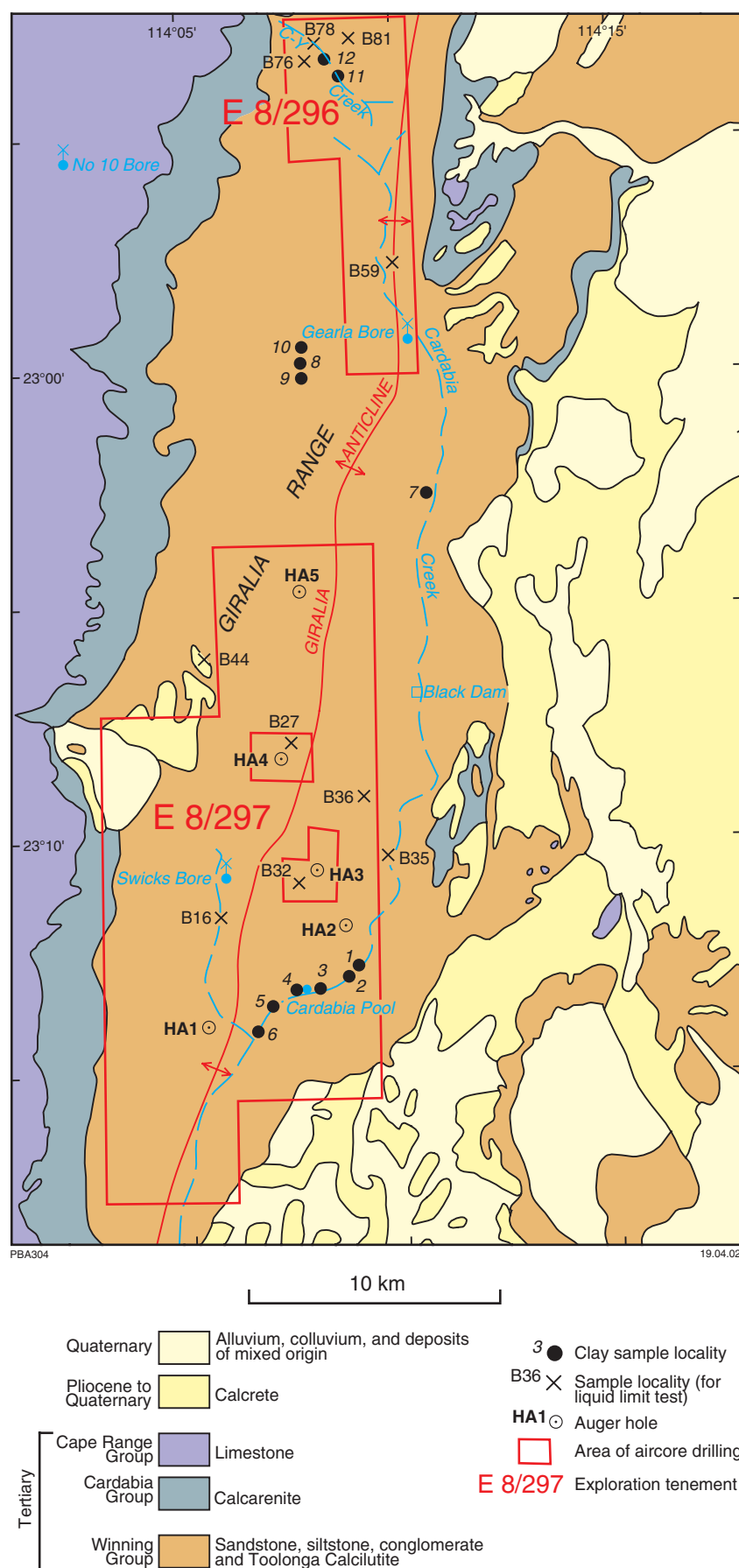


Figure 12. Sample locations and regional geology around Cardabia Creek (modified from Hocking et al., 1984)

transgression the Muderong Shale was formed due to the low-energy offshore marine deposition. Continued high sea levels, deep weathering, and possible excess dissolved silica in the ocean led to substantial siliceous pelagic deposition resulting in the formation of the Windalia Radiolarite and parts of the Gearle Siltstone. In the uppermost part of the Winning Group, the deposition is variable — glauconitic siltstone and greensand of the Alinga Formation were deposited south of Shark Bay; bentonitic siltstone and claystone of the Gearle Siltstone were deposited between Shark Bay and the Dampier Sub-basin; and calcareous marl of the Haycock Marl was deposited in the Dampier Sub-basin. At the termination of the deposition of the Winning Group, there was a basin-wide change to the calcareous pelagic deposition of the Toolonga Calcilutite.

Cardabia bentonite deposits

The bentonites within the Cardabia pastoral lease, approximately 240 km north-northeast of Carnarvon and 40 km east of Cardabia Homestead, have been examined by a number of geologists and companies for their economic potential (Figs 4, 12, and 13). The deposits are located in the Giralia Range, between C–Y Creek and Cardabia Pool, on the eastern side of Cardabia Creek (Fig. 12). The most important host rock is the Gearle Siltstone of the Winning Group.

The bentonite in the Cardabia Creek area was first investigated by Sofoulis (1951) between C–Y Creek and Cardabia Pool. The test results of samples collected during this investigation were discussed in Graham (1952).

In 1966, Garrick Agnew Pty Ltd explored the areas within Temporary Reserves 3397H, 3421H, and 3422H, located in the same general area (Fig. 13). The exploration was for bentonite for use in a proposed iron-ore pelletizing plant in the Robe River region by Cleveland Cliffs Iron Company.

During 1978–79, International Nickel Australia looked for base metals and silver mineralization in the Cardabia Creek area, but deep drilling did not reveal any significant base metal or silver mineralization. There is no record of any bentonite mineralization intersections in these drillholes.

During 1989–92, Hofmann GmbH carried out fairly extensive sampling and drilling in the area west of Cardabia Creek (within Exploration Licences E 8/296 and E 8/297; Fig. 12), to assess the quality of the Cardabia bentonite.

In 1991, GSWA studied samples collected from the Cardabia bentonite deposits.

Occurrence

Bentonite is located along the eastern and western limbs of the Giralia Anticline (Fig. 12). The bentonite is present in the Gearle Siltstone, which is 135 m thick 10 km east-southeast of the No. 10 Bore, and increases in thickness towards the north.

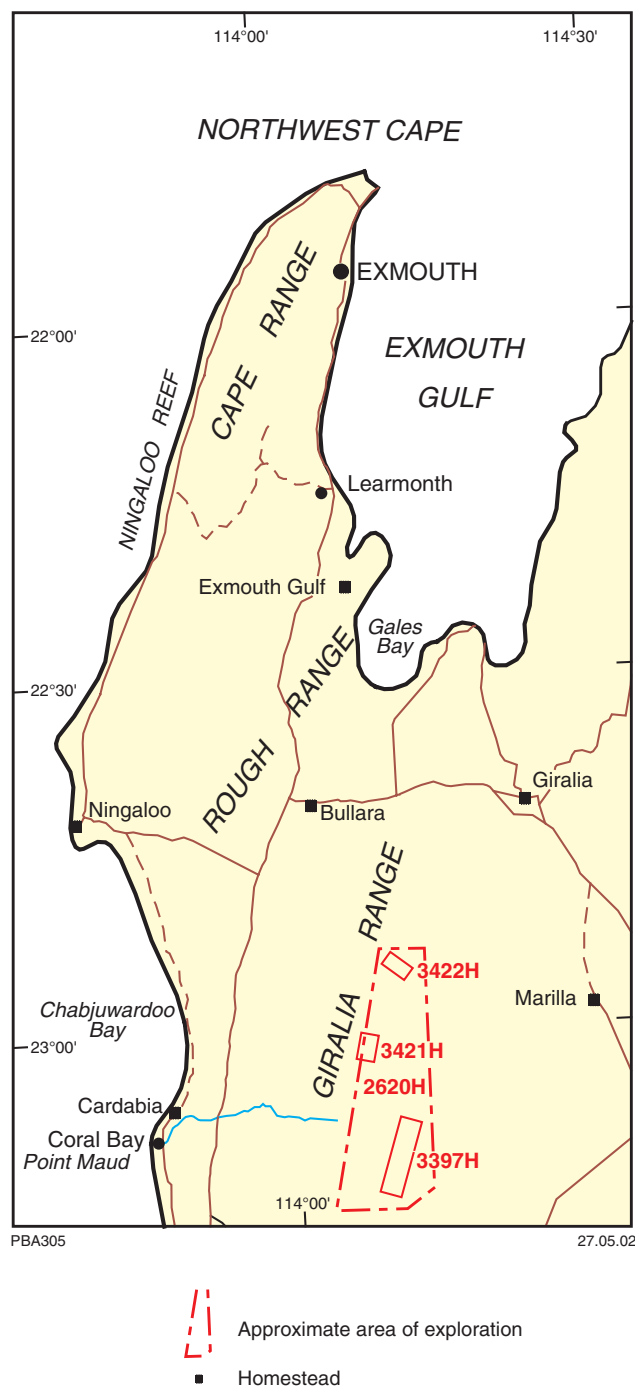


Figure 13. Location map of the area explored for bentonite at Cardabia

In the area of the bentonite deposits, the Gearle Siltstone is fossiliferous and its lithology varies from grey to black siltstone and claystone with horizons containing bentonite, pyrite, barite, and rare phosphate. The Gearle Siltstone is commonly deeply weathered, and up to 3.1 m of residual bentonite has developed on the weathered surfaces. The bentonite is concealed by an overburden of less than 2 m of soil containing a high proportion of gypsum. The best developed zones of bentonite are confined to partially oxidized zones, and the distribution

Table 23. Liquid limit and smectite values for samples of Cardabia clay

Sample no.	Field value for liquid limit	Laboratory value for liquid limit	Smectite (%)
B16	52	71	31
B27	129	111	50
B32	?	100	25
B35	?	95	58
B36	100	92	64
B44	76	101	51
B59	38	42	27
B76	47	68	36
B78	80	105	56
B81	88	70	70

SOURCE: Rohde (1991)

NOTE: See Figure 12 for sample locations

of bentonite is controlled by stratigraphy, as well as topography. The Birdrong Sandstone and Muderong Shale also contain bentonite and pyrite in the Giralia Anticline (Sofoulis, 1951; Hocking et al., 1985; Rohde, 1992a,b).

Exploration prior to 1990 was confined mainly to reconnaissance mapping and sampling. In 1990, Hofmann GmbH (exploration tenements E 8/296 and 297) carried out sampling of the Gearle Siltstone, mostly along creeks, erosion channels, and breakaway slopes (Rohde, 1991, 1992a). During this program 89 samples were collected. The samples were mostly collected using a spade to reach the deepest possible level, but were generally confined to the gypsiferous zone a few centimetres below the surface. An attempt to use an auger drill proved ineffective and was abandoned. All samples were tested in the field to determine their liquid limit, on the assumption that this value is approximately proportional to the bentonite content. The liquid limits ranged from 37.7 to 129.2, and the highest values were obtained from samples along a creek south of Swicks Bore. Encouraging liquid limit values were also obtained from samples in the C–Y Creek area (Fig. 12). Ten samples were tested at the Water

Authority Materials Laboratory in Western Australia as a cross-check for liquid limits obtained in the field (Table 23). These ten samples were also tested using XRD at the University of Western Australia to determine their smectite content (Table 23). The results indicated that there is not always a positive correlation between the smectite content and liquid limit value. Based on the high values of the liquid limits for 89 samples tested in the field, five auger holes were drilled to a target depth of 10 m (Fig. 12). The drilling indicated that the overburden consisted of Quaternary silt and clay sediments ranging from 0.5 to 1.5 m thick. Below this is the Gearle Siltstone, which consists of a dark-green to black layer of clay containing significant gypsum and some goethite. Subsequent work included 35 aircore drillholes around auger holes HA3 and HA4, north of the Cardabia Pool area (Rohde, 1992a; Fig. 12).

Test results

Mineralogy

Mineralogical studies during various phases of the exploration indicated that the dominant mineral present in the Cardabia bentonite is a smectite mineral (40–80%), with varying percentages of mica, illite, quartz, zeolite, and calcite. The main smectite mineral present was found to be nontronite, an iron-rich montmorillonite. Ten samples collected by Rohde (1989) contained 35–60% smectite, 5–15% illite–smectite, and 12–40% quartz (Table 24). Two samples (samples 11 and 12) from the C–Y Creek area contained 45–50% calcite with only 15–20% of smectite. Graham (1952) reported that a sample of Cardabia bentonite contained 40% nontronite, 25% kaolinite, 20% mica and illite, and 15% quartz. XRD studies of samples collected by GSWA showed 5–20% illite and mica, more than 60% smectite, 10–20% quartz, and 5–20% zeolite.

Samples from auger hole HA4 indicated a good correlation between smectite content (80%) and liquid limit (95–100), in contrast to the surface sampling carried out using a spade.

Samples of the Gearle Siltstone intersected in aircore holes from the Cardabia Pool area mostly contained

Table 24. Mineralogy of the Cardabia bentonite

Sample no.	1	2	3	4	5	6	7	8	9	10	11	12
	Percentage											
Smectite	45	60	60	60	55	50	40	55	45	35	10	10
Illite/smectite	5	5	5	5	5	5	5	10	10	15	15–20	15–20
Quartz	12	12	20	12	15	15	10	15	20	40	10	15
Opal/cristobalite	20	15	5	12	20	20	20	10	20	10	–	–
Calcite	5	3	3	2	–	–	–	–	2	3	50	45
Feldspar	3	–	3	2	3	3	–	3	–	–	3	5
Kaolinite	–	–	–	–	–	–	–	–	–	–	5–10	5–10
?Zeolite	10	5	5	10	5	10	25	5	2	–	–	–

SOURCE: Rohde (1989)

NOTE: See Figure 12 for sample locations

Table 25. Details of aircore drillhole samples from the Cardabia Pool area

Aircore drillhole no.	Sample no.	Depth (m)
AC3	116	2–4
	118	6–8
	121	12–14
	130	29–30
AC7	152	2–4
	153	4–6
	158	14–15
AC10	173	2–4
	175	6–8
	180	16–18
	184	23–24
AC13	199	2–4
	201	6–8
	205	14–15
AC14	206	2–4
	208	6–8
	212	14–15
AC16	220	2–4
	221	6–8
	223	8–10
	228	18–20
A19	257	2–4
	265	18–20
	271	29–30
AC27	321	2–4
	324	8–10
	335	29–30
AC31	349	2–4
	351	6–8
	355	14–15

SOURCE: Rohde (1992a)

NOTE: Figure 12 illustrates the aircore drilled area

60–80% smectite, with an average value of 65% (Tables 25 and 26). Other minerals present were illite, quartz, calcite, gypsum, cristobalite–opal, zeolite, and goethite.

Chemical analyses

Chemical analyses of a number of Cardabia bentonite samples (Tables 27 and 28), collected during various phases of exploration, indicated that the bentonite contains relatively low percentages of Al_2O_3 (average of around 11%) compared with about 20% Al_2O_3 for typical commercial-grade Wyoming bentonite, suggesting that the Cardabia bentonite is inferior in quality. High CaO values (26–28%) in samples 11 and 12 are due to the presence of calcite (45–50%).

Samples 1–10 in Table 28 are brown clays derived from the Gearle Siltstone from the Cardabia Pool and Gearla Bore areas, and samples 11 and 12 are from the

headwaters of C–Y Creek. The precise locations of other samples in Tables 27 and 28 are unknown.

Grain-size analysis

A grain-size analysis of a Cardabia bentonite sample yielded the following size fractions:

Size fraction	%
–20 μm	80
+20–63 μm	10
+63 μm	10

Origin of the deposits

Exploration activities in the area have not resulted in a proper understanding of the origin of the Cardabia bentonite, although Butler (1966) suggested that, based on associated mineral compositions, the bentonite in the deposit is sedimentary in origin. The presence of a possible tuffaceous sandstone near Black Dam (Harrison, 1979), on the eastern side of the Giralia Anticline, 5–10 km northeast of the bentonite, is an important feature that could be related to the formation of the bentonite. It would be useful to investigate these possible tuffaceous rocks because in some parts of the world such rocks are well known parental material for large deposits of bentonite. Furthermore, a detailed analysis of the trace elements and whole-rock geochemistry of the smectite minerals present in the deposit would provide definitive evidence on its mode of origin, thus enabling improved geological modelling and targeting of exploration.

Uses

The tests carried out for various applications have not been conclusive, but preliminary tests suggest that the chemically treated Cardabia bentonite could be used as a binding agent in iron-ore pellet production, but more research is required (Butler, 1966). Rohde (1992a) suggested that, depending on the quantities available and beneficiation techniques required, a market for low-quality bentonite would be possible.

Occurrences

Koordarrie (Centipede Well)

In the area around Centipede Well and 16 Mile Well (Fig. 14), approximately 14 km north of Koordarrie, a vacuum drilling program carried out by Western Mining Corporation (WMC) on TR 7074H yielded drill cuttings containing montmorillonite. The drilling was carried out in 1979, during an exploration program for uranium, following high uranium values obtained from a borewater survey. Exploration involved the vacuum drilling of 240 holes to a depth of 1.6 m using a vehicle-mounted rig. The area has no outcrop and contains alluvial material comprising red and reddish-brown sand and clay material within claypans, and sand dunes. Based on XRD, one representative sample from the drillhole cuttings contained 18% montmorillonite, 2% attapulgite, 3% muscovite, 17% kaolinite, 40% quartz, 7% goethite, 3% muscovite, 1% albite, 7% calcite, and 3% hematite (Reeve, 1979a).

Table 26. Mineralogy of bentonite samples from the Cardabia Pool area

Sample no.	Smectite	Illite	Illite/smectite	Quartz	Calcite	Gypsum	Cristobalite/opal	Goethite	?Zeolite
Percentage									
116	65	5	5	17	1.3	0.6	5	—	—
118	70	5	5	10	1.9	1.3	3	—	5
121	75	—	3	7	7.7	5.4	3	—	—
130	65	5	5	10	13.3	3.7	3	3	—
152	65	5	5	10	1.9	12.0	3	—	—
153	65	5	5	7	0.7	3.8	5	—	3
158	65	—	5	10	7.0	1.1	5	—	5
173	55	5	10	7	1.8	16.1	3	3	—
175	70	5	—	10	3.1	6.8	—	—	—
180	70	5	—	10	5.1	4.8	3	—	—
184	65	—	10	10	7.6	4.6	—	—	—
199	60	5	5	10	1.2	7.5	—	—	5
201	65	10	5	10	3.1	3.5	—	—	5
205	65	—	5	7	7.7	2.3	3	—	7
206	55	10	5	10	1.5	14.2	—	—	3
208	65	10	5	7	3.9	1.1	3	—	5
212	70	—	5	10	8.4	1.5	3	3	—
220	55	15	5	10	5.2	10.1	5	—	—
221	80	5	—	10	2.9	1.6	—	—	—
223	65	10	—	10	5.1	8.6	—	—	—
228	65	3	—	7	16.2	5.2	—	—	—
257	65	10	5	10	0.8	5.1	—	—	3
265	60	5	—	10	2.1	9.7	3	—	5
271	45	5	5	7	10.1	18.7	5	—	5
321	60	5	—	7	2.2	20.2	—	—	3
324	80	3	5	7	2.9	5.9	3	—	5
335	80	—	—	10	5.8	1.3	—	—	3
349	45	3	3	10	1.3	34.2	3	—	—
351	65	7	5	7	1.3	9.0	3	—	—
355	75	5	3	10	3.4	0.4	—	—	5

SOURCE: Rohde (1992a)

Minderoo

From Koordarrie northwards to Onslow, there are numerous areas of claypans and bare red-brown sandy clays. The clays, both in and outside claypans, commonly exhibit cracking that is typical of expansive clays. Two samples (GSWA 145194–95), collected about 3 km apart around Minderoo, contained 10–50% smectite minerals (Table 29). Sample GSWA 145194 is a red-brown surface sandy clay that is present as thin, flat, and rounded flakes about 2–4 cm across. Sample GSWA 145195 is a somewhat plastic red clay containing fine biotite mica and was collected from a location near a waterlogged claypan. The dry clay on the surface at this location is cracked and forms rounded thin flakes about 10–20 mm across. The clay horizon, as seen in some of the vertical erosional cliff faces, appears to be more than 2 m thick.

Cane River

Nontronite was intersected at a depth of approximately 40 m during a drilling program carried out by WMC in an area within Temporary Reserve 7073, west of Cane River and approximately 40 km southwest of Onslow (Fig. 15). Drilling involved 22 shallow percussion holes totalling 704 m, and was part of an exploration program for uranium. The holes were drilled along two east–west traverse lines separated by 2 km. Eighteen holes were

drilled along Traverse 1, and four holes along Traverse 2. The holes intersected siltstone below a layer of up to 10 m thick of red sand and gravel. Nontronite, an iron-rich bentonite, was intersected in hole CRP 1, and a sample from this intersection contained 50% saponite–nontronite, 4% kaolinite, 26% quartz, and 20% goethite (Reeve, 1979b).

It is important to note that nontronite was intersected in one of the deepest holes, at a depth of about 40 m below

Table 27. Partial chemical analysis of the Cardabia bentonite^(a)

	%
SiO ₂	62.39
Al ₂ O ₃	10.35
Total iron	3.87
MgO	1.48
CaO	1.44
Na ₂ O	2.12
K ₂ O	1.18
LOI	10.82

SOURCE: Butler (1963)

NOTE: (a) average of three samples

Table 28. Chemical analyses of the Cardabia bentonite

Sample no.	1	2	3	4	5	6	7	8	9	10	11	12	Graham (1952)	GSWA 94470	GSWA 94471	GSWA 94472
	Percentage															
SiO ₂	69.23	66.67	64.67	67.77	68.48	68.10	70.61	68.59	67.10	69.88	36.82	38.62	53.51	54.30	60.7	60.60
Al ₂ O ₃	9.40	10.21	11.46	10.42	10.24	10.66	9.28	10.52	10.61	9.18	4.61	5.20	17.65	13.1	13.20	12.60
Fe ₂ O ₃	5.60	6.13	6.74	6.14	6.50	6.28	5.16	6.32	6.36	5.26	2.94	3.35	8.38	6.08	5.81	7.01
FeO	–	–	–	–	–	–	–	–	–	–	–	–	0.08	0.17	0.89	0.19
MgO	1.47	1.66	1.93	1.74	1.63	1.71	1.37	1.77	1.87	1.60	0.97	1.07	2.22	1.69	2.12	1.70
CaO	3.53	3.39	3.01	2.27	2.04	1.70	1.46	1.52	2.07	2.72	28.66	26.42	0.18	4.03	2.00	1.98
Na ₂ O	0.38	0.30	0.32	0.28	0.26	0.30	0.32	0.29	0.26	0.28	0.21	0.40	1.53	2.20	2.01	2.07
K ₂ O	1.84	1.89	2.21	1.97	1.73	1.88	2.13	2.10	2.11	1.98	0.91	0.99	1.29	2.26	2.71	2.42
MnO	0.02	0.03	0.02	0.02	0.02	0.01	0.02	0.03	0.03	0.03	0.02	0.02	–	<0.05	<0.05	<0.05
TiO ₂	0.60	0.66	0.66	0.61	0.59	0.63	0.68	0.66	0.65	0.58	0.38	0.43	0.67	0.77	0.66	0.79
P ₂ O ₅	0.09	0.11	0.13	0.10	0.09	0.10	0.16	0.13	0.13	0.11	0.09	0.08	–	0.12	0.10	0.17
LOI	6.99	7.94	8.12	7.30	7.21	7.09	6.77	6.79	7.47	6.78	26.59	23.73	–	14.5	9.23	10.00
H ₂ O	–	–	–	–	–	–	–	–	–	–	–	–	12.93	–	–	–
Total	99.15	98.99	99.27	98.62	98.79	98.46	97.96	98.72	98.66	98.40	102.20	100.31	98.44	99.22	99.43	99.53

NOTE: See Figure 12 for sample locations 1 to 12

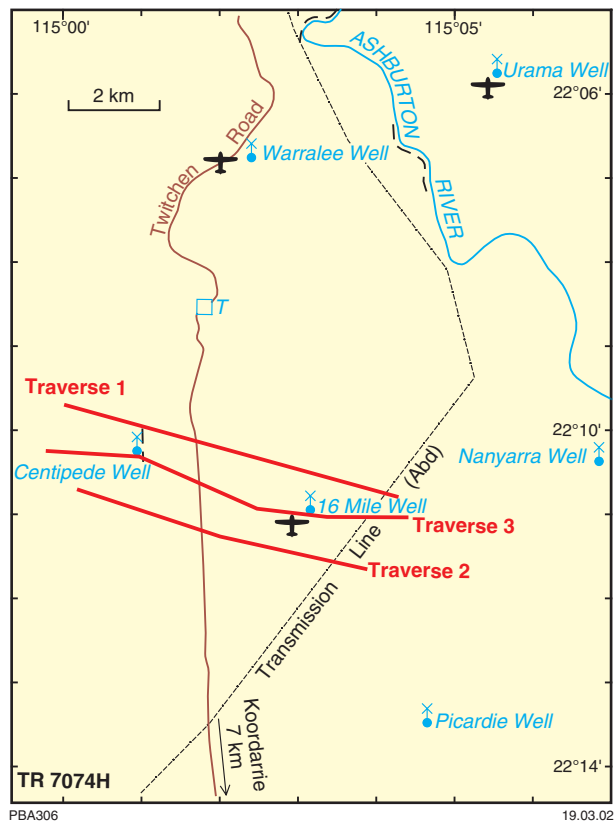


Figure 14. Location map of drillhole traverses around Centipede Well in the Koordarie area

the surface. It is possible that the Cretaceous Winning Group, which contains the montmorillonite-bearing Gearle Siltstone, extends at depth to the Cane River region. Therefore, the potential for substantial bentonite occurrences at deep levels in this region could be significant.

Rocky Pool

At Rocky Pool, 59 km east of Carnarvon (Fig. 8), smectite-bearing clays were reported during an investigation for a dam site for irrigation purposes. The clays contained 16–26% smectite, were hosted by the Cretaceous Toolonga Calcilutite, and were intersected in five auger holes (B9, B10, B12, B58, and B61) drilled along a north–south line across the Gascoyne River. A summary of depths, clay types, and colour is given in Table 30.

Deposits in the Canning Basin

The Canning Basin is the largest sedimentary basin in Western Australia, and contains sediments ranging from Ordovician to Holocene in age. The basin has had a complex depositional and tectonic history, and most of the major Phanerozoic tectonic events that occurred in central and northwestern Australia influenced the depositional style of the basin to some degree. Large parts of the basin are poorly known. However, one of the better known areas

is the northern margin extending from the Broome Platform to the Lennard Shelf (Fig. 9). The following summary is extracted from Middleton (1990).

The Canning Basin is dominated by two elongate, northwesterly trending depocentres, which contain up to 10 km of sedimentary rocks. The northern and southern depocentres are the Fitzroy Trough and Kidson Sub-basin respectively (Fig. 9). Both depocentres began forming during the Ordovician. The intervening Broome Platform contains 2–3 km of sedimentary rocks. The Fitzroy Trough, which is essentially a fault-bounded graben 70–100 km in width, is bounded to the north by the Pinnacle Fault System and to the south by the Fenton Fault System (Fig. 9). The southern fault system typically has a greater throw than the northern system.

In the Canning Basin, bentonite is associated with the tuffaceous crater-lake sediments overlying the Calwynyardah lamproite field, which contains seven lamproite intrusions in the vicinity of the Calwynyardah Homestead. The Calwynyardah lamproite field, apparently controlled by major faulting associated with the Pinnacle Fault System, falls along the northern margin of the Fitzroy Trough. The K–Ar and Rb–Sr ages obtained for 14 separate lamproite intrusions confirm an Early Miocene age (Jaques et al., 1984). These lamproite pipes are covered with varying thicknesses of fine-grained, tuffaceous crater-lake sediments, which are best developed over the Calwynyardah and Laymans Bore East pipes.

Calwynyardah bentonite deposit

Since 1980 the area around Calwynyardah has been explored for diamond by a number companies, which include Samantha Exploration, Metana Minerals, and Kimberley Diamond Company (Wilkinson, 1980; Turley, 1990; Jones, 1996). The exploration work by Kimberley

Table 29. Mineralogy of clay samples from Minderoo

GSWA no.	145194	145195
Kaolinite	major	minor
Smectite	subdominant	major
Mica/illite	minor	minor
Vermiculite	–	?minor
Attapulgite	?minor	–
Talc	–	–
Quartz	dominant	dominant
K-feldspar	minor	minor
Na-feldspar	minor	minor
Amphibole	–	?minor
Calcite	minor	minor
Dolomite/ankerite	–	–
Hematite	minor	minor
Anatase	–	–
Goethite	–	–
Gibbsite	–	–
Halite	–	–

NOTE: Dominant: >50%; subdominant: 40–50%; major: 10–40%; minor: 2–0%

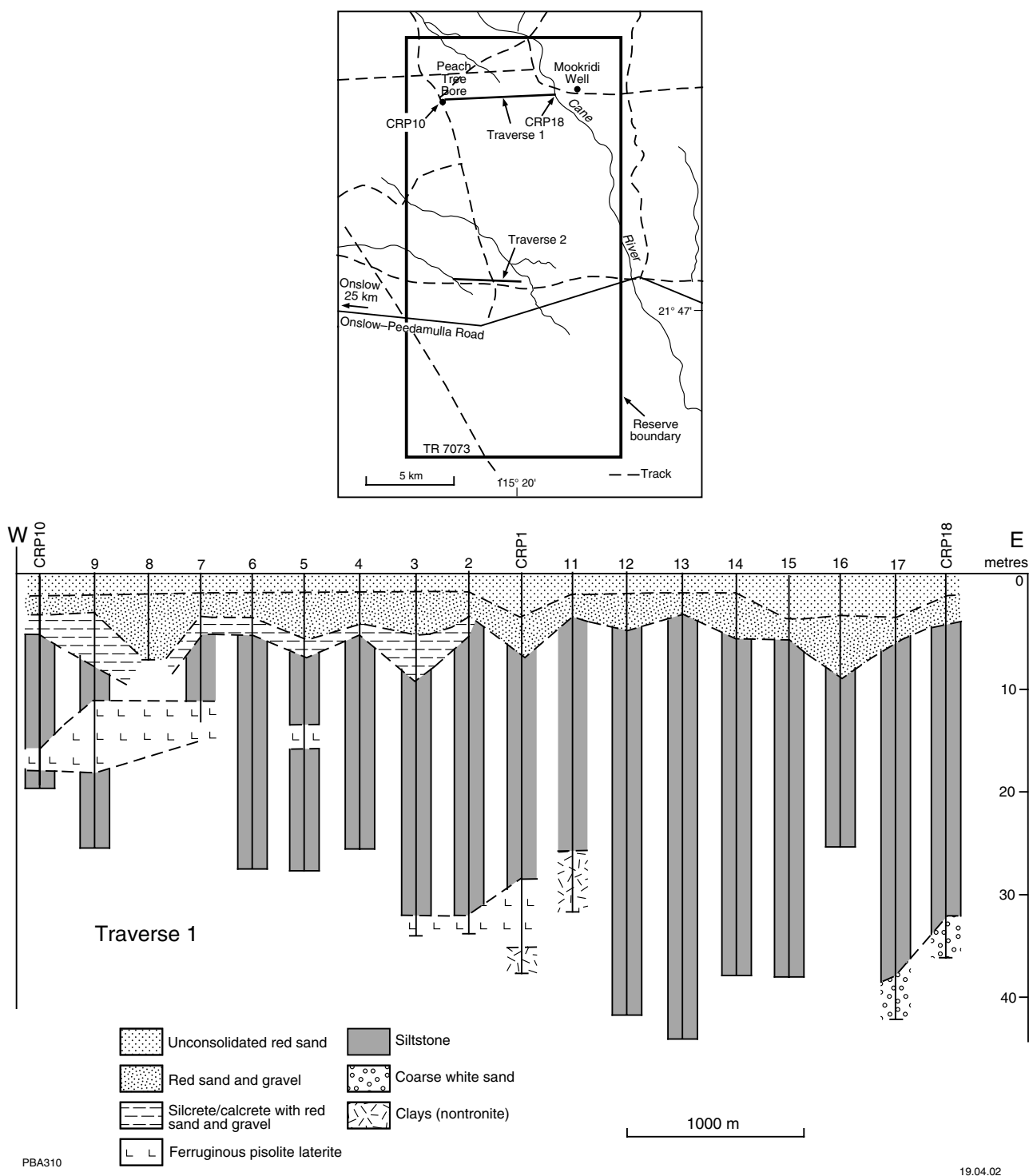


Figure 15. Cross section and location of the area drilled at Cane River

Diamond Company during 1993–95 led to the discovery of an important bentonite deposit that is associated with the Calwynyardah lamproite pipe. The area of exploration was about 55 km northwest of Fitzroy Crossing, just to the south of the Great Northern Highway, about 130 km east of Derby, and is currently held by Kimberley Diamond Company for its bentonite deposits and also for its potential for diamond.

The area consists of Quaternary alluvial deposits of sand, silt, gravel, and pisolitic and massive laterite, and also Permian sedimentary rocks (Fig. 16). Sedimentary rocks, commonly more than 125 m thick, are typically laminated, consist of tuffaceous silts and sands, and are distinctly carbonaceous and pyritic. Lapilli-rich zones are common in some of these sedimentary rocks, particularly in the shallower parts of the lakes.

Table 30. Summary of clay intersections in auger holes at Rocky Pool

Auger hole	Sample no.	Depth (m)	Clay in sample (%)	Colour	Smectite	Illite	Kaolinite %	Quartz	Calcite
B9	19591	17.7 – 17.8	37	green	17	11	1	3	5
B9	19592	26.0 – 26.4	48	blue to black	25	17	2	2	1
B10	19593	11.0 – 11.3	34	green	18	12	2	2	0
B12	19594	4.2 – 4.4	30	green	16	10	1	2	1
B12	19595	19.2 – 19.5	46	blue to black	20	13	2	3	8
B58	19589	5.8 – 6.1	42	green	23	15	2	2	0
B58	19590	14.2 – 14.6	55	blue to black	26	17	2	3	7
B61	19587	2.7 – 2.8	44	green	21	14	2	3	4
B61	19588	4.3 – 4.5	42	blue to black	20	14	2	2	4

SOURCE: modified from Hancock (1969)

The Calwinyardah area is underlain by poorly exposed sedimentary rocks of the Permian Noonkanbah and Hardman Formations and the Triassic Blina Shale. The Noonkanbah Formation consists of grey micaceous mudstone and interbedded calcareous sandstone. The mudstones of the Noonkanbah Formation are conformably overlain by the fine to coarse, well-bedded sandstones of the Hardman Formation. The mudstones of the Blina Shale unconformably overlie Permian rocks (Jaques et al.,

1986; Middleton, 1990; Lewis, 1990; Lanham and Jones, 1996).

Occurrences

Drilling conducted during the 1993–95 exploration program revealed significant concentrations of smectite in tuffaceous crater-lake sediments overlying the Calwinyardah lamproite pipe (Fig. 17). The sediments of the

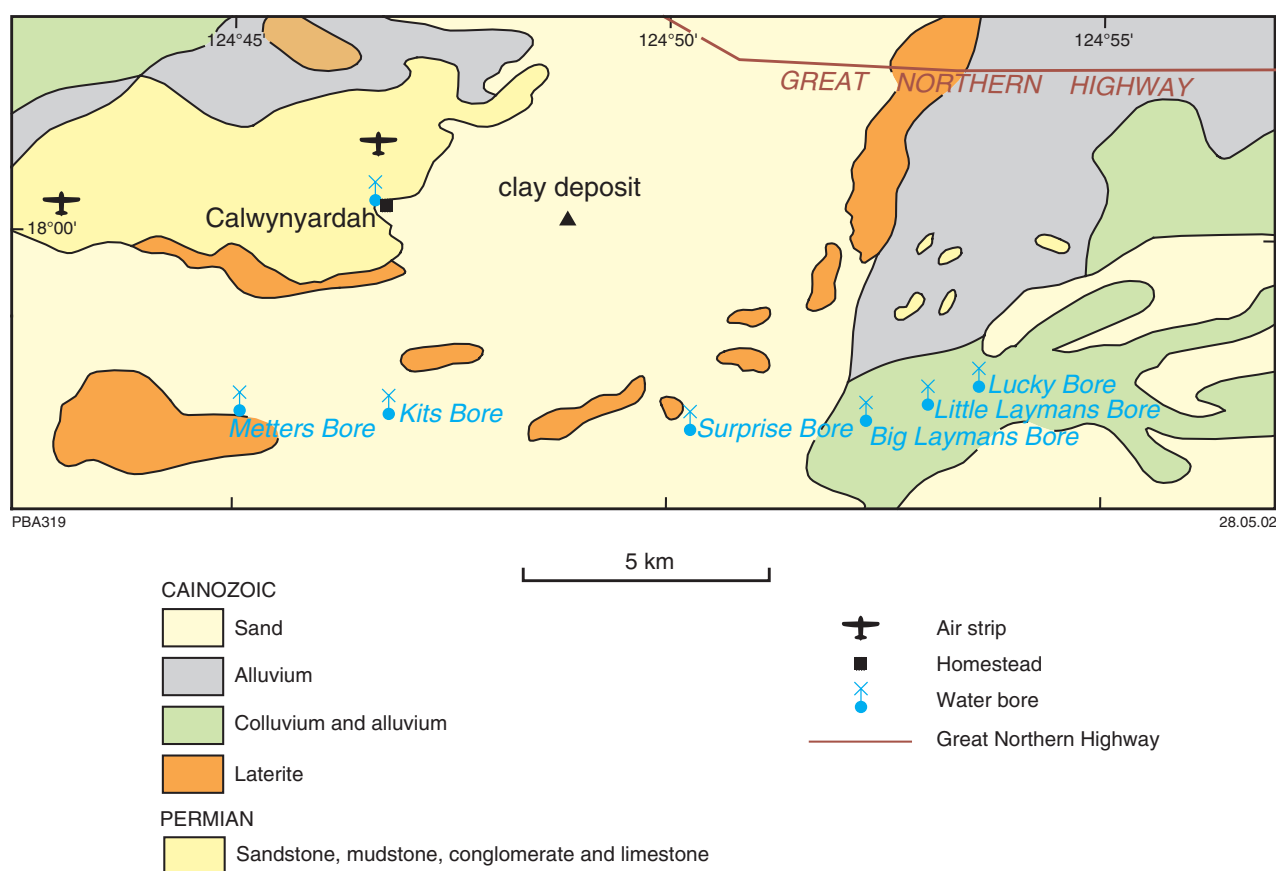


Figure 16. Regional geology of the area around Calwinyardah (modified from Towner et al., 1980 and Griffin and Playford, 1993)

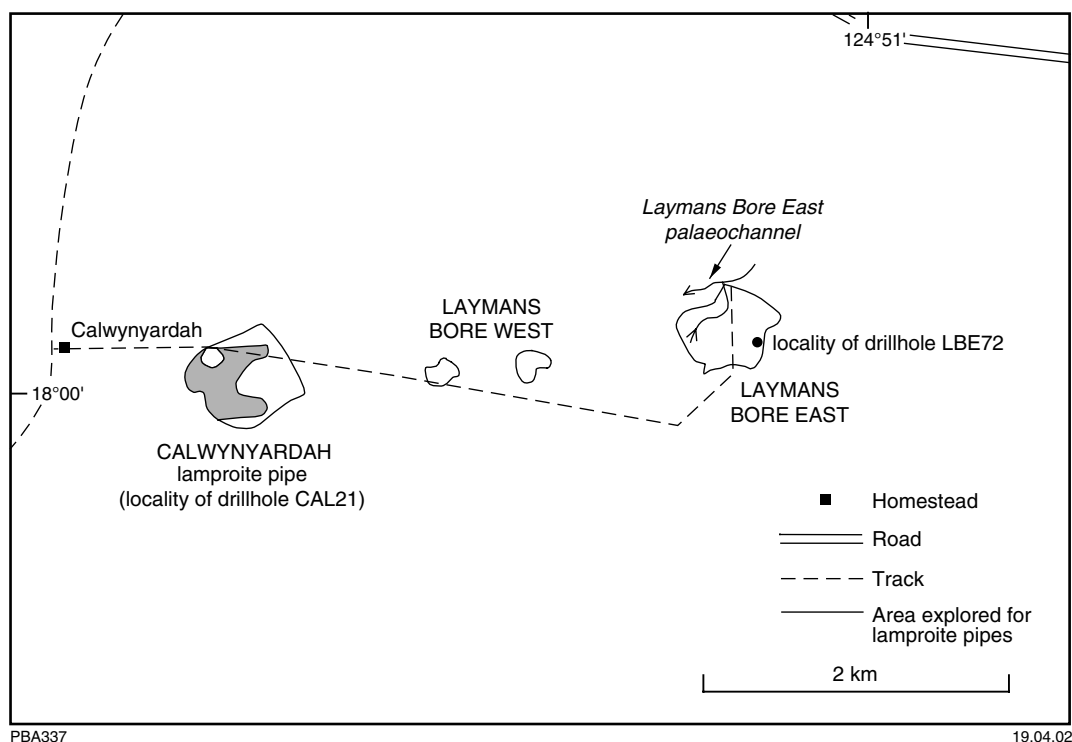


Figure 17. Locality map of the Calwynyardah lamproite pipe area and location of drillhole LBE72

Calwynyardah crater lake are stratified, with a lapilli tuff layer separating two finer sedimentary layers. The sediments of the crater lakes are typically finely laminated, slightly carbonaceous, clay-rich reworked tuffs.

In the Calwynyardah pipe, saponite is abundant (up to 50%) at the margins of the crater lake, but is almost absent in drillholes towards the centre of the lake. Samples from one drillhole (CAL21) at the Calwynyardah lamproite pipe showed up to 25.3% smectite between 15 and 38 m. The material contains 13% MgO (in addition to 53% SiO₂ and 8% Al₂O₃) and the smectite present is saponite, which was confirmed by XRD studies. Other minerals identified in this clay zone were orthoclase, quartz, dolomite, and illite (Lanham and Jones, 1996). Saponite-rich smectite clay is irregularly abundant in the lake sediments. The abundance of saponite indicates that the lake sediments are largely derived from the weathering of magnesium-rich volcanic tuff (Jones, 1997).

Resource

Clay forms a significant proportion of the lake sediments, and extends to a depth of 200 m. Using a cut-off grade of 15% clay, the estimated tonnage of sediments in the Calwynyardah crater lake is about 19.8 Mt, with an average grade of 22% smectite clay. The smectite clay (mainly saponite) inferred resource estimate is about 4.4 Mt (Jones, 1997).

One drillhole (LBE72) at Laymans Bore East (Fig. 17) contained up to 63% smectite clay, but the distribution of smectite clay within the deposit has not been systematically determined.

Although the clay resource at the Calwynyardah crater lake is extensive, the grade of the contained saponite appears to be low. The possibility still remains that the material could be selectively mined and beneficiated for specific uses such as drilling mud and iron-ore pelletizing industries in the Pilbara region (Jones, 1997).

Other smectite clay occurrences in Western Australia

Pilbara Craton

The Quaternary colluvial and alluvial deposits associated with the large number of rivers at the northern margin of the Pilbara Craton, around Karratha and Roebourne, contain considerable areas of red to red-brown clay. Eleven samples (GSWA 145196–99 and GSWA 117801–7) of clay were collected from some of these alluvial and colluvial beds between Maitland River and the Whim Creek region. Of these, nine samples contained significant amounts of smectites (Table 31).

Two samples (GSWA 117814–15) from alluvial clays at the Strelley and De Grey rivers respectively, located about 65–75 km east of Port Hedland, also contained high concentrations of smectites. Examination of sample GSWA 145197 using energy dispersive X-ray analyses indicated that the smectite contained 17.10% Al₂O₃, 18.95% CaO, 5.54% Fe₂O₃, 2.46% MgO, and 35.98% SiO₂. On further testing, some samples showed favourable

Table 31. Mineralogy of smectite-bearing clays around the Karratha, Roebourne, Whim Creek, and Port Hedland regions

<i>GSWA no. Locality</i>	<i>117801 Yannery River</i>	<i>117802 Lulu Creek</i>	<i>117803 Cleaver- ville</i>	<i>117804 Roebourne</i>	<i>117805 Roebourne</i>	<i>117806 Harding River</i>	<i>117807 Jones River</i>	<i>117814 Strelley River</i>	<i>117815 De Grey River</i>	<i>145196 Karratha</i>	<i>145197 Karratha</i>	<i>145198 Karratha</i>	<i>145199 Mailand River</i>
Kaolinite	minor	minor	minor	minor	minor	minor	minor	minor	minor	minor	minor	minor	minor
Smectite	major	major	major	minor	major	major	major	major	major	major	minor	major	major
Mica/illite	minor	–	minor	minor	?minor	minor	minor	minor	minor	minor	minor	?minor	–
Vermiculite	?minor	–	?minor	–	?minor	?minor	?minor	?minor	?minor	–	–	–	–
Attapulgite	?minor	?minor	–	?minor	?minor	minor	minor	–	–	–	–	?minor	?minor
Talc	–	minor	–	–	?minor	–	–	?minor	?minor	–	–	–	–
Quartz	dominant	dominant	dominant	dominant	dominant	dominant	dominant	dominant	dominant	dominant	dominant	dominant	dominant
K-feldspar	minor	minor	minor	major	major	minor	minor	dominant	dominant	major	minor	minor	minor
Na-feldspar	–	minor	–	–	–	minor	–	–	–	–	–	–	–
Amphibole	–	?minor	?minor	–	?minor	?minor	–	minor	minor	–	–	–	?minor
Calcite	minor	minor	minor	?minor	–	minor	minor	–	?minor	minor	major	major	minor
Dolomite/ankerite	–	minor	–	–	?minor	–	?minor	–	–	–	–	minor	–
Hematite	minor	minor	minor	minor	minor	?minor	minor	minor	minor	minor	minor	minor	minor
Anatase	?minor	–	–	–	?minor	–	–	–	–	?minor	–	–	?minor
Goethite	–	–	?minor	–	–	–	–	–	–	–	–	–	–
Gibbsite	–	–	–	–	–	–	–	–	–	–	–	–	–
Halite	minor	–	–	minor	–	–	minor	–	–	minor	–	–	minor

NOTE: Dominant: >50%; subdominant: 40–50%; major: 10–40%; minor: 2–0%

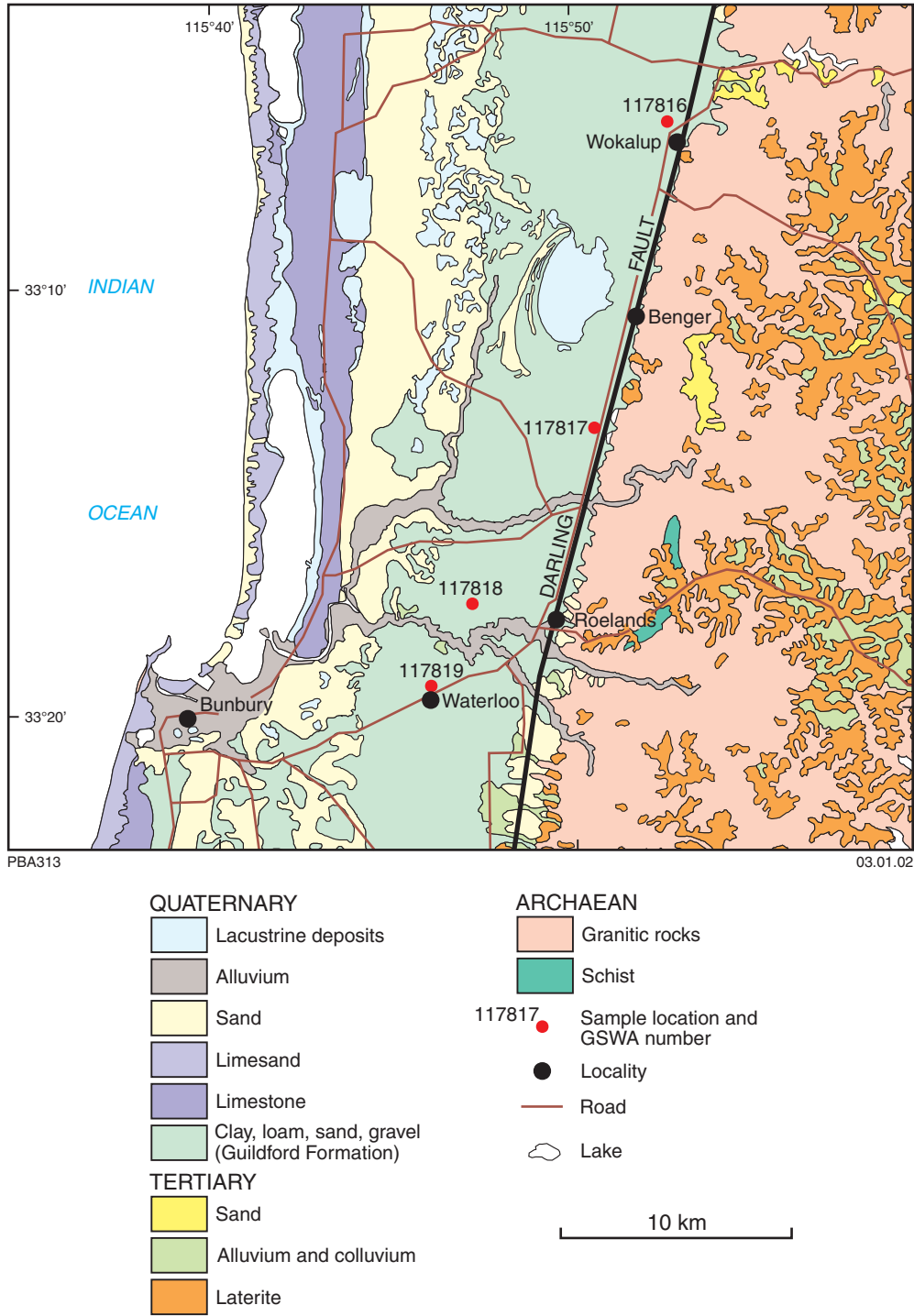


Figure 18. Regional geology of the area around Wokalup and Waterloo (modified from Lowry et al., 1983)

properties for use as structural clay, which are discussed in the chapter on **Construction industry clays**.

Perth Basin

Wokalup

The area around Wokalup has vast stretches of Quaternary alluvial clay from the Guildford Formation, and some of

this material contains smectite. Qualitative XRD analysis of a very dark to dark-grey plastic clay sample (GSWA 117816; Fig. 18) from a vertical face near a creek at the western side of Hocart Road (at Wokalup), running parallel to the South Western Highway, contained a minor amount of smectite. The other minerals present in the sample were K-feldspar, more than 50% quartz, and minor kaolinite (Table 32). Examination of the sample using energy dispersive X-ray analysis indicated that the

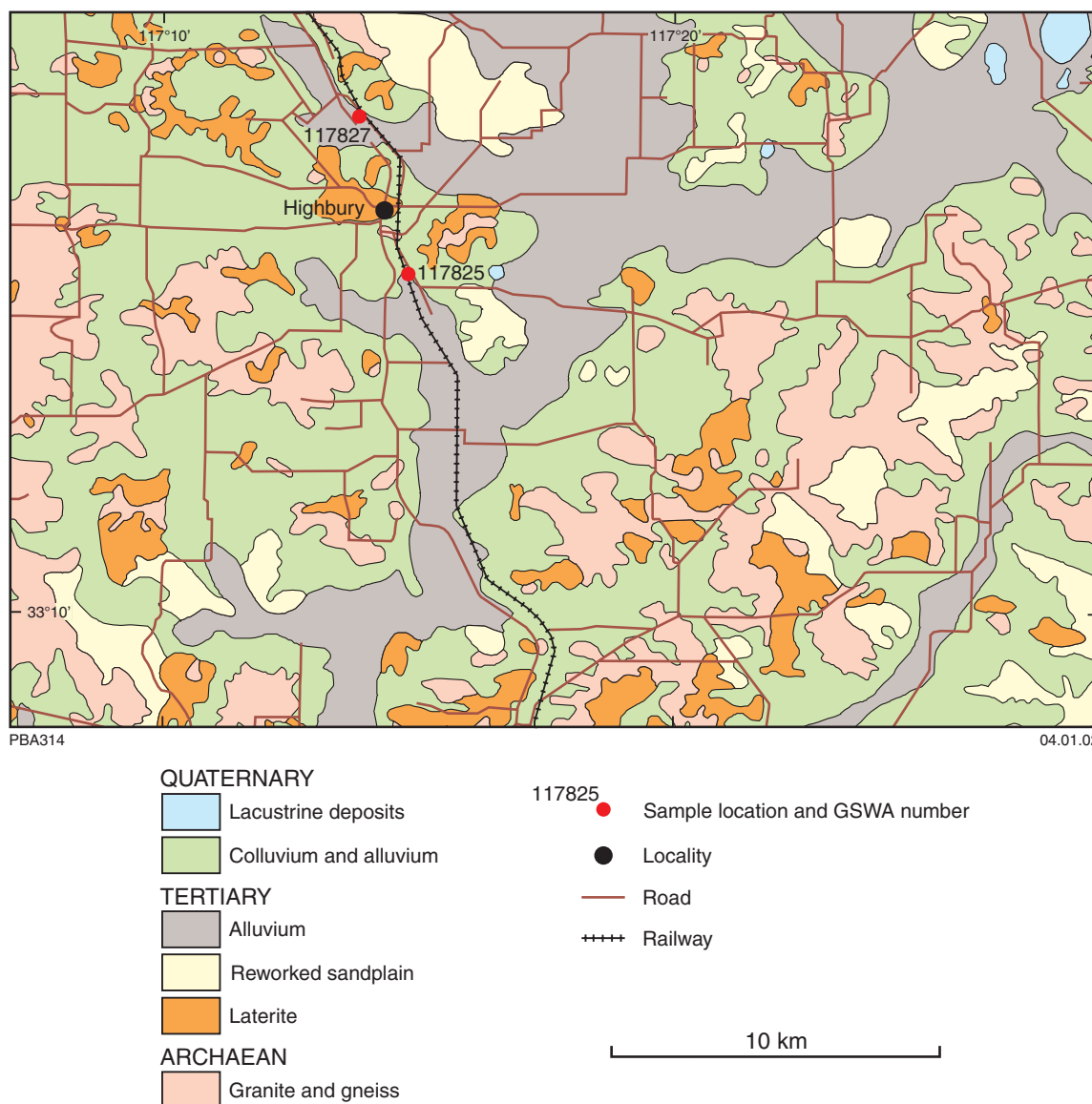


Figure 19. Regional geology of the area around Highbury (modified from Brakel et al., 1985)

smectite contained 18.40% Al_2O_3 , 0.37% MgO , 0.55% CaO , 6.62% Fe_2O_3 , and 52.04% SiO_2 . The area appears to contain a vast resource of potential structural clay, which is discussed in **Construction industry clays**.

Benger

Benger is located about 10 km south of Wokalup, and the area contains vast alluvial plains of Quaternary clay from the Guildford Formation. A sample (GSWA 117817; Fig. 18) of dark-brown to grey plastic clay from a vertical face near a creek on the southern side of Marriott Road (about 0.5 km west of the South Western Highway) contained smectite, K-feldspar, and more than 50% quartz (Table 32). Examination of the sample using energy dispersive X-ray analysis indicated that the smectite contained 18.33% Al_2O_3 , 0.92% MgO , 0.76% CaO , 8.40% Fe_2O_3 , and 54.47% SiO_2 .

Yilgarn Craton

Collie

This location is within the Collie Basin, which is an outlier of the southern Perth Basin within the Yilgarn Craton (Hocking, 1994; Fig. 4). Simpson (1952) stated that clay which could possibly be used as fuller's earth (presumably the bentonitic variety) is known from Locations 1126, 1145–1147, 1161, and 1163 in the Collie region. This clay overlies the Collie Coal Measures.

Highbury

The Highbury region has large areas of alluvial and colluvial clay formations that are probably derived from granitic and gneissic rocks. A sample (GSWA 117825; Fig. 19) of brown clay from a lake dam located on the eastern side of the Whimbin Rock Road (east of the

Table 32. Mineralogy of smectite-bearing clays from Wokalup and Benger

Locality GSA no.	Wokalup 117816	Benger 117817
Kaolinite	minor	?minor
Smectite	minor	major
Mica/illite	minor	—
Vermiculite	—	—
Attapulgite	—	—
Talc	?minor	—
Quartz	dominant	dominant
K-feldspar	major	major
Na-feldspar	—	—
Amphibole	?minor	—
Calcite	—	—
Dolomite/ankerite	—	—
Hematite	?minor	?minor
Anatase	—	—
Goethite	?minor	—
Gibbsite	—	—
Halite	—	—

NOTE: Dominant: >50%; subdominant: 40–50%; major: 10–40%; minor: 2–0%

Table 34. Mineralogy of smectite-bearing clays from Mukinbudin and Ravensthorpe

Locality GSA no.	Mukinbudin 117883	Ravensthorpe 117853
Kaolinite	major	minor
Smectite	major	major
Mica/illite	—	—
Vermiculite	—	—
Attapulgite	—	—
Talc	—	—
Quartz	subdominant	subdominant
K-feldspar	subdominant	major
Na-feldspar	major	major
Amphibole	—	—
Calcite	—	minor
Dolomite/ankerite	—	major
Hematite	—	—
Anatase	—	—
Goethite	—	—
Gibbsite	—	—
Halite	—	—

NOTE: Dominant: >50%; subdominant: 40–50%; major: 10–40%; minor: 2–0%

Table 33. Mineralogy of smectite-bearing clays from Highbury, Woodanilling, and Kendenup

Locality GSA no.	Highbury 117825	Woodanilling 117828	Kendenup 117830
Kaolinite	major	—	major
Smectite	minor	major	major
Mica/illite	—	—	—
Vermiculite	—	—	—
Attapulgite	—	—	—
Talc	—	—	—
Quartz	dominant	subdominant	major
K-feldspar	minor	major	minor
Na-feldspar	—	major	minor
Amphibole	—	—	—
Calcite	—	—	—
Dolomite/ankerite	—	—	—
Hematite	—	—	—
Anatase	?minor	—	—
Goethite	minor	—	?minor
Gibbsite	—	—	minor
Halite	—	—	—

NOTE: Dominant: >50%; subdominant: 40–50%; major: 10–40%; minor: 2–0%

Table 35. Chemical analyses of smectite-bearing clays from Mukinbudin and Ravensthorpe

Locality GSA no.	Mukinbudin 117883	Ravensthorpe 117853
	Percentage	
SiO ₂	73.80	66.40
Al ₂ O ₃	13.00	9.16
TiO ₂	0.53	0.49
Fe ₂ O ₃	2.87	5.56
MnO	0.01	0.05
CaO	0.25	3.47
K ₂ O	2.62	1.69
MgO	0.39	2.15
P ₂ O ₅	0.02	0.008
SO ₃	0.03	0.07
BaO	0.09	0.03
Na ₂ O	0.88	1.23
LOI	5.27	9.21
Total	99.76	99.52
H ₂ O	1.27	2.22

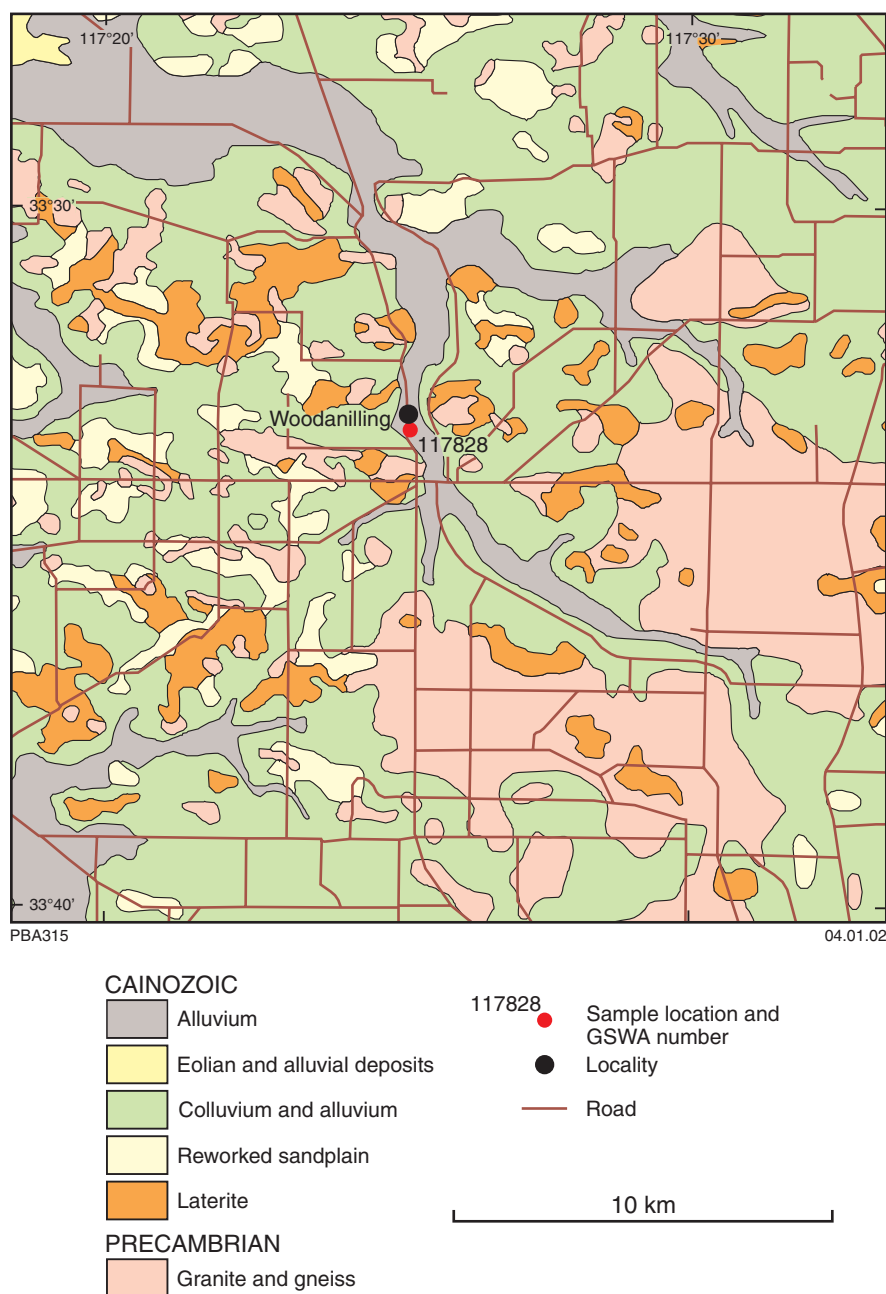


Figure 20. Regional geology of the area around Woodanilling (modified from Brakel et al., 1985)

railway line) contained minor smectite, a major amount of kaolinite, and more than 50% quartz (Table 33). Examination using energy dispersive X-ray analyses indicated that the smectite contained 20.61% Al_2O_3 , 1.6% MgO , 0.29% CaO , 13.89% Fe_2O_3 , and 44.88% SiO_2 . Another sample (GSWA 117827; Fig. 19) from clay in the same area did not contain any smectite.

Woodanilling

In 1970, 18 t of smectite clay was produced from MC 1720H located in the Woodanilling area. The area contains fairly large stretches of colluvial and alluvial

formations that are probably derived from granitic and gneissic rocks. A sample (GSWA 117828; Fig. 20) of clay from dumps of a trench approximately 75 m long, 1 m deep, and 1.5 m wide, on the eastern side of the Southern Highway, was found to be dark grey and somewhat plastic. The trench was dug in a flat terrain that appeared to be in a Government reservation. The sample contained smectite, K-feldspar, Na-feldspar, and 40–50% quartz (Table 33).

Kendenup

The Kendenup region has large areas of alluvial and colluvial clay formations (Fig. 21). A greenish dark-grey,

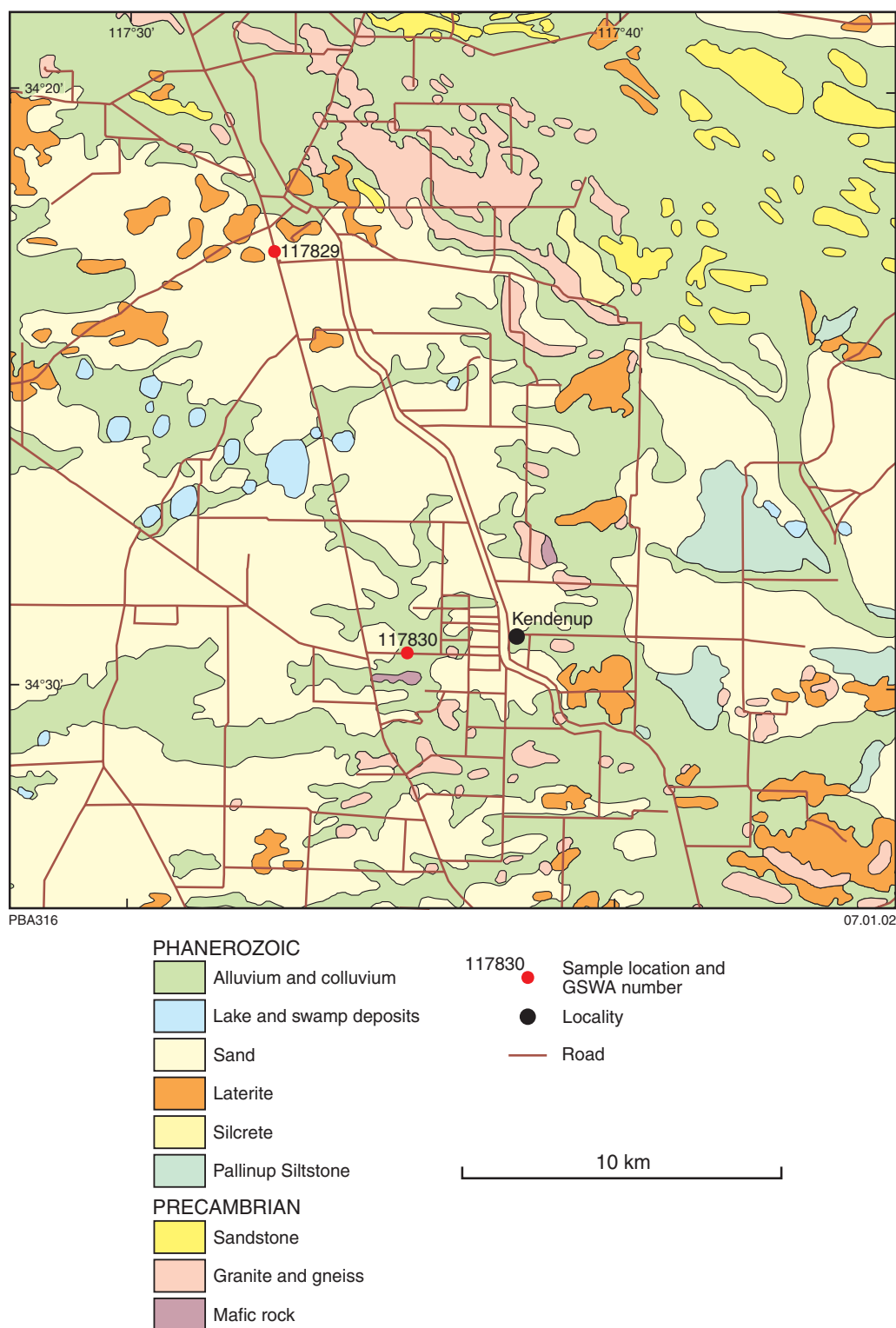


Figure 21. Regional geology of the area around Kendenup (modified from Muhling et al., 1984)

plastic clay sample (GSWA 117830) from a location about 1 km west of the Southern Highway, at the southern side of a road leading to Kendenup from the highway, contained smectite, kaolinite, and quartz (Table 33). Examination using energy dispersive X-ray analysis indicated that the smectite contained 30.77% Al_2O_3 , 1.17%

MgO , 6.22% Fe_2O_3 , and 44.30% SiO_2 . A firing test of this sample indicated that the material could be used as a good red filler in the manufacture of bricks. Another sample (GSWA 117829), about 14 km to the northwest, did not contain any smectite, and produced a soft test bar when fired at 1220°C.

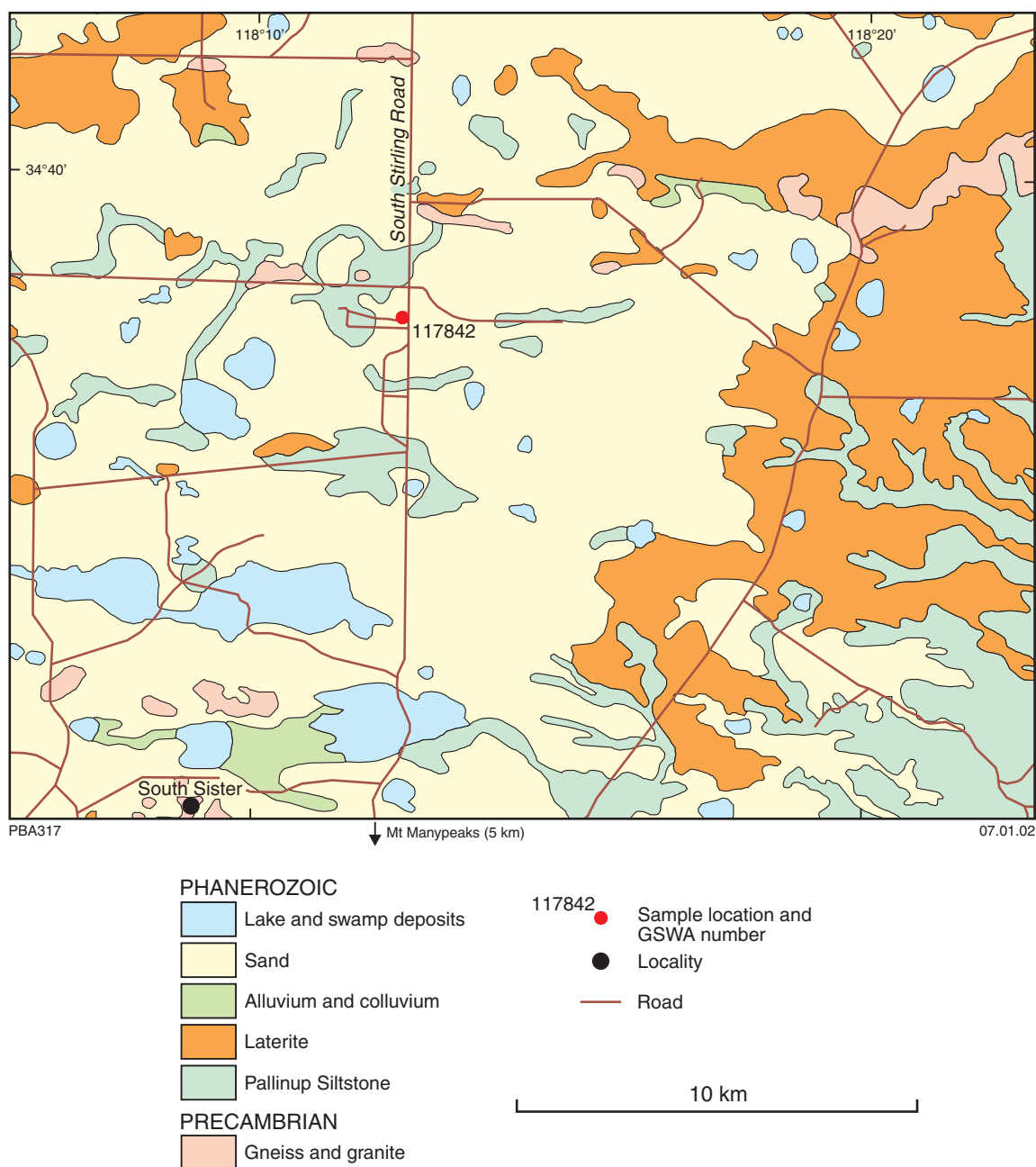


Figure 22. Regional geology of the area north of Manypeaks (modified from Muhling et al., 1984)

Mukinbudin

A gritty sample (GSWA 117883) of grey to brown clay from a lake dam located 10 km west of Mukinbudin (Fig. 4) contained smectite, kaolinite, abundant quartz and feldspar, and 13% Al_2O_3 and 73.80% SiO_2 (Tables 34 and 35). Examination using energy dispersive X-ray analyses indicated that the smectite contained 28.14% Al_2O_3 , 1.15% MgO , 0.34% CaO , 6.93% Fe_2O_3 , and 49.01% SiO_2 .

Ravensthorpe

A sample (GSWA 117853) of dark-brown to grey clay from a lake dam, situated on a flat alluvial plain about 15 km east of Ravensthorpe (Fig. 4) and north of the South

Coast Highway, contained smectite, kaolinite, feldspar, and approximately 40–50% quartz. The chemical analysis of the sample showed 9.16% Al_2O_3 and 66.40% SiO_2 (Tables 34 and 35). Examination of the sample using energy dispersive X-ray analyses indicated that the smectite contained 16.80% Al_2O_3 , 3.06% MgO , 1.18% CaO , 9.25% Fe_2O_3 , and 49.09% SiO_2 .

Bardoc

In 1931, 30 t of clay, which were used as fuller's earth (presumably the bentonitic variety), were mined 2 km south of Bardoc (Fig. 4). The clay was considered to be suitable for decolourizing and clarifying oils, but its shrinkage was too high for use in pottery (Simpson, 1952).

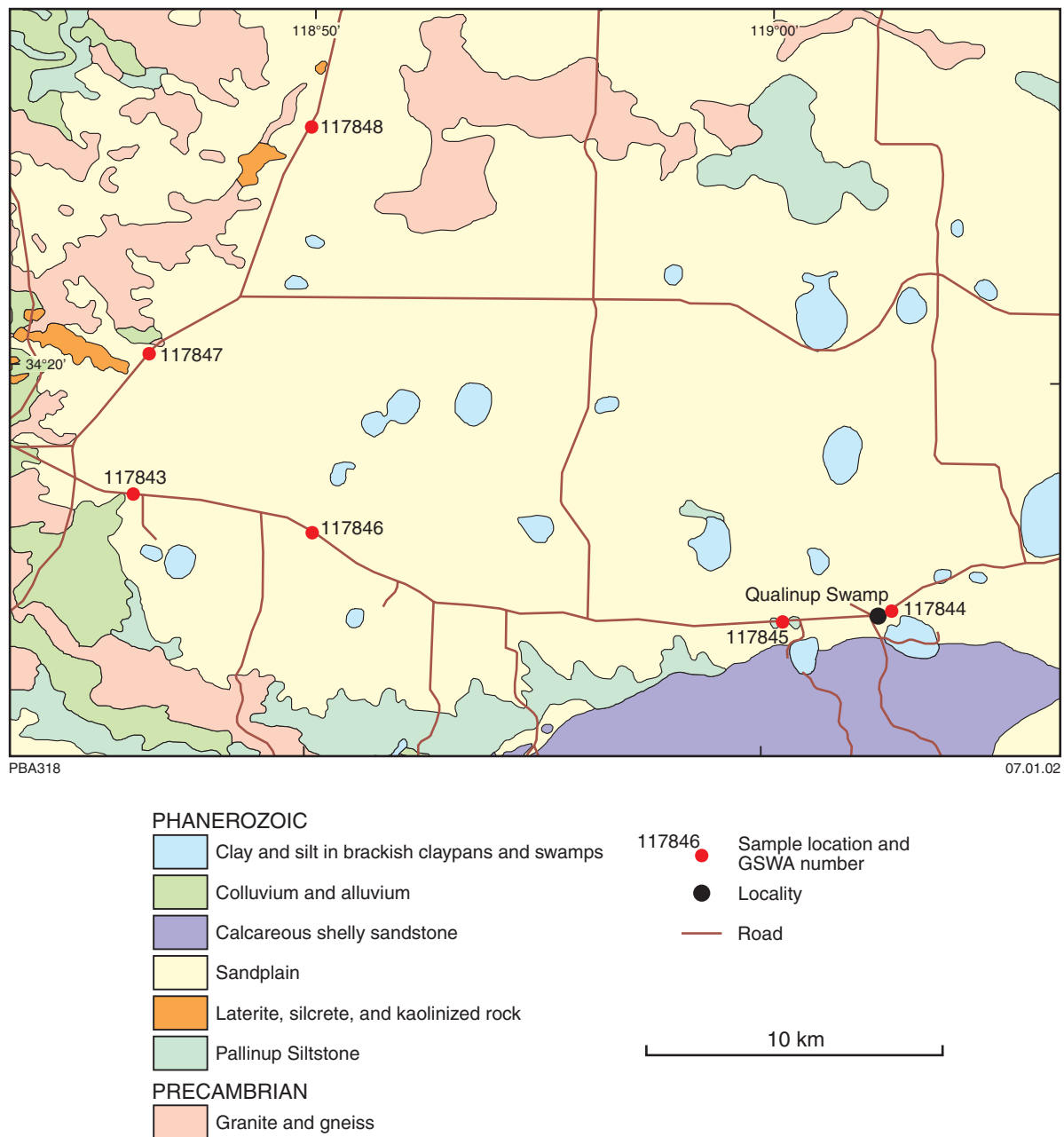


Figure 23. Regional geology of the area around Qualinup Swamp (modified from Thom and Chin, 1984)

Bremer Basin

Manypeaks

A greenish-grey clay sample (GSWA 117842) was collected from a small farm dam, located north of the Hassell Road, along the South Stirling Road (Fig. 22). The area is generally flat, with abundant clay-rich formations of Quaternary age. Mineralogical studies of the sample using semi-quantitative XRD analysis indicated 40–50% smectite and 40–50% quartz (Table 36). Detailed examination of the smectite using energy dispersive X-ray analyses indicated 16.61% Fe_2O_3 , 12.63% Al_2O_3 , 2.49% MgO , and 51.41% SiO_2 , suggesting that it is nontronite.

Qualinup Swamp

Qualinup Swamp is situated in flat terrain about 35 km west of Bremer Bay. Many farm dams in the area contain clays varying in colour from yellow to brown to grey to white. Two samples (GSWA 117844–45) were collected from lake dams about 5 km apart (Fig. 23). Sample GSWA 117844 was a yellow-brown plastic clay and the other was a whitish-grey to brown plastic clay. Both samples contained major amounts of smectite and more than 50% quartz. Sample GSWA 117844 contained a high proportion of kaolinite and GSWA 117845 contained a minor amount of kaolinite (Table 36). Examination of the smectite in sample GSWA 117845, using energy

Table 36. Mineralogy of smectite-bearing clays from Manypeaks and Qualinup Swamp

<i>Locality</i>	<i>Manypeaks</i>	<i>Qualinup Swamp</i>	<i>Qualinup Swamp</i>
<i>GSWA no.</i>	<i>117842</i>	<i>117844</i>	<i>117845</i>
Kaolinite	minor	major	minor
Smectite	subdominant	major	major
Mica/illite	—	—	—
Vermiculite	—	—	—
Attapulgite	—	—	—
Talc	—	—	—
Quartz	subdominant	dominant	dominant
K-feldspar	?minor	?minor	minor
Na-feldspar	?minor	—	—
Amphibole	?minor	—	—
Calcite	—	?minor	?minor
Dolomite/ankerite	—	—	—
Hematite	—	—	—
Anatase	—	—	—
Goethite	—	?minor	—
Gibbsite	—	—	—
Halite	—	—	—

NOTE: Dominant: >50%; subdominant: 40–50%; major: 10–40%; minor: 2–0%

dispersive X-ray analysis, indicated 20.46% Al₂O₃, 1.05%MgO, 0.44% CaO, 7.71% Fe₂O₃, and 55.30% SiO₂, and for sample GSWA 117844 the smectite contained 22.10% Al₂O₃, 5.02% Fe₂O₃, and 51.93% SiO₂.

Attapulgite (palygorskite)

Definition and mineralogy

Attapulgite (also known as palygorskite) and sepiolite are classified within the group of clay minerals known as the ‘hormite group’. The hormite-group minerals have an open-channel (ribbon-like) structure forming needle-shaped crystals (Table 37). These elongate minerals are made up of a series of channels (or holes), which is unique to the hormite-group minerals, and it is these structures (about 6 Å in diameter) that normally fill with water molecules or hydrated cations in the clay’s natural state.

The origin of the name attapulgite is from the type locality of Attapulgis in Georgia, USA. However, attapulgite was later found to be the same mineral as palygorskite, which was already known from the Palygorsk locality near the Ural Mountains. Currently both terms are used, although the term ‘palygorskite’ is considered to be the mineralogical name and ‘attapulgite’ the commercial name (Harben, 1995b). Attapulgite is the term commonly used in Western Australia. The same mineral is also referred to by other names including ‘mountain cork’ or ‘mountain leather’. Adding to the confusion of names is the fact that attapulgite is also known as fuller’s earth (as well as palygorskite) in the USA, and therefore, one has to be aware of the country of origin when these mineral names are used.

Sepiolite is another complex magnesium silicate, which is similar to attapulgite, and also has a fibrous or ribbon-like structure. Attapulgite and sepiolite, as well as bentonite, have some common properties such as a medium to high surface area, good sorptive abilities, and excellent decolorizing, binding, and thickening power.

However, their different crystal structures result in important differences. For example, bentonite flocculates in salt water, whereas attapulgite is virtually unaffected by electrolytes (Heivilin and Murray, 1994; Harben and Kuzvart, 1996).

Mineralogy

Attapulgite and sepiolite are hydrated magnesium silicate minerals. Attapulgite comes in a variety of colours such as white through cream to grey, whereas sepiolite is grey in colour.

In natural attapulgite and sepiolite, Mg is typically partially replaced by Al or even Fe. The attapulgite structure consists of two silica chains linked in an amphibole chain-like structure that has both monoclinic and orthorhombic symmetry, with one orthorhombic and three different monoclinic geometric unit cells. Such a structure gives attapulgite more diverse properties than sepiolite, which is dioctahedral (Heivilin and Murray, 1994; Harben, 1995b).

The water molecules (commonly referred to as zeolite water) in the hydrated cations of the hormite-group clay minerals can be removed by heating to a temperature of about 500°C. Hydration of such heated material is very slow, and therefore, these open-channels can readily absorb polar organic or inorganic molecules. In industrial applications, these hormite-group minerals (heated up to about 500°C) are designated as low volatile material (LVM), and those that are dried at a lower temperature of about 200°C are designated as regular volatile material (RVM).

The mineralogy, physical properties, chemical composition, and size fractions of some commercial attapulgites are given in Tables 38–41.

Table 37. Hormite clay group

	<i>Attapulgite</i>	<i>Sepiolite</i>
Industrial term	Palygorskite, mountain cork, mountain leather, etc	Meerschaum (in lump form)
Regional term	Fuller’s earth (USA)	–
Chemical composition	(Mg, Al) ₂ Si ₄ O ₁₀ (OH).4H ₂ O	Mg ₄ Si ₆ O ₁₅ (OH) ₂ . 6H ₂ O

Table 38. Mineralogy of commercial attapulgite

	%
Attapulgite	80–90
Quartz	5–10
Dolomite	0–10
Kaolinite	0–10

SOURCE: Harben (1995b)

Table 39. Physical properties of commercial attapulgite

Colour	White to light buff–gray
Moisture (as packed)	3.0 – 8.0%
Loose bulk density	0.45 – 0.65 g/cm ³ (450–650 kg/m ³)
Water absorption	80–120%
Oil absorption	70–110%
Surface area (BET)	135–140 m ² /g
Cation exchange capacity	30–40 meq/100 g
pH (5% suspension)	7.5 – 9.5

SOURCE: Harben (1995b)

Mode of occurrence

Attapulgite and sepiolite deposits can form in any of the following geological environments as:

- Chemical sediments in epicontinental and inland sea and lake environments, or as diagenetic products of earlier clays;
- Hydrothermal alteration products of basaltic glass, volcanic and sedimentary rocks, or clays found in fore-arc basins and oceanic rises;
- Crystallized derivatives of calcareous soils;
- Clay derived from marine deposits formed by slumping and turbidity currents from nearshore materials;
- Clay derived from windblown dust; or
- A weathering product of serpentinite and magnesite.

In general, attapulgite and sepiolite found in lakes, shallow seas, and calcareous soils have formed mostly in Mediterranean to semi-arid climatic conditions that were prevalent in the Late Devonian to Carboniferous and the Late Permian to Triassic in the northern hemisphere, and during the Early and Late Eocene, Late Oligocene, and possibly Late Cretaceous in both hemispheres (Harben and Kuzvart, 1996).

Uses

Suspending agent

The elongate or needle-shaped crystals in attapulgite and sepiolite make them useful as viscosity-enhancing and suspending agents. When dispersed in water, needle-shaped attapulgite crystals (1 µm long and 0.01 µm wide) form a random ‘lattice’ entrapping liquid and providing excellent thickening, suspending, and thixotropic (gelling) properties. Such properties have useful applications in adhesives, cosmetics, sealants, liquid detergents, shampoos, flexographic inks, latex paints, polishes, and ready-mix tape compounds. In addition, sepiolite can form bundles of agglomerated needles that disperse in polar solvents such as water to create a randomly intermeshed network of fibres in the solvent. This results in raising the viscosity, and various rheological properties can be generated by the control of concentration, agitation, and pH (Harben and Kuzvart, 1996).

Drilling fluid

Attapulgite and sepiolite can be useful in drilling fluids because the specifications for these minerals are similar to those for bentonite. Tests to check the suitability of attapulgite and sepiolite for drilling applications are performed by adding water and mixing slurries of specific concentrations, and then obtaining measurements of viscosity, yield, yield point, and filtrate according to standard procedures recommended by the American Petroleum Institute. Specifications for attapulgite and sepiolite for use as drilling mud are given in Table 42.

In drilling applications, attapulgite and sepiolite are most effective in salt-saturated environments such as saltwater brines because they are unaffected by electrolytes. The resistance of hormite-group minerals to flocculation in water is due to the fact that when these minerals are dispersed in water they form a bulk of randomly intermeshed, elongate particles that prevent flocculation. However, these minerals are considered inferior to bentonite in most other drilling mud applications.

Manufacture of NCR (no carbon required) paper

Attapulgite is used in the manufacture of NCR papers. In this application, the upper or receiving surface of the copy sheet is coated with attapulgite and the lower or transfer surface of the upper sheet is coated with starch containing minute encapsulated droplets of colourless dye. During writing or typing, the droplets break and release the dye so that it penetrates the attapulgite, which catalyses the conversion to a coloured product (Haden and Schwint, 1967).

Animal feed

In animal feed, attapulgite and sepiolite are used for their ability to act as binders for pelletized feeds, as carriers of supplements such as minerals, vitamins, and antibiotics, as free-flowing additives for very fine grained feeds, as lubricants to reduce die friction, and to improve the yield in the pelletization process. These minerals can also increase feed efficiency and improve digestive hygiene.

Table 40. Typical chemical composition of commercial attapulgite

	%
SiO ₂	59.0
Al ₂ O ₃	13.4
MgO	8.25
Fe ₂ O ₃	5.34
CaO	0.96
K ₂ O	2.12
Other oxides	1.2
LOI	9.73

SOURCE: Wakelam and Abeyasinghe (1999)

Table 41. Specifications for granular and powder grades of commercial attapulgite

<i>Grade</i>	<i>Size range</i>	<i>Mean particle size</i>	<i>Comments</i>
Granular grade			
0416G	4.75 – 1.18 mm	2.36 mm	>4.75 mm, 3.0% maximum <1.18 mm, 7.0% maximum
1630G	1.18 – 0.6 mm	0.85 mm	>1.18 mm, 3.0% maximum <0.60 mm, 7.0% maximum
2560G	0.71 – 0.25 mm	0.425 mm	>0.71 mm, 3.0% maximum <0.25 mm, 7.0% maximum
Powder grade			
050F	85–90% passing 250 µm	160 µm	
080F	85–90% passing 160 µm	35 µm	

SOURCE: Harben (1995b)

The advantages of using a sepiolite binder are greatest when trying to incorporate high levels of fat or oil, as the sepiolite allows greater amounts of fat to be used in the mix without impairing the quality of the pellet. Various studies have shown that sepiolite can also be used to enhance animal growth, which is attributed to the clay's colloidal properties, high absorption capacity, and CEC. Loughbrough (1993) suggested that sepiolite forms a gel in the animal's gut, allowing a longer time for digestion and thereby increasing the amount of available nutrients from the same amount of feed. Most research into the use of sepiolite has centred on pigs, but boiler and layer chickens have also exhibited encouraging results.

Pet litter

Both attapulgite and sepiolite have excellent absorbent properties, largely because of their extremely porous structure that translates to a BET (Brunauer–Emmett–Teller) surface area of about 150 m²/g for attapulgite and 300 m²/g for sepiolite. BET surface area is the specific external surface of a solid determined with the use of a specific gas that is adsorbed under controlled conditions (Somorjai, 1972). The CEC of attapulgite and sepiolite is in the range of 20–50 milliequivalents per 100 g, and is not as high as for smectite, but is considerably higher than kaolinite. These properties of attapulgite and sepiolite make them suitable for many applications, including pet litter. In pet litter applications, these clays have densities of 0.4 – 0.7 g/cm³ (400–700 kg/m³), and are classified as lightweight clays (LWC). Pet litter made of bentonitic clays, with apparent densities of 0.8 – 0.98 g/cm³ (800–980 kg/m³), are classified as heavyweight clays

(HWC). LWC are the leading type of clay (mainly attapulgite and sepiolite) used in the European market and account for about 70% of the total tonnage (Santaren, 1993).

Pharmaceuticals

Many varieties of clay are used as inactive components in pharmaceutical products. However, some varieties are also used as active ingredients because of their intrinsic properties such as their adsorbent capability. Attapulgite is one such clay, as it has a high capacity to adsorb pathogenic intestinal bacteria, enzymes, and toxins. Attapulgite and thermally activated attapulgite are used as intestinal adsorbents in anti-diarrhoeic products.

Other

The absorbent properties of attapulgite and sepiolite clays are utilized in many applications other than pet litter. These applications include animal bedding, tank cleaning, dust control, packaging (the clay acts as a cushion or shock absorbent for the prevention of breakages), to remove oil films in machinery parts, floor scrubbing, potting mixes (as a carrier for fertilizers), the removal of pesticides and agrochemicals (such as herbicides, fungicides, and insecticides), and in the transportation of hazardous chemicals (liquids can be transported as free-flowing solids).

Attapulgite is also used to decolourize, dehydrate, and neutralize various mineral, vegetable, and animal oils. Other industries using attapulgite include paint, radio-active waste disposal, molecular sieves, glazes, pottery and ceramics, lubricants, fertilizers, detergents, mortar, catalysts, paper coating, seed coating, adhesives, and water purification (Santaren, 1993).

Exploration and evaluation

The first step in exploration for attapulgite is to identify target areas based on a knowledge of attapulgite's mode

Table 42. Physical requirements for attapulgite and sepiolite for use in drilling muds

Suspension properties	
Viscometer dial reading @ 600 rpm (centipoise)	30
Residue >75 µm (200 mesh US Series), maximum	8.0 wt%
Moisture, maximum	16.0 wt%

SOURCE: Griffiths (1994)

of occurrence. After the identification of target areas, a reconnaissance field program is commonly conducted to establish whether any clay deposits are present. The clay has no characteristic or unique appearance, but is often massive, cream to gray or off-white in colour, and dries rapidly on exposure to air. After identification of a deposit in the field, it must be evaluated from samples taken from core drilling, with the aim of proving resources that will last for a minimum of 5–10 years. The drilling should be on a grid spacing of approximately 50 m down to 15 m apart, depending on the size and uniformity of the deposit. However, in some countries (e.g. China and Senegal) the evaluation of the deposit is done by means of a number of test pits, due to the relatively lower costs of such an evaluation method (Heivilin and Murray, 1994).

The cores are typically sampled at 1 m intervals and initially tested for use in drilling muds, gelling clays, and for absorbent uses. Gelling clays must meet standard viscosity and grit requirements, and the absorbent tests are conducted with water and oil. In the USA these clays must meet the standards of Federal Specification P-A-1056A. Some speciality uses may require chemical analyses, brightness values, colour, and special absorption and adsorption tests.

Based on drilling and testing, maps are compiled that show the overburden thickness, clay thickness, and quality. If the final estimates indicate that the deposit contains clay of adequate quality and quantity, it is advisable to open a small test pit to obtain a relatively large quantity that can be run through a typical processing plant. The steps at this stage involve crushing the clay, drying the material to produce regular volatile material (RVM) and low volatile material (LVM), screening the dried product to estimate the granule size distribution, and pulverizing the material to various fine sizes (e.g. -200 mesh, -325 mesh) to determine the quality and recovery. Tests such as extruding the clay with the addition of MgO can also be done to see whether the drilling application properties of the clay can be improved. If the test results are favourable and the deposit has enough reserves, then a mine can be established.

Mining and processing

Attapulgite is mined from openpits worldwide. The stripping is done with scrapers, draglines, or bulldozers and the clay is mined with shovels, backhoes, small draglines or front-end loaders. The clay is transported by trucks to the processing plant. Processing simply involves crushing, drying, classification, and pulverization. A flow sheet for processing hormite-group minerals (including attapulgite) is shown in Figure 24. However, more sophisticated processing may include extrusion, the addition of 1–2% MgO to improve viscosity characteristics for drilling muds, heating to yield LVM with improved sorbent properties, or ultra-fine pulverization to enhance suspension properties for pharmaceuticals (Heivilin and Murray, 1994; Harben and Kuzvart, 1996).

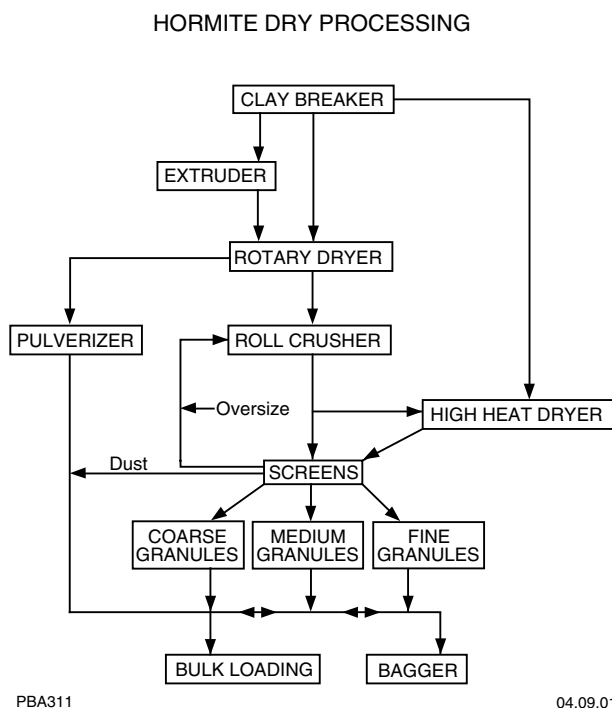


Figure 24. Typical process flow sheet for hormites (after Elzea and Murray, 1994)

Production and market trends

Production

The available global production figures for attapulgite are very approximate because the figures for hormite production are commonly combined with fuller's earth. However, available production figures indicate that global production of attapulgite is approximately 2.8 Mtpa (Table 43), and of this more than 90% (2.5 Mtpa) is produced in the USA. Other countries producing attapulgite include Senegal, Spain, Australia, Turkey, India, Russia, China, and France.

USA

The production of attapulgite in the USA is approximately 2.6 Mtpa (Cameron, 1998). Of this, approximately 1.5 Mt is from the Meigs–Attapulgas–Quincy district in southwestern Georgia, where attapulgite is produced from the Hawthorn Formation of Miocene age. Within the Hawthorn Formation, attapulgite is found in two stratigraphic intervals that comprise the younger Meigs Member from the early Middle Miocene and the Dogtown Clay Member from the late Early Miocene, with the former unconformably overlying the latter. The Meigs Member contains smectite, 'short-length' (<2 µm) attapulgite, and a small amount of sepiolite, opal, and minor and sporadic amounts of clinoptilolite, as well as diatoms. The Dogtown Clay Member contains 'longer-length' (>10 µm) attapulgite, and minor amounts of quartz, smectite, and dolomite, with traces of pyrite. Large lenses

Table 43. World attapulgite production (thousand tonnes)

Country	1992	1993	1994	1995	1996	1997	1998
USA	2 413	2 484	2 640	2 640	2 580	na	na
Senegal	148	119	119	120	120	na	na
Spain	87	91	91	94	90	na	na
Australia ^(a)	20	20	19	20	20	20.5	24
South Africa	8	7	10	8	14	na	na
India ^(b)	—	—	—	—	—	—	30
Ukraine ^(b)	—	—	—	—	—	—	10
China ^(b)	—	—	—	—	—	—	5
Total	2 676	2 721	2 879	2 882	2 824	—	—

SOURCE: Cameron (1998b); Heivilin and Murray (1994)

NOTE: (a) production during financial years (July–June)
 (b) average annual production
 na not available

of attapulgite, locally forming continuous beds, extend for more than 80 km from near Meigs in Georgia to south of Quincy in Florida. Deposits of commercial significance are concentrated at the northern and southern ends of the belt. The deposits to the north near Meigs and Ochlocknee in Georgia are 10–20 m thick, commonly contain clay-pebble zones, and are commonly at or near the top of the Hawthorn Formation. The deposits to the south near Attapulgis in Georgia and Quincy in Florida are 2–3 m thick and clay-pebble zones are absent. There is as much as 24 m of the Hawthorn Formation between the deposit and the overlying Miccosukee Formation. The attapulgite content of the northern deposits rarely exceeds 20%, whereas some deposits in the Attapulgis–Quincy district in the south contain 70–80% attapulgite. The deposits in the northern area may contain approximately 10% sepiolite, which is virtually absent in the southern deposits (Heivilin and Murray, 1994; Harben and Kuzvart, 1996).

The main producers in the area are Engelhard Mineral and Chemicals Corporation near Attapulgis and Quincy in Florida, Milwhite at Attapulgis, and Oil–Dri Corporation of America near Ochlocknee in Georgia.

Senegal

Senegal has a long history as a supplier of attapulgite to the European market, and has an annual production of approximately 120 000 t. The processing plants in Senegal have a production capacity of approximately 300 000 t. The attapulgite beds are Miocene in age, and are present as overburden material in the phosphate mines near Thies, about 100 km east of Dakar. The attapulgite produced from this area is mainly used for industrial absorbents and pet litter, but approximately 15 000 t is used in drilling mud applications.

There are two producers of attapulgite in Senegal. One is Ste Sénégalaise des Phosphates de Thiès (SSPT), which is jointly owned by the Senegalese Government, and Cie Industrielle et Minière, a subsidiary of Rhône–Poulenc in France. The export of attapulgite in Senegal is handled by Rhône–Poulenc and its subsidiaries, under the brand name

of Rhône’sec, who sell it as cat litter to European producers such as Laporte and Steetley in the UK. The other producer is Prochimât (owned by the French company Ceca SA), which produces attapulgite from its deposits near Dakar and processes the attapulgite at Ceca’s plant at Honfleur in France. Amongst other things, production from Prochimât is used in the manufacture of molecular sieves (O’Driscoll, 1992; Heivilin and Murray, 1994).

Spain

Spain produces approximately 500 000 tpa of sepiolite and 90 000 tpa of attapulgite, of which approximately 90% is exported. The regions of significant sepiolite production are in the provinces of Madrid and Toledo in central Spain. Tolsa SA is the world’s largest sepiolite producer, and is known to supply 40% of Europe’s cat-litter market. The company has openpit mines in the Vicalvaro–Yuncillos region. Tolsa has a plant in Madrid with a production capacity of approximately 600 000 tpa. The plant produces a number of grades of sepiolite used for pet litter (60%), animal feed (25%), and special grades for industrial uses such as a catalyst carrier and elastomer filler (15%). Another big producer is Minería y Tecnología de Arcillas (Myta), with production of about 100 000 tpa from deposits in Orera, Zaragoza, Maderuelo, and Segovia.

Attapulgite-producing areas in Spain include the provinces of Cáceres in west-central Spain, close to the Portuguese border, and Cadiz in the south. Minas Volcan SA produces approximately 25 000 tpa of attapulgite from mines in Almería, and processing is done in one of the company’s two plants in Murcia. Bentonitas Especiales SA (Benesa), a sister company of Minas Volcan, produces approximately 5000 tpa of attapulgite from deposits in Almería, for applications in absorbent granules, drilling fluids, and animal feedstuffs. Myta produces approximately 20 000 tpa of attapulgite, for domestic and industrial absorbents, from mines at Maderuelo and Segovia. Tolsa, a subsidiary of Minas de Torrejón SA (Mitosa), produces approximately 5000 tpa of attapulgite, mainly for animal feed and saltwater drilling clays, from mines in Cáceres (Griffiths, 1991; O’Driscoll, 1992).

Australia

Australian attapulgite production is approximately 20 000 tpa, and all of this is from the Lake Nerramayne deposit in Western Australia. Production from the Lake Nerramayne deposit began in 1979–80, and until 1998–99 the total reported production was 305 956 t (Table 44). There was a peak production of 44 065 t in 1988–89. During the ten year period of 1989–99 average production was 19 816 tpa. The geology of the Lake Nerramayne deposit, the quality of the attapulgite, and other relevant information on attapulgite in Western Australia are discussed in the section on **Attapulgite in Western Australia** later in this chapter.

In Queensland, attapulgite has been produced on a small scale from a deposit mined by Newgate Metals at Peaks Crossing, 27 km south of Ipswich. The material has been used mostly as an additive for stockfeed (Keeling, 1997).

In South Australia, drilling in the Garford Palaeo-channel, 720 km northwest of Adelaide, intersected attapulgite up to 2 m in thickness and over a length of 18 km. In inland Australia, attapulgite is widely associated with clay and carbonate sediments in river channel and lake deposits of Late Tertiary age (Callen, 1984).

South Africa

In 1996, South Africa produced 14 000 t of attapulgite, which is found in the Springbok Flats area, northeast of Pretoria, and in the Dwaalboom area in northeastern Transvaal. There are two significant producers of attapulgite in South Africa — Atta Clay (Pvt) and the

Foundrex Division of G & W Base and Industrial Minerals.

Atta Clay produces attapulgite and calcium montmorillonite clay from a mine at Burgersfort in East Transvaal that has resources of over 1 Mt. The processing of clay from this mine involves drying using a rotary dryer to produce a product with only 2% moisture, and subsequent screening. The clay is supplied in two sizes: 1180–250 µm and 4.5 – 1.18 mm. The smaller size is used in agricultural applications as a carrier for pesticides and herbicides, and also in metallurgical applications to absorb moisture.

The Foundrex Division produces attapulgite from a mine in Dwaalboom in northeastern Transvaal, which is then processed in Bulcania in the East Rand. The clay from this area contains up to 20% coarse silica, but this is reduced to less than 2.5% by processing in a closed circuit. The attapulgite is supplied as a gel for liquid fertilizers.

Other producers include Kimony Holding, which produces from a deposit near Thambazi in the north-western Transvaal, and the Calais attapulgite mine, which produces a small amount of attapulgite for use in cat litter from a deposit in Fontainbleau.

India

In India, attapulgite is mined and processed in the Bhavnagar district in the State of Gujarat, and is used in drilling mud, pet litter, and as an industrial absorbent. The buff-blue coloured clays found to the south of Adhevada, Akvada, and Tagadi in the Bhavnagar district and described by Shah (1997) could possibly be attapulgite. India has an approximate annual production capacity of 30 000 t of attapulgite (Russell, 1991; Heivilin and Murray, 1994).

China

Attapulgite is mined from sedimentary rocks near the town of Xuyi in the Jiangsu Province. The attapulgite has formed in Pliocene lacustrine sediments and volcanoclastic rocks consisting of basalt intercalated with claystone, mudstone, and siltstone. The thicknesses of these sedimentary beds range from 20 to 90 m. Other attapulgite deposits are known in the boundary regions between the Jiangsu and Anhui Provinces. These deposits, including the one near Xuyi, are estimated to contain about 50 Mt of attapulgite. Recent production figures are not available, but annual production was 5000 t in 1987 (Heivilin and Murray, 1994; Wen Lu, 1998).

Market trends

In the United States, which is by far the world's largest producer, the prices of various grades of attapulgite have remained nearly stable from 1994 to 1997, and have shown an increasing trend from 1997 to 1999. The increasing trend is more pronounced in the price of speciality gel grades, which in 1999 were approximately

Table 44. Western Australian attapulgite production

<i>Year</i>	<i>Tonnes</i>
1979–80	1 330
1980–81	4 251
1981–82	6 372
1982–83	6 602
1983–84	6 202
1984–85	8 424
1985–86	8 704
1986–87	10 458
1987–88	11 387
1988–89	44 065
1989–90	28 137
1990–91	15 403
1991–92	19 329
1992–93	20 208
1993–94	20 351
1994–95	18 796
1995–96	19 753
1996–97	20 473
1997–98	24 023
1998–99	11 688
Total	305 956

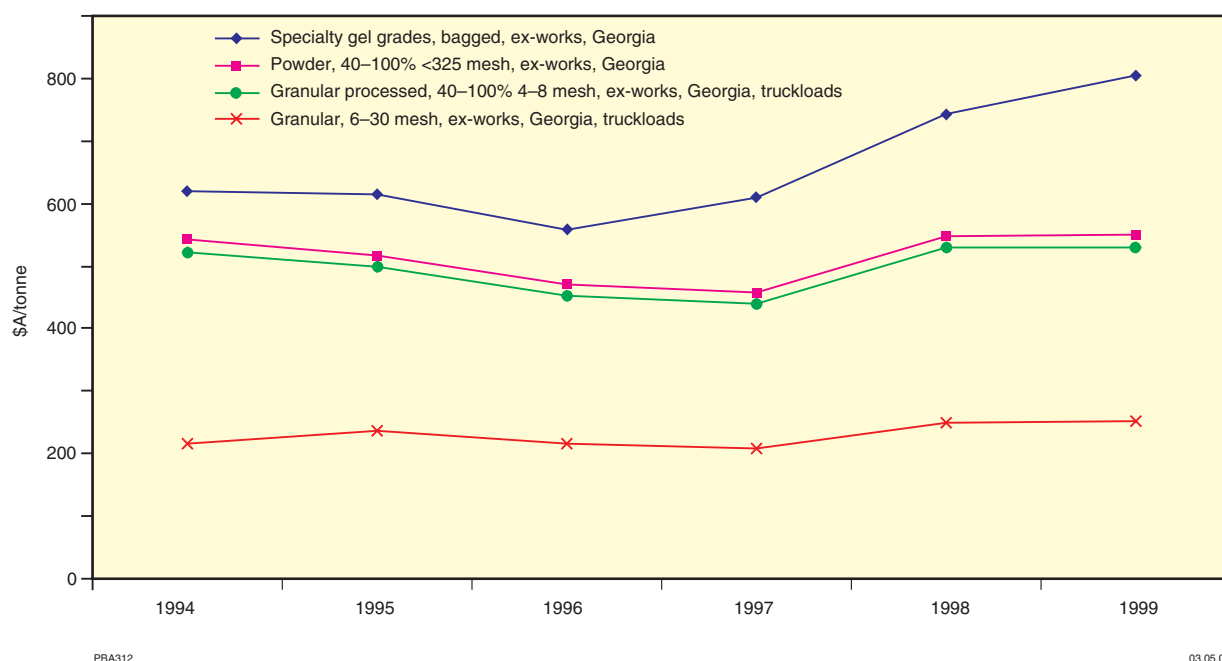


Figure 25. Price trends of different attapulgite grades in the United States (adjusted to 1999 dollars; after Cameron, 1998b)

\$A805 per tonne, whereas that of granular grades ranged from \$A252 to \$A530 per tonne (Fig. 25).

The most significant growths in attapulgite applications are expected to be in its use as a thickener, gellant, suspension agent, or stabilizer in a wide range of industries. The outlook for such uses is strong, particularly for gellant grade in the paint industry, as indicated by the expansion planned by the major companies such as ITC Inc in the USA. The granular attapulgite market is also expected to perform well. An increase in demand is expected for animal feed applications in the European market. Such increase in demand for various grades is supported by the upward trend in prices from 1997 to 1999.

Attapulgite in Western Australia

The only known locality with commercially significant attapulgite deposits in Western Australia is Lake Nerramyne, located 480 km north of Perth and 157 km northeast of Geraldton. The deposits are found in playa lakes on the western margin of the Narryer Terrane and about 7 km east of the northerly trending Darling Fault (Figs 26 and 27).

The Lake Nerramyne attapulgite deposit is being mined at present. The mine can be approached from Geraldton via a sealed bitumen road to Yuna (70 km) and then by gravel road.

The only other known occurrence of attapulgite in Western Australia is at Boodanoo Hill, 75 km southeast of Mount Magnet.

Other areas that have a similar geological setting to Lake Nerramyne are found along the western margin of the Yilgarn Craton. Prospective targets for attapulgite are the claypan–playa lakes north of the Murchison River in the Byro Pool area, and the extensive lake system further north on Muggen Station, about 130 km north of Lake Nerramyne (Derry, Michener & Booth Pty Ltd, 1977).

Lake Nerramyne deposit

Previous exploration and mining

The first report of the presence of attapulgite in the Lake Nerramyne area was Simpson (1952), who stated that attapulgite (referred to as palygorskite) had been obtained in considerable quantity from a well at Location 7220 (north of the Lake Nerramyne area). The material was mined from a depth of approximately 5 m to the bottom of the well at 6.5 m.

In May 1977, Derry, Michener & Booth Pty Ltd, on behalf of Vas D'Esterre and Doug Dawes, carried out geological investigations within the Lake Nerramyne area (Fig. 27). This work confirmed that the area had potential for economic deposits of attapulgite. The area was further explored by Henderson (1977, 1978), and this work involved observation and testing of surface outcrops, costeans, and dump material near water wells, and the drilling of 30 holes during 1976–77. The area was opened up for mining in 1979 by Mallina Holdings, with a first reported production of 1330 t during 1979–80. Another 35 holes were drilled in 1986 (White, 1986). In 1997, Mallina Holdings was taken over by Hudson Resources, who hold the main deposits under tenure of Mining Leases 70/389, 70/483, and 70/606.

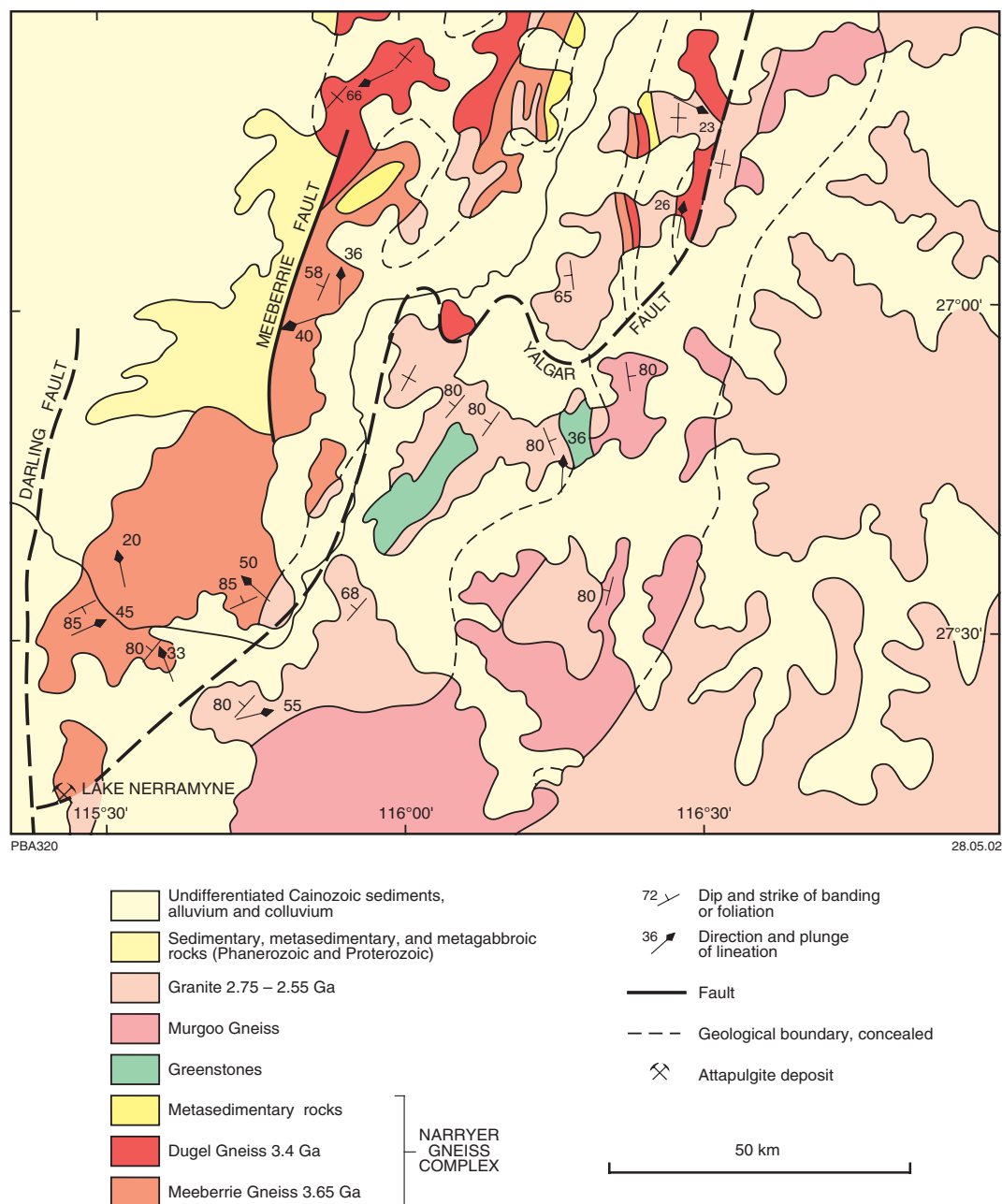


Figure 26. Regional geology of the area north and east of the Lake Nerramyne deposit (after Myers, 1990b)

Regional geology

The Narryer Terrane forms the northwestern part of the Yilgarn Craton, and is bounded by the Carnarvon and Perth Basins to the west, the Gascoyne Complex to the north, the Bryah and Padbury Basins to the east, and the Murchison Granite–Greenstone Terrane to the south. The Narryer Terrane was previously included in the Western Gneiss Terrane and was referred to as the Narryer Gneiss Complex. Later work in the region by GSWA led to the separation of the Western Gneiss Terrane into the Narryer and South-West terranes (Myers and Hocking, 1998). The rocks in the Narryer Terrane are older than

3 Ga and consist of two groups of gneiss: the Meeberrie Gneiss and the Dugel Gneiss (Fig. 26). The Meeberrie Gneiss is derived mainly from monzogranite, whereas the Dugel Gneiss is derived from leucocratic syenogranite and monzogranite that intruded the Meeberrie Gneiss. Both groups of gneiss contain inclusions from the layered mafic–ultramafic intrusions that form the Manfred Complex, from narrow layers of metasedimentary rocks, and from a variety of mafic intrusions. The Manfred Complex rocks contain abundant amphibolite (interpreted as metagabbro), which locally has coarse-grained, ophitic and subophitic textures, and igneous plagioclase, olivine, and orthopyroxene. The Manfred

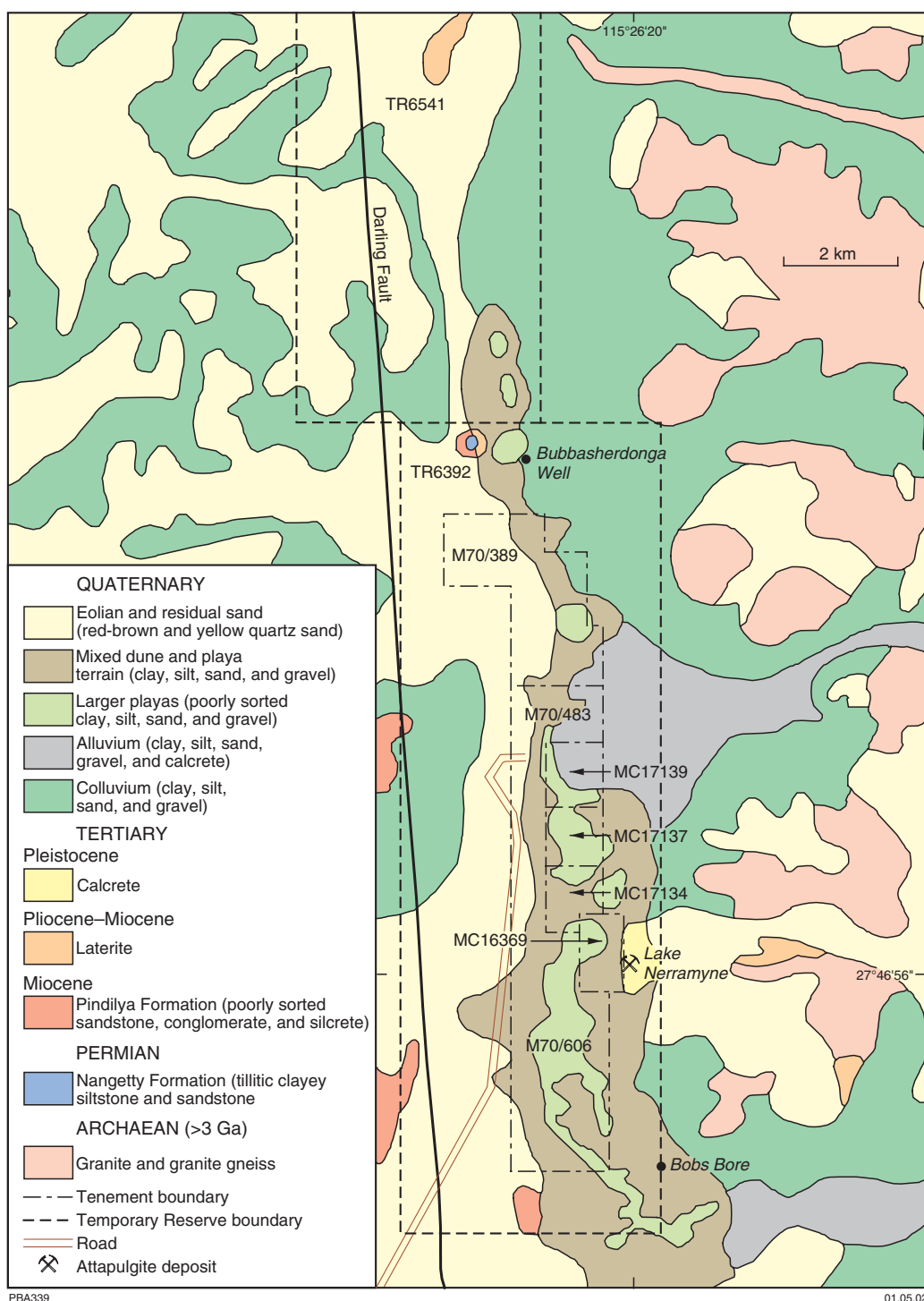


Figure 27. Geology of the area around the Lake Nerramyne attapulgite deposit (modified from Hocking et al., 1982b)

Complex also contains ultramafic rocks such as metamorphosed dunite, peridotite, and pyroxenite, and most of these rocks are serpentinized.

The main lithological units in the Lake Nerramyne area are Quaternary alluvial, colluvial, and playa lake deposits containing clay, silt, sand, and gravel. The area also contains localized calcrete exposures, possibly of

Pleistocene age. The Pindilya Formation, consisting of sandstone and conglomerate of Miocene age, is exposed on the western side of the Darling Fault. Medium-grained, foliated granitic rocks that are mostly exposed to the east of Lake Nerramyne probably belong to the Archaean Meeberrie Gneiss. These granitic rocks constitute the basement rocks of the Lake Nerramyne area (Fig. 26). The northerly trending Darling Fault is

a prominent structural feature in the Lake Nerramyne area.

Geology

Lake Nerramyne is one of a series of northerly trending playa lakes about 7 km east of the Darling Fault (Fig. 26). In the vicinity of Lake Nerramyne, there are scattered boulders and outcrops of attapulgite, but the surface is typically covered with a veneer of Quaternary lake sediments consisting of red to brown sandy soil and some calcrete rubble. The attapulgite deposits have developed in a Tertiary sequence believed to be an outlier of Tertiary sediments preserved in a shallow depression of Archaean basement rocks. The basement rocks in this area comprise Archaean granite and granite gneiss, possibly belonging to the Meeberrie Gneiss (Henderson, 1977, 1978; White, 1986).

Derry, Michener & Booth Pty Ltd (1977) suggested that during the Paleocene–Eocene attapulgite was deposited at Lake Nerramyne as a chemical sediment under evaporative conditions in a very low energy environment. This process was considered to have occurred in a shallow, restricted marginal marine or lagoonal environment. This model is based on the deposits being related to magnesium-rich groundwater derived from the alteration of magnesium-rich minerals in mafic to ultramafic rocks, with precipitation of attapulgite under evaporitic conditions. Mafic–ultramafic rocks have not been intersected in the shallow drilling so far conducted at Lake Nerramyne, but the geological setting of the deposits suggests three possible sources for such rocks:

- Mafic dykes emplaced during the Phanerozoic breakup of Gondwana and the formation of the Perth Basin;
- Mafic intrusions emplaced during the Proterozoic Pinjarra Orogen; or
- The Archaean Manfred Complex that contains metagabbro, metamorphosed dunite, and localized serpentinized ultramafic rocks. Hocking et al. (1982a) stated that poorly exposed bands of ultramafic rocks, marked by magnesite and chrysoprase rubble, are present in the Archaean granitic gneiss basement.

White (1986) suggested the possibility that the deposits are derived in part from reworked volcanic rocks or tuffs. However, such volcanic or volcanoclastic rocks have not yet been identified in the shallow drillholes.

The structural control on the mineralization is obvious, with deposits elongate and parallel with the north–south Darling Fault. The Darling Fault is likely to have controlled the sedimentation in Tertiary basins and the channelling of magnesium-rich groundwaters. However, neither of the above models have been fully tested, and deeper drilling is required to provide more information. The deepest drillhole at Lake Nerramyne is only 19 m deep, with all other drillholes less than 13 m.

Both models do suggest, however, that a broad zone, perhaps up to 5 km wide and parallel to the Darling Fault, is likely to be prospective, but that deposits may be

completely obscured by Quaternary sediments. The zone is bounded to the east by outcrops of granite and to the west by the Darling Fault.

Occurrences

The attapulgite deposits are developed in and adjacent to Lake Nerramyne, mostly within the eastern flank of the Lake Nerramyne drainage system. A number of creeks flow into the lake system from the east. The ground immediately adjacent to the lakes is generally flat, but with low hummocks.

During the exploration phase of 1976, the best evidence of attapulgite was found in a costean near the present mining area and in the dumps of Bubbasherdonga Well. This costean and other small occurrences in the area were aligned in an 11 km linear belt. The distribution of the Tertiary sediments suggests that the length of the attapulgite occurrence could be further extended by about 5 km to the south (Fig. 26). For example, at Bobs Bore (about 5 km south of the Lake Nerramyne mine) there are pieces of white, calcareous, fine-grained bedded sandstone in the dumps. This sandstone is derived from a sequence that was considered to be a part of the attapulgite-bearing beds (Derry, Michener & Booth Pty Ltd, 1977).

The typical lithology inferred from 30 drillholes drilled during 1976–77, on Mineral Claim 16369, is summarized in Table 45. Eighteen of these holes intersected high-grade attapulgite. Of the 35 holes drilled during 1986 on Mineral Claims 17134, 17137, and 17139, 30 holes intersected both high- and low-grade attapulgite. Most of the holes terminated at about 7 m, with the deepest being 19 m, and all the other drillholes were less than 13 m. The walls of the recent openpits indicate an upper layer of approximately 1 – 3.5 m-thick red-brown loam or calcrete overburden underlain by an approximately 0.5 – 1.0 m-thick layer of low-grade iron-oxide stained attapulgite. Beneath this layer is a high-grade zone of massive attapulgite, varying in thickness from approximately 1 to 8 m (Fig. 28). The Tertiary sequence that contains the attapulgite is commonly less than 10 m thick. The sediments contain varying amounts of attapulgite, kaolin, montmorillonite, dolomite, calcite, illite, and quartz. The beds containing attapulgite dip slightly to the west and their thickness is influenced by the topography of the basement rocks. The basement is deepest below Lake Nerramyne and shallows gently to the east.

Quality

The high-grade horizons commonly contain in excess of 65% attapulgite, smectite, and kaolinite, and the content of these minerals in the low-grade horizons ranges from 45 to 65%. The attapulgite content in drillchip samples varies from 25 to 80%, with variable amounts of kaolinite, smectite, quartz, and dolomite (Table 46). Semi-quantitative mineralogical identification of raw samples (using XRD) from the Lake Nerramyne deposit indicates that attapulgite is the dominant mineral and is accompanied by variable percentages of quartz, kaolinite, and dolomite (Table 47). Chemical analyses of raw attapulgite from the stockpiles indicate an average of

Table 45. Typical vertical lithology at Lake Nerramyne, as inferred from drilling in 1976–77

Depth (m)	Age	Lithology
0–2	Quaternary	Brown soil
2–4	Tertiary	Calcrete, thin clay, and hard silcrete horizons
4–8		Massive, fine-grained, greenish-white attapulgite beds
8–10		Soft, friable, cream to brown siliceous attapulgite
10–12	Archaean	White to brown kaolinitic clays and weathered granite

SOURCE: Henderson (1977)

12.50% Al₂O₃, 51.77% SiO₂, 4.12% Fe₂O₃, and 4.50% MgO (Table 48). Photomicrographs using an SEM show the attapulgite to be somewhat similar to the ‘short-length’ (<2 µm) type from the Meigs Member in southern Georgia in the USA (Fig. 29). Typical mineralogy, chemical composition, and physical properties of the processed commercial-grade Lake Nerramyne attapulgite are summarized in Tables 49–51.

Resource

The measured and inferred resources of attapulgite-bearing sediments at the Lake Nerramyne deposit are estimated at 10 Mt and 100 Mt respectively (Mallina Holdings Ltd, 1993; Hudson Resources Ltd, 1998).

Mining

The Lake Nerramyne attapulgite is mined by simple opencut methods. Approximately 3 m of overburden is stripped to expose the generally flat-lying beds of attapulgite. The ore is then selectively mined using a Kato long-reach shovel (Fig. 30). The watertable is 2–7 m below the surface (Fig. 31) and the mining area is dewatered with a small pump. The pits are subsequently backfilled with the waste material. The mined attapulgite is stockpiled in small heaps on-site for solar drying (Fig. 32), since wet attapulgite is almost twice the weight of the dry material. After several months, the sun-dried attapulgite is transported to the processing plant at Narngulu, near Geraldton. Mining of the deposit is on a campaign basis, but is sufficient to ensure constant plant feed. Mining commonly takes place during the summer months.

In June 1999, the amount of attapulgite in the stockpiles amounted to approximately 100 000 t. Most of

Table 46. Mineralogy of samples from drilling at Lake Nerramyne during 1976–77

Hole no.	Sample no.	Depth (m)	Attapulgite	Kaolinite	Smectite	Quartz	Dolomite
Percentage							
5	RSG 1	4–5	80	10	–	5	5
7	RCD 8	4–5	55	10	5	30	–
	RCD 9	5–6	60	15	5	20	–
	RCD 10	6–7	60	15	5	15	5
	RCD 11	7–8	25	20	10	25	10
	RCD 12	8–9	35	30	10	35	10
12	RCD 33	4–5	65	15	5	15	–
	RCD 35	5–6	60	25	–	15	–
	RCD 37	6–7	65	20	5	10	–
	RCD 38	7–8	45	20	5	30	–
	RCD 39	8–9	25	25	10	30	10
8	RCD 20	8–9	45	25	10	15	5
	RCD 21	9–10	40	30	10	10	10
11	RCD 43	5–6	45	30	5	20	–
15	RCD 34	4–5	45	20	–	35	–

SOURCE: modified from Henderson (1977)

Table 47. Semi-quantitative mineralogy of raw attapulgite samples from the Lake Nerramyne deposit

GSWA no.	145183	145184	145185	145186	145187	145188	145189
Kaolinite	minor	minor	minor	major	major	major	minor
Attapulgite	major	major	dominant	major	major	major	major
Quartz	major	major	major	major	major	major	major
Dolomite/ankerite	major	minor	–	minor	–	–	major

NOTE: Dominant: >50%; subdominant: 40–50%; major: 10–40%; minor: 2–0%

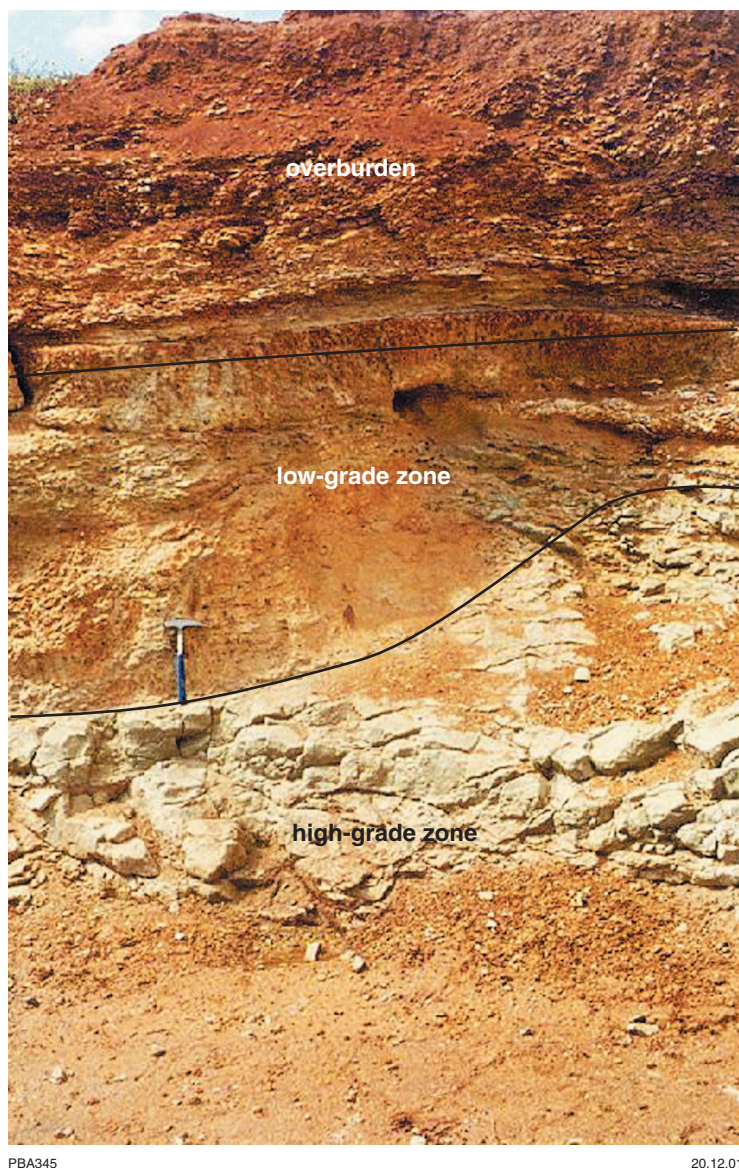


Figure 28. Vertical lithology of the Lake Nerramyne attapulgite deposit

the stockpiles consist of high-grade material, with some low-grade material stockpiled separately. The high-grade attapulgite is white and generally massive, with some finer fractions, whereas the low-grade material contains small amounts of reddish material (iron oxides) and also small amounts of dark spotty material, possibly a manganese mineral. Both high- and low-grade material are used in the final commercial products.

Processing

Processing at the plant is relatively simple and involves milling, followed by drying at approximately 130°C, and then screening to various size fractions (Fig. 33). During the milling process, precautions are taken to avoid overheating in order to retain the absorptive capacity of the material and prevent production of excess fines. At the plant site, stockpiles are based on grade and density, and

materials from different stockpiles are blended to obtain a product with a consistent density. The current production capacity of the plant is 30 000 tpa, but the reported production in 1999 was 5639 t. There are plans to increase the plant's capacity and modify it to produce more specialized grades.

Uses

Hudson Resources produces milled products of various sizes that are bagged to customer specifications.

Pet litter

The main product from the processing plant at Lake Nerramyne is pet litter, which is sold in Australia, New Zealand, Japan, and Asia. The highly absorbent granules absorb pet odour and waste in scratch trays and cages. The

Table 48. Chemical analyses of the Lake Nerramyne attapulgite

GSWA no.	145183	145184	145185	145186	145187	145188	145189
Percentage							
Al ₂ O ₃	9.01	12.50	12.10	15.90	15.10	11.80	11.10
SiO ₂	38.90	48.10	53.00	53.60	49.80	58.50	60.50
TiO ₂	0.46	0.63	0.64	0.75	0.78	0.61	0.64
Fe ₂ O ₃	3.04	3.96	3.87	6.29	4.60	3.65	3.40
MnO	0.07	0.03	<0.01	0.01	<0.01	<0.01	0.02
CaO	9.36	3.03	0.08	0.28	0.09	0.08	0.72
K ₂ O	1.22	1.59	1.76	1.95	1.74	1.66	1.38
MgO	8.34	5.00	4.37	3.27	3.42	3.77	3.33
P ₂ O ₅	0.01	0.00	0.01	0.02	0.01	0.01	0.02
SO ₃	0.16	0.21	0.03	0.08	0.18	0.12	0.15
BaO	0.04	0.04	0.07	0.02	0.01	0.02	0.02
Na ₂ O	0.45	1.00	0.43	0.83	0.80	1.22	0.82
LOI	28.50	23.40	23.20	16.60	23.00	18.30	17.40
Total	99.56	99.49	99.56	99.60	99.53	99.74	99.50
H ₂ O ⁻	8.91	11.20	15.77	7.88	14.14	11.34	9.53
Parts per million							
Mo	4	2	2	4	3	3	4
Nb	4	10	10	9	11	9	9
Ni	30	33	27	35	27	33	27
Pb	18	15	14	21	13	15	10
Rb	38	57	57	54	55	57	44
Sn	<10	<10	<10	<10	<10	<10	<10
Sr	101	66	50	35	25	25	36
Zn	15	17	17	22	14	17	17
U	<3	5	5	3	<3	4	<3
Th	13	17	19	18	19	17	14

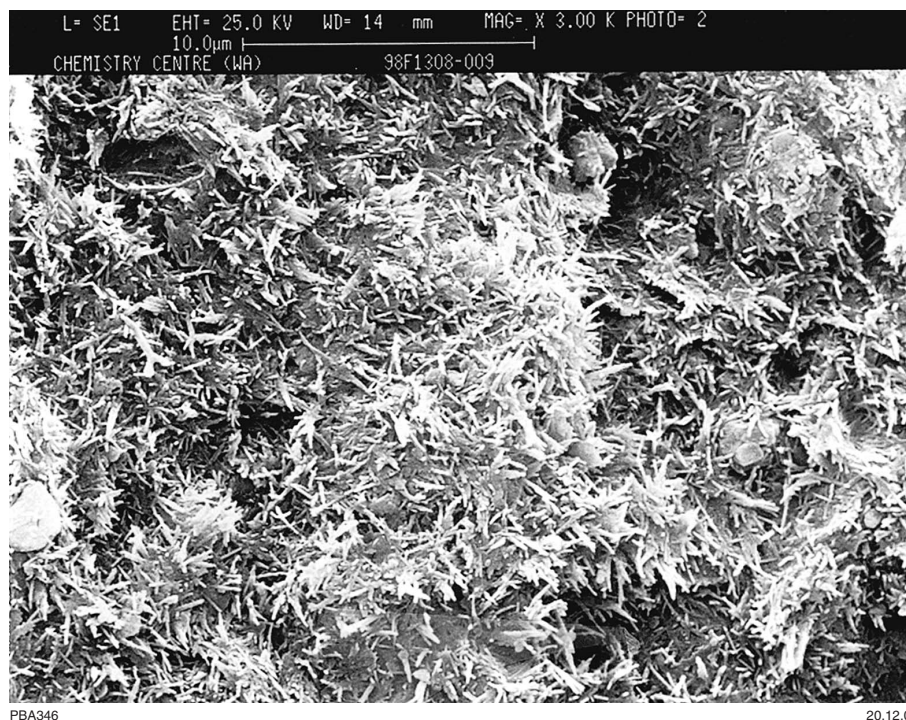


Figure 29. Scanning electron photomicrograph of the Lake Nerramyne attapulgite

Table 49. Typical mineralogy of the Lake Nerramyne processed commercial-grade attapulgite

	%
Attapulgite	80–90
Quartz	5–10
Dolomite	0–10
Kaolinite	0–10

SOURCE: Wakelam and Abeyasinghe (1999)

size of the milled particle for this use is 1.1 – 6.70 mm and averages 2.36 mm.

Pesticide carrier

The company produces attapulgite for local and export markets for use as a pesticide carrier. Two size grades are produced — one averaging 0.5 mm (0.25 – 0.71 mm) and the other averaging 160 µm. The method used to apply the pesticide in the field determines the particle size used for the carrier, with the larger size material applied directly to the ground, and the finer material applied by dusting.

Stockfeed and fertilizer binder

Attapulgite is produced for use as a binder in the making of stockfeeds and in the production of various fertilizers for agricultural use. The size of these products is at the finer end of the range, with 85–90% passing 250 µm.

Soil conditioner

Some attapulgite is used as a soil conditioner because attapulgite helps to maintain pH in soils due to its buffering capacity and good absorption abilities. The average size of particles produced for this use is 0.85 mm, but the size varies from 0.60 to 1.18 mm.

Table 50. Typical chemical composition of the Lake Nerramyne processed commercial-grade attapulgite

	%
SiO ₂	59.00
Al ₂ O ₃	13.40
Fe ₂ O ₃	5.34
MgO	8.25
CaO	0.96
K ₂ O	2.12
Other oxides	1.20
LOI	11.30
Total	101.57

SOURCE: Wakelam and Abeyasinghe (1999)

Table 51. Typical physical properties of the Lake Nerramyne commercial-grade attapulgite

Colour	white to grey
Loose bulk density	0.46 – 0.50 g/cm ³
Free moisture content	2–5%
Water absorption	100–125%
Oil absorption	100–120%
Cation exchange capacity	21 meq/100 g
pH (10% suspension)	7.4 – 7.8

SOURCE: Wakelam and Abeyasinghe (1999)

Other

The company sells attapulgite for the following applications, depending on customer demands:

- To clean up accidental oil spills in places such as factories and workshops by sprinkling the material over the spill, allowing the spilled liquid to be absorbed, and then removal by sweeping. It can also be used on garage floors and driveways to absorb oil spills and leaks, leaving the areas clean and unstained;
- As an addition to potting mix (for potted plants) to help drainage, breakup clay lumps, and retain moisture;
- To absorb fats and grease in trays under barbecue grills;
- To clean and deodorize poultry sheds; and
- As a deodorizer under straw when bedding down livestock.

At present, research is under way to introduce new products into the market. Successful trials have been run using Lake Nerramyne attapulgite in the purification and decolourization of edible oils such as palm and canola oils. Edible oils have a large growing market in nearby Asia and represent a potential major user of attapulgite. Research is also under way into the use of attapulgite in animal feed pellets, as a viscosity improver, and as a filler in plasterboard. Testing for uses such as suspending agents, drilling fluids, in the manufacture of NCR paper, paint, and radioactive waste disposal will eventually be included in a research program.

Future

The Lake Nerramyne attapulgite deposit is yet to be developed to its true potential. With a measured reserve of 10 Mt and an inferred resource of another 100 Mt, Hudson Resources is well placed to diversify its products and increase its markets and production. At the current production levels the deposit could last well over 100 years. The location of the processing plant at Narngulu, close to port facilities at Geraldton, makes the deposit even more valuable, as it is at the doorstep of many rapidly developing countries in South East Asia. The apparent economic resurgence in this region should encourage an evaluation of the Lake Nerramyne operation, with a view to expanding markets and increasing production levels (Wakelam and Abeyasinghe, 1999).



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Figure 30. Mining attapulgite at Lake Nerramyne



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Figure 31. A water-filled openpit at the Lake Nerramyne attapulgite deposit



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Figure 32. Stockpiles of attapulgite at Lake Nerramyne



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Figure 33. Milled attapulgite in the plant at Narngulu, near Geraldton

Boodanoo Hill

In 1996, a reconnaissance survey carried out by Fleurieu Mines for platinum group minerals at Boodanoo Hill indicated that the area has a potential for attapulgite within the lacustrine sediments over the Windimurra Complex. Boodanoo Hill is located 75 km southeast of Mount Magnet. The potential for attapulgite mineralization was based on the examination of drillchips along a line of drillholes that had previously been drilled within the expired Exploration Licence E59/622 by Pancontinental Mining. However, the drillchips have not been tested in a laboratory to confirm the presence of attapulgite minerals. The surface lithology in the area is restricted mainly to Cainozoic lacustrine, alluvial, or colluvial deposits, and on the eastern boundary, partially by residual laterite (Fleurieu Mines NL, 1997).

Construction industry clay

Definitions

Construction industry clay includes a wide variety of clay and other fine-grained rocks, such as shale, that are used to make products such as structural and fire bricks, drain tiles, vitrified pipes, and roofing tiles. Construction industry clays receive less attention in the literature in comparison with clays such as bentonite because they are derived from abundant low-value surface clays found in many types of rock of all ages. The surface weathering of almost any hard rock, with the exception of pure quartz-rich sandstones and limestone, can form clay. The type of clay produced depends on the climatic and geochemical environments. Clays that are used in the industry can be grouped into the three categories of structural clays, cement clays, and clays that are used in lightweight aggregates.

Construction-industry clay resources in many countries are virtually unlimited and so the statistics for global production are of little relevance. Since these clays are low-priced commodities, resources are normally located close to manufacturing facilities and population centres. However, in areas of population growth, access to economically exploitable high-quality clay deposits is often restricted due to landuse and environmental constraints.

Most of the construction industry clay produced in Western Australia is used in the manufacture of bricks and tiles. Significant exceptions are the use of clay in the aluminium industry for residue liners, and in the cement-manufacturing industry.

Structural clay

Structural clay can be defined as low-value clay that is used in large quantities for the manufacture of products such as bricks and roofing tiles. This material typically consists of loose, earthy fine material ($<4\ \mu\text{m}$) composed mainly of clay minerals. Some fireclay and kaolin are also included in this clay group when they are used in the manufacture of structural clay products (Patterson and Murray, 1983; McHaffie and Buckley, 1995; Harben and

Kuzvart, 1996). Since most of the construction industry clay produced in Western Australia is used for structural products (in the manufacture of bricks and tiles), details of construction industry clay in this Bulletin focus mainly on structural clays.

The dominant clay mineral in a given deposit may be illite, kaolinite, smectite, mixed-layer clay minerals, or chlorite. In many clay deposits, one or more mica-group minerals, such as illite, sericite, muscovite, and biotite, are found in equal or larger proportions than the clay minerals. Some deposits also contain significant proportions of quartz and other detrital minerals.

Cement clay

In cement manufacture, limestone and clay are calcined to produce clinker, with the proportion of limestone to clay (or weathered shale) commonly being 3:1. The governing factor of the clay used in this process is its chemical composition, which should preferably contain equal proportions of silica to alumina and iron oxides combined. Most of the clays used in the cement industry are ordinary clays and weathered shales, although in some instances kaolin is added in the manufacture of white cement. However, in rare instances, some manufacturers use argillaceous limestone containing the correct amount of clay material to produce clinker, thus eliminating the use of a separate clay raw material.

The West Australian cement manufacturers use either clay or shale from sources in Perth* and most of the production has been from Armadale, Maida Vale, and Gosnells.

Lightweight aggregate

Some clays and shales can be expanded (or 'bloomed') to produce a lightweight concrete aggregate. These clays have the property of expanding to form a cellular mass when they are rapidly heated to 1000–1300°C. This is due to the evolution of gas (such as oxygen, sulfur dioxide, or carbon dioxide) from non-clay minerals and their fusion to a liquid state that is viscous enough to trap this gas. Sudden cooling of this cellular mass forms a porous slag-like material. This product can then be screened to produce a lightweight concrete material weighing

* In this Bulletin, the term Perth is used to denote the Perth Metropolitan Area, unless otherwise indicated.

960–1760 kg/m³ that is used in products such as concrete building blocks, clay-bonded blocks, or in insulating material. The suitability of a clay for this application is determined by experimentation (Klinefelter and Hamlin, 1957; Harben and Kuzvart, 1996).

There is no known production of lightweight concrete aggregate in Western Australia either in the present or in the past.

Uses and specifications

The common uses of structural clays are in the manufacture of a wide variety of bricks, pipes, and tiles. Other uses include the manufacture of terracotta, art pottery, modelling clays, and aggregates.

Specifications of raw materials for structural clay-based industries are not readily available. In many instances, a particular industry will apply its own combination of tests and specifications to ensure that the clay quality requirements are met. However, some of the physical properties of structural clay generally applicable to many industries include screen analysis, dry strength, drying and firing shrinkage, moisture content, colour, plasticity (or friability), and the temperature range of vitrification. A knowledge of chemical composition, mineralogy, soluble salts, and pH are also important criteria for various applications (Harben and Kuzvart, 1996).

Screen analysis of samples is carried out to gain an understanding of the particle-size distribution, which has an affect on a number of properties such as shrinkage, dry strength, and the plasticity of the clay.

Dry strength is the ability to maintain shape after drying. The factors influencing dry strength include the proportion of fine particles present, the shape of the individual particles, and the degree of hydration of the clay fraction. The method of manufacturing depends on the dry strength and the rate and thoroughness of drying.

Drying shrinkage is the loss of volume during drying, and firing shrinkage is the loss of volume during firing. These properties depend on the moisture content, the character of the clay minerals, and the particle-distribution size of the material. For brick manufacture, the drying or firing shrinkages should not exceed about 8%. The firing temperature for bricks should be approximately 1100°C.

Uniform colour is an essential property for many structural clay products, with colour an important customer requirement. The colour of a clay product is heavily dependent on a number of factors, which include the state of oxidation and particle size of the iron minerals in the clay; the firing temperature and degree of vitrification; the proportion of alumina, lime, and magnesia in the clay; and the composition of the gases in the kiln during the burning operation. High-grade, white-burning clay contains less than 1% Fe₂O₃, buff-burning clay contains 1–5% Fe₂O₃, and red-burning clay contains 5% or more Fe₂O₃. Generally, structural clays used in the

industry are likely to contain 3–8% Fe₂O₃. The colour of the final product can be modified by adding pigments to the raw clay. For example, the addition of manganese dioxide to a cream clay base results in a grey brick, and when added to a red clay base produces a brown brick. Clays of different colour can be blended to produce a wider range of colour products for the market.

Plasticity is the ability of a material to undergo permanent deformation in any direction, without rupture, under stress beyond that of elastic yielding. For brick manufacture, the clay should be semi-plastic to plastic, and for pipe and tile manufacture the clay should be plastic. The factors that influence the plasticity of a material include the type of clay mineral present, particle size and shape, content of organic matter, soluble salts, adsorbed ions, and the amount and type of non-clay minerals.

The range of vitrification is the temperature range over which a clay converts to glass. The presence of illite, smectite, or chlorite results in a lower vitrification temperature than kaolinitic clays. The levels of Al₂O₃ and SiO₂ dictate the fusion temperature of a clay. Levels of undesirable elements present in the clay, such as excessive Na and K (approximately >1% and >2.5% respectively) can have the effect of lowering the firing temperature. The presence of Ca (approximately >2%) can cause scumming and efflorescence effects in the final product, and the presence of any SO₃ may result in the liberation of environmentally unfriendly gases during burning. The presence of vanadium can cause yellow, brown, green, blue, or pink stains in light-coloured products.

Mineralogical studies are important for assessing the percentages of clay minerals such as kaolinite, since these determine the quality of the clay. Such studies also enable the detection of undesirable minerals such as calcite and other carbonate and sulfate minerals.

The physical testing standards applicable for various clay products in Australia and New Zealand are according to those specified for masonry units in standards AS/NZS 4455 and AS/NZS 4456.

Below is a discussion of some of the specific uses and specifications for structural clay.

Brick

The results of the tests discussed above are important in assessing the suitability of a clay for brickmaking. The clay must have a fair degree of plasticity, but not too much because if it is too plastic the column of clay will laminate. Little or no sand is desirable. In many Western Australian clays, the presence of vanadium has been found to be a common problem. During the firing of clay, any vanadium present is converted into potassium vanadate, a water-soluble salt with a brilliant yellow colour, which is brought out on the surface during drying and remains as a brilliant yellow stain. In the presence of reducing agents, the stain may be greenish yellow or green. The same stain can be produced on a stack of bricks wetted for the first time by a shower of rain and then dried again by the sun. Some brick manufacturers add glucose or

barium carbonate to inhibit premature migration of salts to the surface during drying. Bowley (1941) reported such effects in briquettes made using clays from a number of localities, including Glen Forrest, Albany, Balkuling, Boyup Creek, Quairading, and Jacob's Well. The presence of sulfates of magnesium, aluminium, calcium, sodium, and potassium can also lead to efflorescence in bricks.

Brick manufacturers commonly blend white and coloured clays, clays rich in illite, and clays containing small amounts of mica to produce products with consistent and diverse colours. Therefore, brick manufacturers generally use clay from many different localities to obtain clay products of different colours. The brick industry commonly uses additives such as crushed dolerite and gabbro to enhance the texture of bricks. For example, the addition of crushed gabbro results in a brick with dark grey to dark-greenish spots on the fired bricks. Brick manufacturers in Western Australia commonly use about 20% high-quality plastic clay in their blends. There is ongoing research aimed at reducing this figure and some brick manufacturers have been able to use as little as 10% plastic clay in their mixes.

Midland Brick, one of Australia's best known brick companies, uses several different types of clays and fillers to create a large variety of bricks and pavers (Swierlowycz, W., Midland Brick, 2001, written comm.). These can be classified as clay, non-plastic material fillers, and shale and schist. Suitable clay should be very plastic, with 25–80% less than 2 μm , and capable of accepting up to 50% sand and still be extrudable. A typical mineral composition of a white-firing clay is kaolinite, quartz, muscovite, smectite, and some talc, with a typical chemical composition of 53% SiO_2 , 29% Al_2O_3 , up to 2% Fe_2O_3 , up to 1% $\text{MgO} + \text{Na}_2\text{O}$, 0.7% K_2O , 0.8% TiO_2 , and 14–15% loss on ignition (LOI). Typical dominant minerals of a red-firing clay are illite, montmorillonite, and quartz, with biotite, kaolinite, albite, and smectite as accessory minerals. Red-firing clays have a typical chemical composition of 65% SiO_2 , 15% Al_2O_3 , 5% Fe_2O_3 , 1.5% Na_2O , 2% K_2O , 1% TiO_2 with some (0.5%) $\text{MgO} + \text{CaO}$ and 10–12% loss on ignition. Non-plastic material fillers are used to reduce the plasticity of the clay, and to create special physical properties and the firing colour of the product. Midland Brick obtains white-firing fillers from Archaean granitic rocks with a high percentage of silica, and from some ironstones and dolerite. White-firing fillers have a typical chemical composition of 70% SiO_2 , 18% Al_2O_3 , 3% Fe_2O_3 , and 8% loss on ignition. Red-firing fillers are generally obtained from Archaean shale, weathered quartz–biotite schist, and gabbroic rocks with basaltic material, and have a typical composition of 53% SiO_2 , 13% Al_2O_3 , 10–12% Fe_2O_3 , 7.4% CaO , 9.5% MgO , 0.5–1% Na_2O and K_2O , 1.8% TiO_2 , and 3.5% loss on ignition. The company uses shale and schist to make the raw material semi-plastic and fast drying, and to improve the extrusion process. A typical chemical composition for this shale and schist is 62% SiO_2 , 18% Al_2O_3 , 4% Fe_2O_3 , 0.8–1.0% Na_2O , 2.5–4% K_2O , 0.5–1.5% TiO_2 , 1.5% MgO , and 8.5% loss on ignition. Two types of shale and schist are used. These are white-firing and red-firing materials. The white-firing material consist of soft to semi-soft muscovite schist containing a large percentage of

muscovite and quartz, and some kaolinite. The red-firing material consists of soft to semi-soft weathered shale containing biotite, quartz, some illite, and traces of montmorillonite.

The common method of making bricks is to mix clay with 13–20% water to a stiff plastic condition and then passing it through an extruder, which is known as the extrusion process (also known as the stiff-mud or stiff-plastic process). Midland Brick in Western Australia, which processes up to 4000 t of clay in a normal working day, uses this extrusion process.

A summary of the various steps in the production process of bricks and pavers in Western Australia is as follows. Clay from the stockpiles is extensively tested to determine the quality and best blends for bricks and pavers. The blended clay is fed through a primary crusher to reduce the raw clay to a uniform size, and further size reduction is done by means of a hammer mill. The milled clay is passed over heated vibrating screens, and then conveyed into a pug mill where water is added to convert the clay into a plastic state. From the pug mill, clay is screwed forward into a vacuum chamber and forced out under great pressure, as it is extruded through a small aperture (Fig. 34). Then as the column of clay passes through the die, core holes and two dimensions of the brick are formed. The clay column then passes along the slug cutter, which cuts the column into lengths suitable for the brick cutters that finally slice the column to form bricks. These extruded bricks are automatically set onto kiln cars. The bricks are then dried slowly to prevent any cracking that can occur during firing. This is done inside a tunnel dryer for up to 48 hours, with temperatures maintained at up to 250°C. The dried bricks are then pushed into the kiln for firing. In the kiln, bricks are gradually heated as they move through the firing zones, where temperatures up to 1300°C can be reached (Fig. 35).

Bricks can also be made by pressing (dry press and repressing), but this method is considered to be more expensive than extrusion, and the structural qualities are at times inferior to those of the extruded type (Klinefelter and Hamlin, 1957). In the dry-press process, the clay is first ground and mixed with a small (7–10%) amount of water, fed into steel moulds or die boxes, and then compressed. The amount of manpower required for this method is much higher than for the extrusion process. The higher cost of dry-press bricks in New South Wales (typically 40% more than extruded face bricks) reflects the higher labour content of the manufacturing process. However, some brick manufacturers in New South Wales have improved productivity in some instances with the dry-press method by integrating dry-pressing machinery with drying and the kiln plant. Repressing is a two-stage process in which a solid clay column is extruded to produce cut bricks that are shorter, narrower, and higher than the final product. They are then pressed into a mould to form the normal dimensions.

Appearance, impurities, freedom from cracks, and warpage are important factors in the evaluation of a brick. The brick manufacturers in Western Australia produce a wide range of products with varying dimensions. These



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Figure 34. The extrusion of clay during brick manufacture (courtesy of Midland Brick Company)

include solid, cored, hollow, and special purpose varieties. For example, the dimensions (length \times width \times height) of a common solid brick are $230 \times 110 \times 76$ mm and those of a vertical cored brick are $305 \times 90 \times 162$ mm. The specifications for some of the bricks produced in Western Australia are given in Table 52.

Tile

Roofing tile

The clays used in the manufacture of roofing tile are similar in quality to those used in bricks, but of better grade. The methods of manufacture generally involve extrusion and pressing, as in the case of brick manufacture. To meet the product specifications, the shrinkages should be low and water absorption should not

generally be more than 10% if the tile is unglazed. No warping or cracking is permissible, especially for tiles that are used in interlocking applications. The tile manufacturers in Western Australia prefer a minimum of 40% high-plasticity clay, but the declining quality in the plastic clay available in recent years has resulted in increasing this figure to approximately 52%.

Drain tile

The quality of clays used and the method of manufacture for drain tile is similar to that of the brick industry. The clays should be fairly plastic and contain little or no sand. Shrinkages of the product should be moderate, and the colour is immaterial. Commonly, clay drain tiles are unaffected by the acid or alkaline properties of the soil or drainage waters of any type. The product specifications



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Figure 35. Relief port door in a brick manufacturing kiln (courtesy of Midland Brick Company)

include strength and absorption tests similar to those for other clay products.

Structural tile

The term 'structural tile' includes a wide variety of tiles such as glazed or unglazed, and floor or wall tiles. The clays used to manufacture these tiles are of the same general type as those used in the brick industry, but the clays must be of a better grade. For example, the clay must have a higher degree of workability, be free of sand, and should have relatively lower dry and fired shrinkages. Colours generally vary from reds to buffs, but this is not as important as in the brick industry. In tile manufacturing, clays are extruded in a similar manner to brick manufacturing. The standard specifications for the products are similar to those of bricks, and include tests such as compressive strength and absorption.

Other structural clay products

Other uses of structural clay include the manufacture of sewer pipe, terracotta, art pottery, and modelling clays.

Sewer pipe is made from surface clays, fireclays, shales, and combinations of these materials. The clays have properties similar to those used in the manufacture of bricks and tiles. In addition, the mixture should have a wide vitrification range. The absorption of the product should not exceed 8%.

Terracotta is fired or kiln-burnt clay of commonly reddish colour that is used to make statuettes, figurines, vases, and ornamental work on the exterior of buildings. The clay is characterized by low fired shrinkage, freedom from warping, strong bonding, and the absence of soluble salts.

Table 52. Specifications for some brick varieties in Western Australia

<i>Specification</i>	<i>Standard common solid brick</i>	<i>Standard common cored brick</i>	<i>Standard special- performance cored brick</i>	<i>Fastwall cored brick</i>
Dimensions (length × width × height) (mm)	230 × 110 × 76	230 × 110 × 76	230 × 150 × 76	305 × 90 × 162
Unit weight (kg)	2.8	4.1	4.3	5.2
Number per square metre	48.5	48.5	48.5	18.5
Wall surface density (kg/m ²)	180	250	257	102 (rendered 127)
Number per pack	264	198	204	132
Pack weight (kg)	739	812	877	687
Pack dimensions (mm)	935 × 690 × 860	935 × 690 × 860	940 × 690 × 910	920 × 710 × 955
Average unconfined compressive strength (MPa)	>16	>22	>18	>5.3
Characteristic unconfined compressive strength (MPa)	>12	>18	>14	>3.7
Cold water absorption (%)	<11	<11	<11	<11
Boiling water absorption (%)	<14	<14	<14	<14
Bulk brick density (kg/m ³)	>2000	>2000	>2000	>1950
Coefficient of expansion (mm/m)	<0.6	<0.6	<0.6	<0.6
Durability class	general purpose	general purpose	general purpose	general purpose
Initial rate of absorption (kg/m ² /min)	<1.4	<1.4	<1.3	<1.3
Liability to efflorescence	nil to slight	nil to slight	nil to slight	nil to slight

SOURCE: Midland Brick, Western Australia

Art pottery clays are obtained from many kinds of clays such as whiteware clays and buff- to red-burning and stoneware clays. All clays used for art pottery should be clean and free from grit. Some artists who produce original designs typically like high-plastic clays that can be hand moulded or used on a potter's wheel. A low maturing temperature (about 1000°C) of the clay is most desirable, as most studios do not have high-temperature kilns common to commercial producers. Shrinkage on drying or firing is not a major concern as long as it does not cause undue problems in the drying and subsequent firing. In the case of commercial-scale operations, the castability of the clay or body mix is important, as the majority of artware is turned out by casting.

For modelling clays, any fairly plastic clay can be used. For some uses involving large pieces, fine sand or semi-plastic clay can be used in the mix. Since it is commonly desirable to have the material in a plastic condition for a long time, the dry clay is mixed with vaseline, light machine oil, glycerin, or other lubricating agents instead of water. The firing characteristics are not important as the modelled piece is not fired, but is used to form moulds.

Clay liners

In Western Australia, clay is used by Alcoa to line its bauxite residue areas to protect the underground aquifer. Approximately 60 000 tpa of clay is used for this purpose. Bauxite residue consists of sand and clay formed as a byproduct in alumina production. For every tonne of alumina produced, two tonnes of bauxite residue is produced. At the current rate of alumina production, there

is the production of 10 000 t of bauxite residue per day (Landvision, 1996).

Substitutes for clay products

The main substitutes for clay-based products are concrete tiles and pavers, aerated cement blocks (thermalite), and the use of pre-mixed or pre-cast products in applications such as paving. Galvanized iron roofing used as an alternative to tiles, and the minor use of timber for outer walls, also compete with clay-based products. According to figures given by Landvision (1996), 98% of the outer walls of residential buildings in the metropolitan area are constructed from clay bricks. Clay tiles constitute approximately 30% of the Perth roofing market, concrete tiles approximately 50%, and steel roofing about 20%.

Exploration

Structural clay suitable for brick, tile, and related industries is commonly found on alluvial or colluvial plains and in many weathered formations (other than sandstone or limestone). Although clays resources are generally plentiful, the deposits are typically irregular, discontinuous, and show extreme variation in quality. The high-quality horizons are commonly found as lenses within low-grade sandy clays and sands, and in one deposit there can be several grades of clay. Therefore, closely spaced drilling must be carried out for quality and resource assessment. Samples obtained by drilling are tested for various physical and chemical characteristics, as discussed above, to determine the suitability of the clay for specific applications.

Mining and rehabilitation

Mining

At the mining stage, the overburden and topsoil are removed and stored for later rehabilitation. The clay is then extracted using a dragline or backhoe. In some places dozing may be necessary, but blasting is very rarely required. Mining is generally carried out periodically and mostly during the summer months, as mining in the wet season is difficult. However, some operations are worked periodically throughout the year. Most of the clay pits in Western Australia are small and are mined out within a few years.

Rehabilitation

Rehabilitation and environmental controls of mining operations in Western Australia are regulated by a number of institutions such as the Department of Environmental Protection, the Department of Mineral and Petroleum Resources, and local government. The regulations involve various restrictions such as time limits on operations, drainage, removal of trees, and dust and noise factors (related mainly to transport). As clay mining is generally carried out in environmentally sensitive areas, there is minimal disturbance in the surrounding area and, apart from the access roads, the only other disturbance to the ground is restricted to the area used for storing the overburden and topsoil.

The mined area is rehabilitated using the stored topsoil and overburden, and then used in a variety of ways depending on the local environment. For example, some pits are returned to farmland and some are used for dry rubbish disposal (provided the hydrological environment is not disturbed). Many clay pits are suitable for rehabilitation to wetlands.

Production and market trends in Western Australia

Production

Accurate figures for production of construction industry clay in Western Australia are not readily available, as some producers do not report production to DMPR. The structural clays used in the brick and tile industries belong to the basic raw material category, which is outside the definition of a 'mineral' in the Western Australian Mining Act when mined on private land. The production reported to DMPR is mostly that of high-grade kaolinitic varieties, which are covered by the Mining Act (i.e. regarded as a mineral even if mined from private land). According to the production reported to DMPR, Western Australia produced a total of 7.6 Mt of clay valued at \$A11.3 million during 1959–99 for the brick and tile industries (Tables 53 and 54). In addition, there was a reported production of 1.2 Mt (valued at \$A3.9 million) of clay for use in the cement industry during the same period (Tables 55 and 56).

In 1999, the reported production of structural clay in Western Australia was 72 059 t, but the true figure is considered to be significantly higher. According to Landvision (1996), the total production of clay from Perth alone in 1993–94 was 2.3 Mt. Of this amount, approximately 446 000 t (20%) were alluvial plastic clay, 662 000 t (29%) were semi-plastic clay, and the remaining 1 164 500 t (51%) were non-plastic clay. Annual production was estimated at about 500 million bricks, pavers, and blocks, and 21 million tiles.

More than 99% of the structural clay produced in the State is from the Perth region. The geological formations and other relevant information on brick and tile clay resources in Western Australia are discussed later in this chapter.

Brick and tile industries

A few decades ago, the general trend for the brick and tile industry in Australia was of relatively small-scale manufacturing companies operating in regional centres and supplying local markets. In recent times and at present, such regional operators face stiff competition from well-established, large-scale manufacturers who have adopted superior technological and marketing strategies. In Western Australia, mergers and acquisitions in recent years have seen the consolidation of the industry into only a few large companies that have secured substantial markets in many regional centres, other States, and overseas. Currently, the major brick manufacturing companies in Western Australia are Midland Brick Company Pty Ltd, and Metro Brick, and the only clay roofing tile manufacturer is Bristile Clay Tiles. Both Metro Brick and Bristile Clay Tiles are owned by Bristile Ltd. In Perth, there are five brick plants (20 kilns) and one tile plant (2 kilns). These plants have the capacity to produce around 500 million bricks, pavers and blocks, and 21 million tiles per year.

Brick industry

Midland Brick and Metro Brick are both located in Perth. Both companies have large operations of international standard and produce a wide range of products for diverse applications. Another relatively large company, Geraldton Brickworks Pty Ltd located in Geraldton (approximately 420 km north of Perth), manufactures bricks using locally available clays.

Midland Brick

Midland Brick is one of Australia's best known brick companies and has been at the forefront of clay brick manufacture for over 50 years. According to company sources, Midland Brick's Middle Swan brick plant is the largest brickworks operation in the world. The company promotes itself as Western Australia's leading supplier and Australia's major exporter of clay bricks and pavers. The company uses clay from a number of quarries on the Swan Coastal Plain and Darling Range (Fig. 36). These localities include Muchea (Figs 37–39), Bullsbrook East (Fig. 39),

Table 53. Production of brick and tile clays in Western Australia (tonnes)

Year	Bedforddale	Jarrahdale	Byford	Glen Forrest	Bullsbrook	Metro area (unspecified localities)	Caversham	Middle Swan	Red Hill	Bickley	Irwin	Herne Hill	Wungong	Chandler	Total
1959	1 016	—	19 073	4 632	—	—	—	—	—	2 335	—	—	—	—	27 056
1960	—	—	21 758	4 685	—	—	4 099	—	8 387	5 501	—	—	—	—	44 430
1961	—	—	23 172	7 315	—	—	8 365	—	2 379	—	—	—	—	—	41 231
1962	2 835	—	19 736	4 325	—	—	1 896	—	1 061	—	589	—	—	—	30 442
1963	—	—	50 256	10 371	—	—	—	7 947	4 793	—	—	5 520	—	—	79 476
1964	—	—	45 305	19 546	—	—	—	6 958	2 422	—	—	21	—	—	74 252
1965	—	—	56 715	33 421	—	91 494	—	5 156	9 513	—	—	31	—	—	196 330
1966	1 283	—	49 738	32 324	—	77 059	—	5 162	14 976	—	—	732	—	—	181 274
1967	—	—	57 921	44 301	—	47 656	—	2 134	17 001	—	—	—	—	—	169 013
1968	—	—	76 781	41 053	—	18 572	—	3 782	10 111	—	—	—	—	—	150 299
1969	1 593	—	121 842	35 155	5 610	90 301	—	5 590	25 873	—	—	—	—	—	285 964
1970	—	—	118 752	2 025	19 786	20 339	—	—	—	—	—	—	—	56	160 959
1971	—	—	41 752	—	49 185	67 985	—	—	—	—	—	—	—	50	158 972
1972	—	—	116 324	—	108 569	50 122	—	—	—	—	—	—	20 327	—	295 342
1973	—	—	103 848	—	143 021	53 126	—	—	—	—	—	—	49 705	—	349 700
1974	—	—	42 325	—	176 890	277 131	—	—	—	—	—	—	33 762	—	530 108
1975	—	—	52 350	—	149 839	—	—	—	—	—	—	—	22 410	—	224 599
1976	—	—	—	—	220 718	—	—	—	—	—	—	—	—	—	220 718
1977	—	—	51 431	—	207 445	—	—	—	—	—	—	—	—	—	258 876
1978	—	—	97 847	—	162 436	—	—	—	—	—	—	—	—	—	260 283
1979	—	—	122 120	—	258 672	—	—	—	—	—	—	—	—	—	380 792
1980	—	—	95 774	—	262 947	—	—	—	—	—	—	—	—	—	358 721
1981	—	—	68 046	—	174 432	—	—	—	—	—	—	—	—	—	242 478
1982	—	—	—	—	215 504	—	—	—	—	—	—	—	—	—	215 504
1983	—	44 766	—	—	151 644	—	—	—	—	—	—	—	—	—	196 410
1984	—	52 156	—	—	221 518	—	—	—	—	—	—	—	—	—	273 674
1985	—	—	—	—	255 257	—	—	—	—	—	—	—	—	—	255 257
1986	—	125 187	—	—	203 597	—	—	—	—	—	—	—	—	—	328 784
1987	—	72 176	—	—	206 567	—	—	—	—	—	—	—	—	—	278 743
1988	—	1 697	—	—	212 703	—	—	—	—	—	—	—	—	—	214 400
1989	—	1 709	—	—	119 478	—	—	—	—	—	—	—	—	—	121 187
1990	—	171 401	—	—	234 367	—	—	—	—	—	—	—	—	—	405 768
1991	—	—	—	—	—	—	—	14 611	—	—	—	—	—	—	14 611
1992	—	—	—	—	6 508	—	—	22 575	—	—	—	—	—	—	29 083
1993	—	—	—	—	43 813	—	—	22 984	—	—	—	—	—	—	66 797
1994	—	—	—	—	10 812	—	—	67 077	—	—	—	—	—	—	77 889
1995	—	—	—	—	67 802	—	—	38 596	—	—	—	—	—	—	106 398
1996	—	—	—	—	104 850	—	—	13 003	—	—	—	—	—	—	117 853
1997	—	—	—	—	84 688	—	—	2 360	—	—	—	—	—	—	87 048
1998	—	—	—	—	56 663	—	—	—	—	—	—	—	—	—	56 663
1999	—	—	—	—	72 059	—	—	—	—	—	—	—	—	—	72 059
Total	6 727	469 092	1 452 866	239 153	4 207 380	793 785	14 360	217 935	96 516	7 836	589	6 304	126 204	106	7 638 853

Production locality details

Bedforddale MC 504–505H; Jarrahdale M 70/41, 42, 170, and 245; Byford MC 522–523H, 685H, 690H, 789H, 1110H, and 1302H; Glen Forrest Loc. 84, Lot 157, MC 585H, 732H, and 1114H; Bullsbrook ML 435–436H and M 70/635; Caversham MC 670H and 672H; Middle Swan pp Lot 1 and 38; Red Hill pp Lot 137; Bickley MC 584H; Irwin MC 736H; Herne Hill pp; Wungong MC 1438H; Chandler pp

NOTE: pp private property

Table 54. Value of brick and tile clay extracted in Western Australia (\$A)

Year	Bedforddale	Jarrahdale	Byford	Glen Forrest	Bullsbrook	Metro area (unspecified localities)	Caversham	Middle Swan	Red Hill	Bickley	Irwin	Herne Hill	Wungong	Chandler	Total
1959	3 000	—	52 875	7 075	—	—	—	—	—	1 210	—	—	—	—	64 160
1960	—	—	59 519	8 767	—	—	8 068	—	16 510	2 708	—	—	—	—	95 572
1961	—	—	10 000	11 275	—	—	16 466	—	4 684	—	—	—	—	—	42 425
1962	8 270	—	48 496	6 159	—	—	3 732	—	2 088	—	1 160	—	—	—	69 905
1963	—	—	119 446	15 599	—	—	—	15 642	9 436	—	—	10 866	—	—	170 989
1964	—	—	108 763	20 284	—	—	—	13 696	4 768	—	—	42	—	—	147 553
1965	—	—	139 040	36 395	—	64 878	—	10 150	18 726	—	—	62	—	—	269 251
1966	2 715	—	129 870	36 651	—	78 710	—	10 162	29 480	—	—	1 440	—	—	289 028
1967	—	—	91 507	47 831	—	23 506	—	4 200	33 466	—	—	—	—	—	200 510
1968	—	—	113 070	26 265	—	9 140	—	7 444	19 904	—	—	—	—	—	175 823
1969	4 939	—	222 421	32 817	2 761	48 884	—	11 004	50 932	—	—	—	—	—	373 758
1970	—	—	142 527	997	9 739	11 011	—	—	—	—	—	—	—	825	165 099
1971	—	—	40 093	—	24 204	34 630	—	—	—	—	—	—	—	742	99 669
1972	—	—	193 987	—	43 693	26 145	—	—	—	—	—	—	20 006	—	283 831
1973	—	—	147 208	—	34 844	50 770	—	—	—	—	—	—	48 920	—	281 742
1974	—	—	41 657	—	43 520	276 634	—	—	—	—	—	—	33 229	—	395 040
1975	—	—	51 523	—	36 871	—	—	—	—	—	—	—	22 056	—	110 450
1976	—	—	—	—	137 932	—	—	—	—	—	—	—	—	—	137 932
1977	—	—	50 931	—	39 571	—	—	—	—	—	—	—	—	—	90 502
1978	—	—	97 847	—	24 856	—	—	—	—	—	—	—	—	—	122 703
1979	—	—	122 120	—	37 273	—	—	—	—	—	—	—	—	—	159 393
1980	—	—	95 774	—	39 442	—	—	—	—	—	—	—	—	—	135 216
1981	—	—	68 046	—	45 723	—	—	—	—	—	—	—	—	—	113 769
1982	—	—	—	—	258 607	—	—	—	—	—	—	—	—	—	258 607
1983	—	134 298	—	—	181 971	—	—	—	—	—	—	—	—	—	316 269
1984	—	148 645	—	—	265 822	—	—	—	—	—	—	—	—	—	414 467
1985	—	—	—	—	306 309	—	—	—	—	—	—	—	—	—	306 309
1986	—	356 783	—	—	244 317	—	—	—	—	—	—	—	—	—	601 100
1987	—	209 528	—	—	247 881	—	—	—	—	—	—	—	—	—	457 409
1988	—	20 364	—	—	405 629	—	—	—	—	—	—	—	—	—	425 993
1989	—	20 503	—	—	143 373	—	—	—	—	—	—	—	—	—	163 876
1990	—	1 529 000	—	—	457 335	—	—	—	—	—	—	—	—	—	1 986 335
1991	—	—	—	—	—	—	—	160 718	—	—	—	—	—	—	160 718
1992	—	—	—	—	7 810	—	—	225 745	—	—	—	—	—	—	233 555
1993	—	—	—	—	52 576	—	—	249 946	—	—	—	—	—	—	302 522
1994	—	—	—	—	12 975	—	—	656 898	—	—	—	—	—	—	669 873
1995	—	—	—	—	81 363	—	—	385 960	—	—	—	—	—	—	467 323
1996	—	—	—	—	125 820	—	—	130 030	—	—	—	—	—	—	255 850
1997	—	—	—	—	101 626	—	—	14 160	—	—	—	—	—	—	115 786
1998	—	—	—	—	67 995	—	—	—	—	—	—	—	—	—	67 995
1999	—	—	—	—	86 471	—	—	—	—	—	—	—	—	—	86 471
Total	18 924	2 419 121	2 146 720	250 115	3 568 309	624 308	28 266	1 895 755	189 994	3 918	1 160	12 410	124 211	1 567	11 284 778

Production locality details

Bedforddale MC 504–505H; Jarrahdale M 70/41, 42, 170, and 245; Byford MC 522–523H, 685H, 690H, 789H, 1110H, and 1302H; Glen Forrest Loc. 84, Lot 157, MC 585H, 732H, and 1114H; Bullsbrook ML 435–436H and M 70/635; Caversham MC 670H and 672H; Middle Swan pp Lot 1 and 38; Red Hill pp Lot 137; Bickley MC 584H; Irwin MC 736H; Herne Hill pp; Wungong MC 1438H; Chandler pp

NOTE: pp private property

Table 55. Western Australian production of clay for use in cement manufacturing (tonnes)

<i>Year</i>	<i>Mount Helena</i>	<i>Gosnells</i>	<i>Maida Vale</i>	<i>Armadale</i>	<i>Collie</i>	<i>Total</i>
1945	788	—	—	—	—	788
1946	904	—	—	—	—	904
1947	725	—	—	—	—	725
1948	1 130	—	—	—	—	1 130
1949	450	—	—	—	—	450
1950	—	—	—	—	—	—
1951	—	—	38 928	—	—	38 928
1952	—	—	15 556	—	—	15 556
1953	—	—	13 838	—	—	13 838
1954	—	—	12 092	—	—	12 092
1955	—	6 702	28 783	—	—	35 485
1956	—	6 111	12 497	—	—	18 608
1957	—	7 116	4 620	—	—	11 736
1958	—	7 306	6 416	—	—	13 722
1959	—	13 717	8 963	—	—	22 680
1960	—	5 174	8 050	—	—	13 224
1961	—	11 219	6 931	—	—	18 150
1962	—	14 335	7 647	—	—	21 982
1963	—	6 980	12 093	—	—	19 073
1964	—	18 705	9 083	—	—	27 788
1965	—	21 834	4 572	—	—	26 406
1966	—	15 927	6 349	2 032	—	24 308
1967	—	—	6 309	10 775	—	17 084
1968	—	—	6 234	16 734	—	22 968
1969	—	—	6 380	4 595	—	10 975
1970	—	—	6 761	16 012	—	22 773
1971	—	—	5 770	2 085	—	7 855
1972	—	—	724	32 054	—	32 778
1973	—	16 349	—	18 614	—	34 963
1974	—	9 244	—	25 731	—	34 975
1975	—	30 931	—	28 894	—	59 825
1976	—	16 490	—	29 775	—	46 265
1977	—	—	—	28 390	—	28 390
1978	—	—	—	22 927	—	22 927
1979	—	—	—	21 348	—	21 348
1980	—	—	—	25 328	—	25 328
1981	—	—	—	26 919	—	26 919
1982	—	—	—	25 118	—	25 118
1983	—	—	—	20 082	—	20 082
1984	—	6 508	—	22 185	—	28 693
1985	—	—	—	22 513	—	22 513
1986	—	—	—	23 495	—	23 495
1987	—	—	—	23 217	—	23 217
1988	—	—	—	22 999	—	22 999
1989	—	—	—	23 025	—	23 025
1990	—	—	—	11 020	—	11 020
1991	—	—	—	32 795	—	32 795
1992	—	—	—	6 940	—	6 940
1993	—	—	—	—	—	—
1994	—	—	—	—	74 351	74 351
1995	—	—	—	—	19 634	19 634
1996	—	—	—	—	14 559	14 559
1997	—	—	—	—	45 530	45 530
1998	—	—	—	—	5 541	5 541
1999	—	—	—	—	26 615	26 615
Total	3 997	214 648	228 598	545 602	186 230	1 179 076

Production locality details

Mount Helena ML 357H; Gosnells MC 480–483H and 490–492H; Maida Vale MC 725H, 1016H, 1018–1019H, and pp; Armadale MC 788; Collie

NOTE: pp private property

Table 56. Value of clay extracted for use in cement manufacturing in Western Australia (\$A)

Year	Mount Helena	Gosnells	Maida Vale	Armadale	Collie	Total
1945	766	—	—	—	—	766
1946	890	—	—	—	—	890
1947	714	—	—	—	—	714
1948	1 162	—	—	—	—	1 162
1949	465	—	—	—	—	465
1950	—	—	—	—	—	—
1951	—	—	23 196	—	—	23 196
1952	—	—	11 329	—	—	11 329
1953	—	—	10 533	—	—	10 533
1954	—	—	11 807	—	—	11 807
1955	—	18 186	32 705	—	—	50 891
1956	—	16 539	13 877	—	—	30 416
1957	—	19 257	5 424	—	—	24 681
1958	—	19 775	7 104	—	—	26 879
1959	—	36 190	9 920	—	—	46 110
1960	—	12 730	8 958	—	—	21 688
1961	—	27 575	8 244	—	—	35 819
1962	—	35 272	7 026	—	—	42 298
1963	—	17 176	13 042	—	—	30 218
1964	—	46 026	9 954	—	—	55 980
1965	—	53 723	4 839	—	—	58 561
1966	—	39 187	6 749	5 600	—	51 536
1967	—	—	6 706	29 694	—	36 400
1968	—	—	5 906	46 115	—	52 021
1969	—	—	5 834	4 884	—	10 718
1970	—	—	6 263	41 288	—	47 551
1971	—	—	5 276	5 746	—	11 022
1972	—	—	1 768	88 134	—	89 903
1973	—	40 226	—	51 296	—	91 522
1974	—	22 740	—	72 930	—	95 670
1975	—	76 090	—	72 235	—	148 325
1976	—	40 565	—	74 437	—	115 002
1977	—	—	—	70 969	—	70 969
1978	—	—	—	57 317	—	57 317
1979	—	—	—	53 369	—	53 369
1980	—	—	—	63 319	—	63 319
1981	—	—	—	68 046	—	68 046
1982	—	—	—	62 795	—	62 795
1983	—	—	—	50 205	—	50 205
1984	—	16 270	—	55 464	—	71 734
1985	—	—	—	56 283	—	56 283
1986	—	—	—	58 729	—	58 729
1987	—	—	—	58 043	—	58 043
1988	—	—	—	57 499	—	57 499
1989	—	—	—	57 564	—	57 564
1990	—	—	—	27 550	—	27 550
1991	—	—	—	234 039	—	234 039
1992	—	—	—	74 168	—	74 168
1993	—	—	—	—	—	—
1994	—	—	—	—	148 700	148 700
1995	—	—	—	—	240 248	240 248
1996	—	—	—	—	179 079	179 079
1997	—	—	—	—	663 502	663 502
1998	—	—	—	—	55 410	55 410
1999	—	—	—	—	266 150	266 150
Total	3 997	537 527	216 460	1 597 718	1 553 089	3 908 791

Production locality details

Mount Helena ML 357H; Gosnells MC 480–483H and 490–492H; Maida Vale MC 725H, 1016H, 1018–1019H, and pp; Armadale MC 788; Collie

NOTE: pp private property

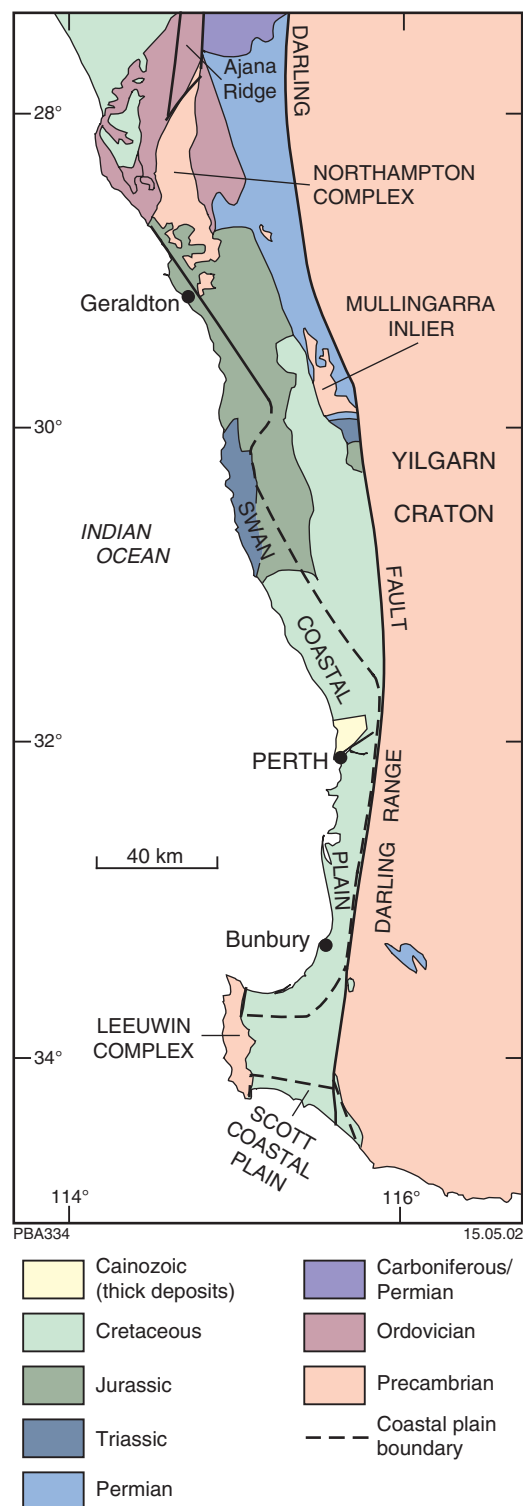


Figure 36. Solid geology of the Perth Basin (after Cockbain, 1990)

Upper Swan (Fig. 40), Gidgegannup (Fig. 41), Red Hill (Fig. 38), and Jimperding Hill (Fig. 41).

Since 1982, the company has established successful export markets in many overseas countries including Bahrain, Brunei, China, Hong Kong, Indonesia, South Korea, Kuwait, New Zealand, Malaysia, Papua New

Guinea, Singapore, Taiwan, and the United Arab Emirates, and is now a world leader in exporting quality clay bricks and pavers to Japan.

Metro Brick

Metro Brick was established in 1922, and the original brickwork site dates back to the turn of the century. Metro Brick has manufacturing plants in five locations within Western Australia, with a capacity to produce over 200 million clay bricks and pavers each year. In the Perth metropolitan region, Metro Brick has brick plants at Midland, Malaga, Armadale, and Cardup (Fig. 41). The quarries at Muchea, Bullsbrook, Upper Swan, and Toodyay provide clay to the plants at Midland and Malaga, and the quarries at Cardup, Toodyay, Beverley, and North Dandalup provide clay to the plants at Cardup and Armadale. Metro Brick has been a successful exporter for over 12 years, with its products used in many countries including Korea, Japan, Hong Kong, Taiwan, Indonesia, New Zealand, and Singapore.

Tile industry

Bristle Clay Tiles is the only clay roofing-tile manufacturer in Western Australia. The company has its plant at Caversham in Perth and exports to many markets including Brunei, Singapore, New Zealand, and the Philippines. Bristle has a long history in the clay-manufacturing and building supplies industry of Western Australia, dating back to the pioneering days of 1910. Bristle Clay Tiles' current kiln and plant were constructed in 1986 and have been upgraded to include the latest technology. This facility is the largest clay tile plant in Australia, with an annual output in excess of 20 million pieces. The company produces four tile profiles, which are known as Marseille, Swiss, Roman, and Vienna. Bristle Clay Tiles has access to high-quality clay deposits at Upper Swan and Toodyay (Figs 40–41).

Demand and outlook

Approximately 98% of the outer walls of residential buildings in Perth are constructed from brick, and approximately 30% of the roofs in Perth use clay tiles. Industry estimates suggest that the demand for bricks could increase by 50% over the next 20 years, which corresponds to an annual growth rate of 2%.

Western Australian regolith

Clay deposits throughout the world are found in unconsolidated to indurated rocks that blanket the older rocks. The unconsolidated to indurated rock layer contains a variety of transported or residual materials, and is generally referred to as regolith (Hocking and Cockbain, 1990). An important factor in the development of clay deposits is the relationship between regolith types.

In Western Australia, virtually all near-surface rocks have been affected to some degree by deep weathering



Ferruginous duricrusts

87

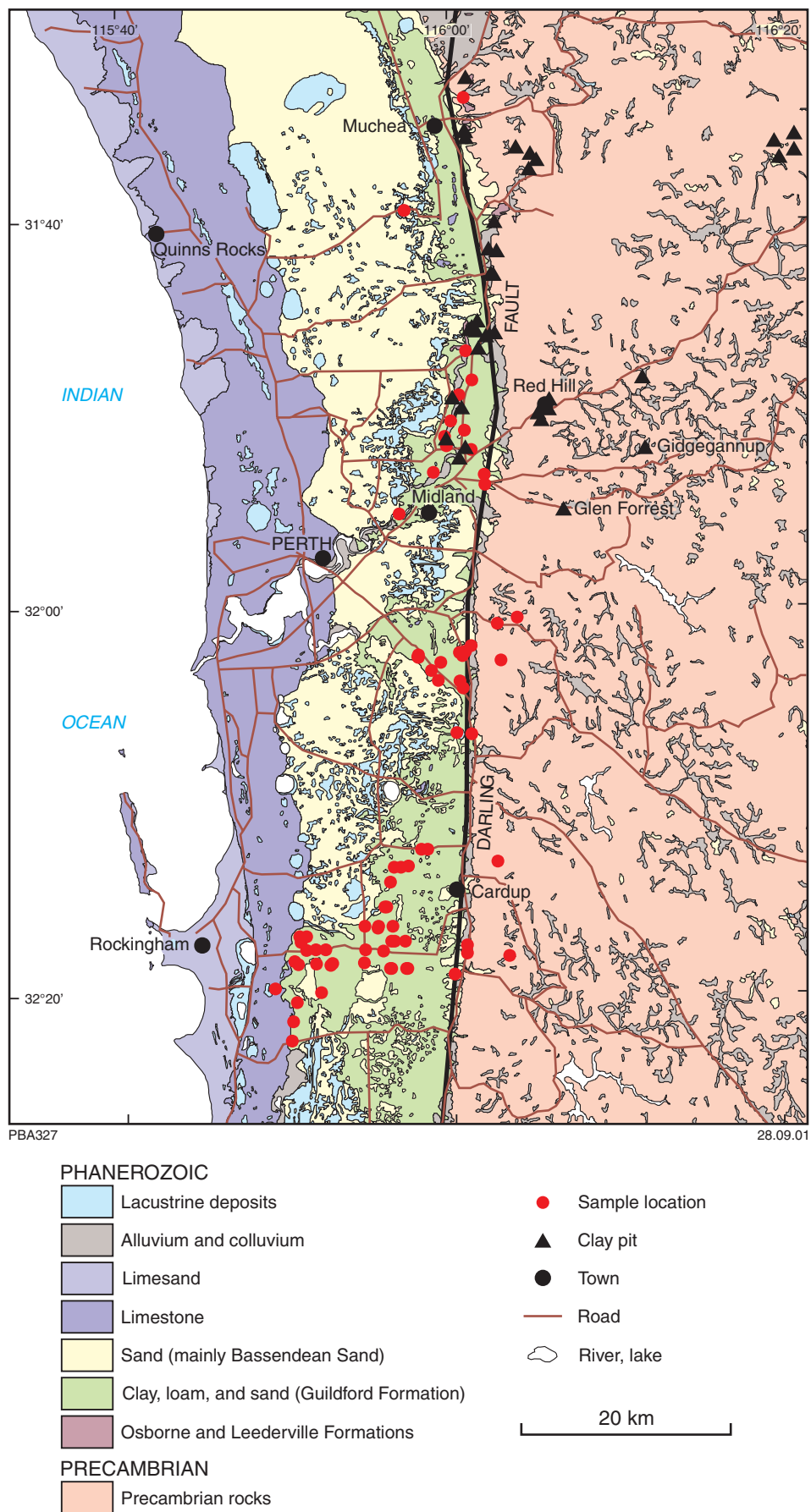


Figure 38. Regional geology of the Perth area (modified from Low et al., 1978, 1980)

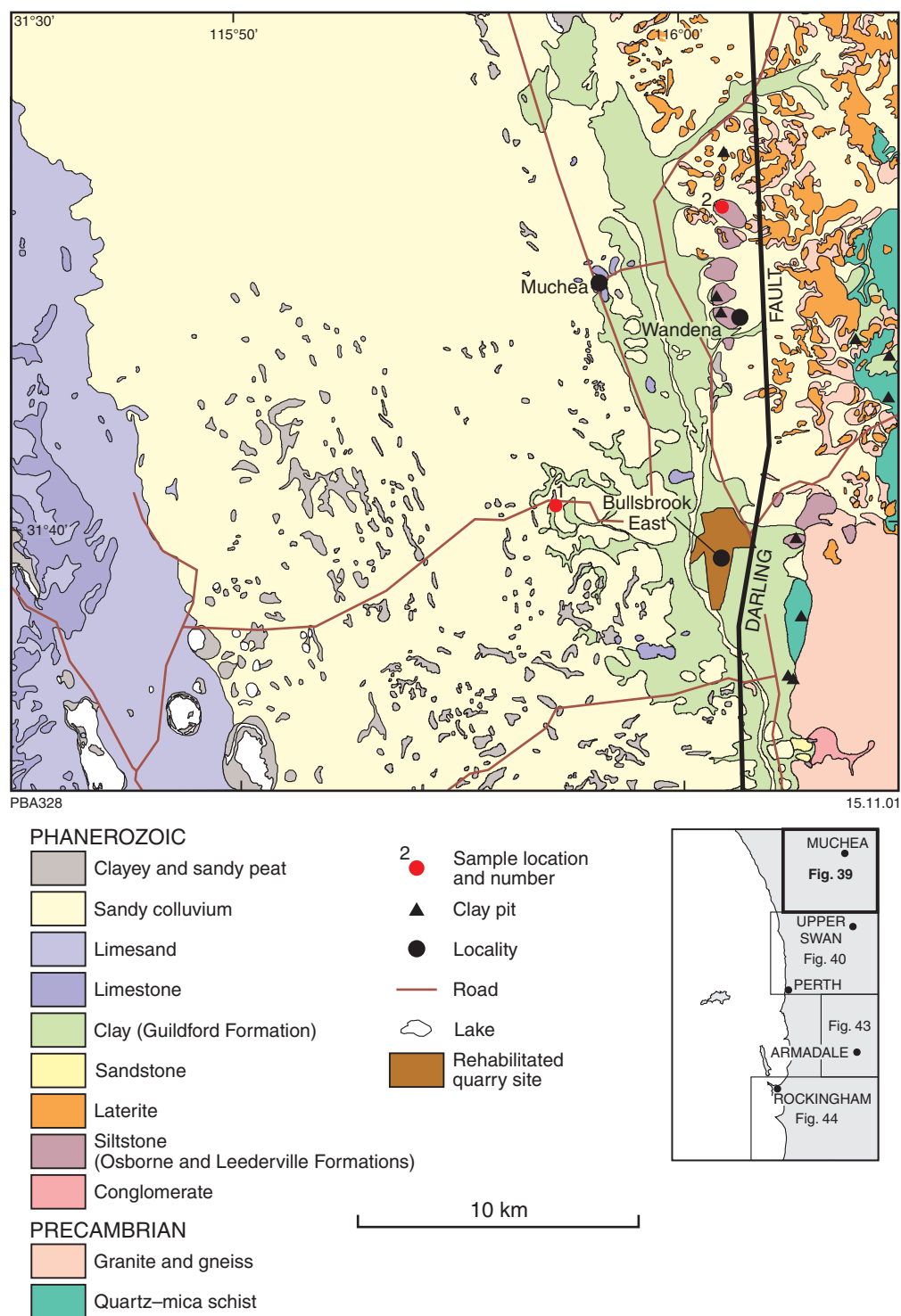


Figure 39. Geology of the area around Muchea (modified from Gozzard, 1982)

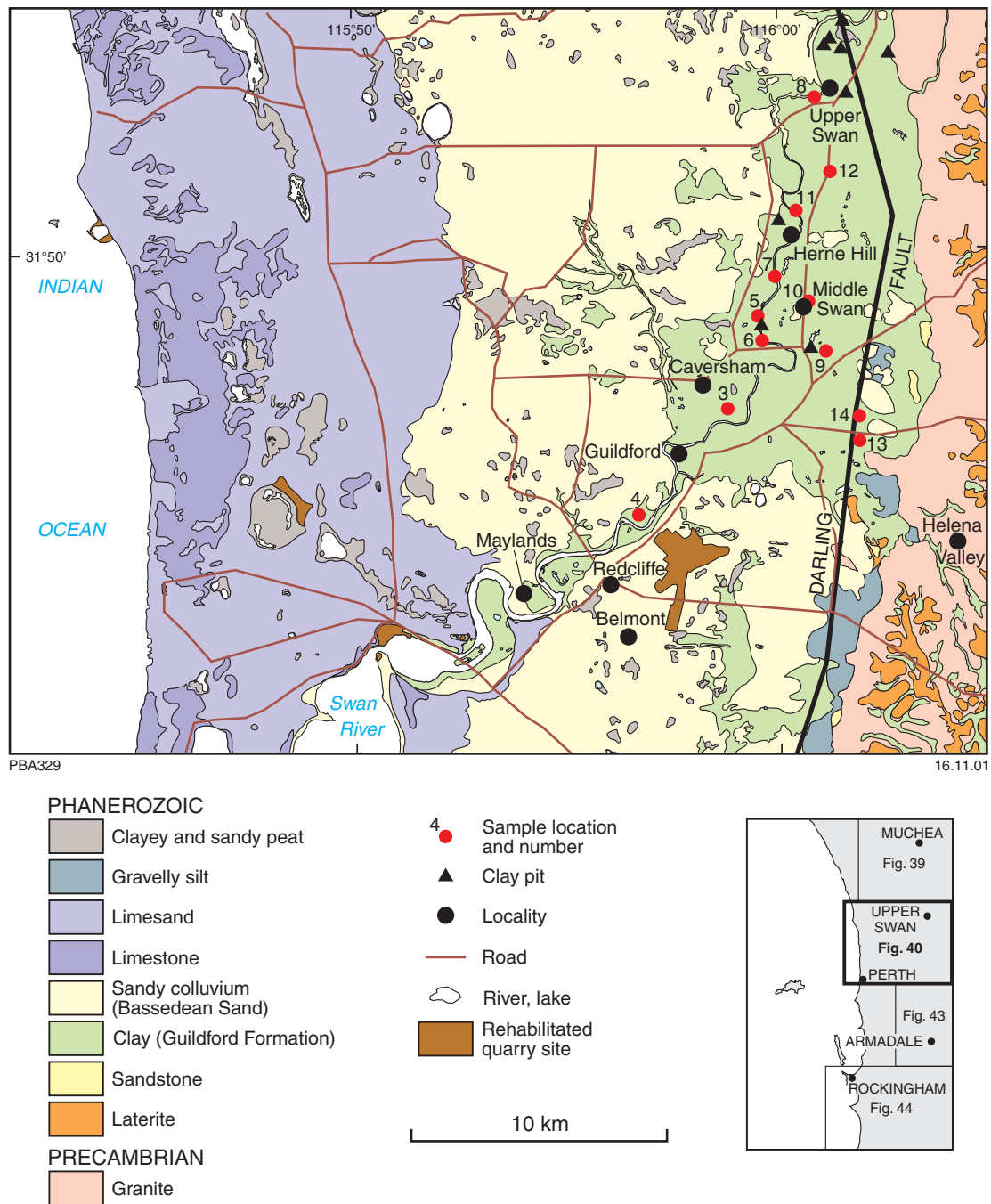


Figure 40. Geology of the area around Upper Swan – Herne Hill – Guildford (modified from Gozzard, 1986)

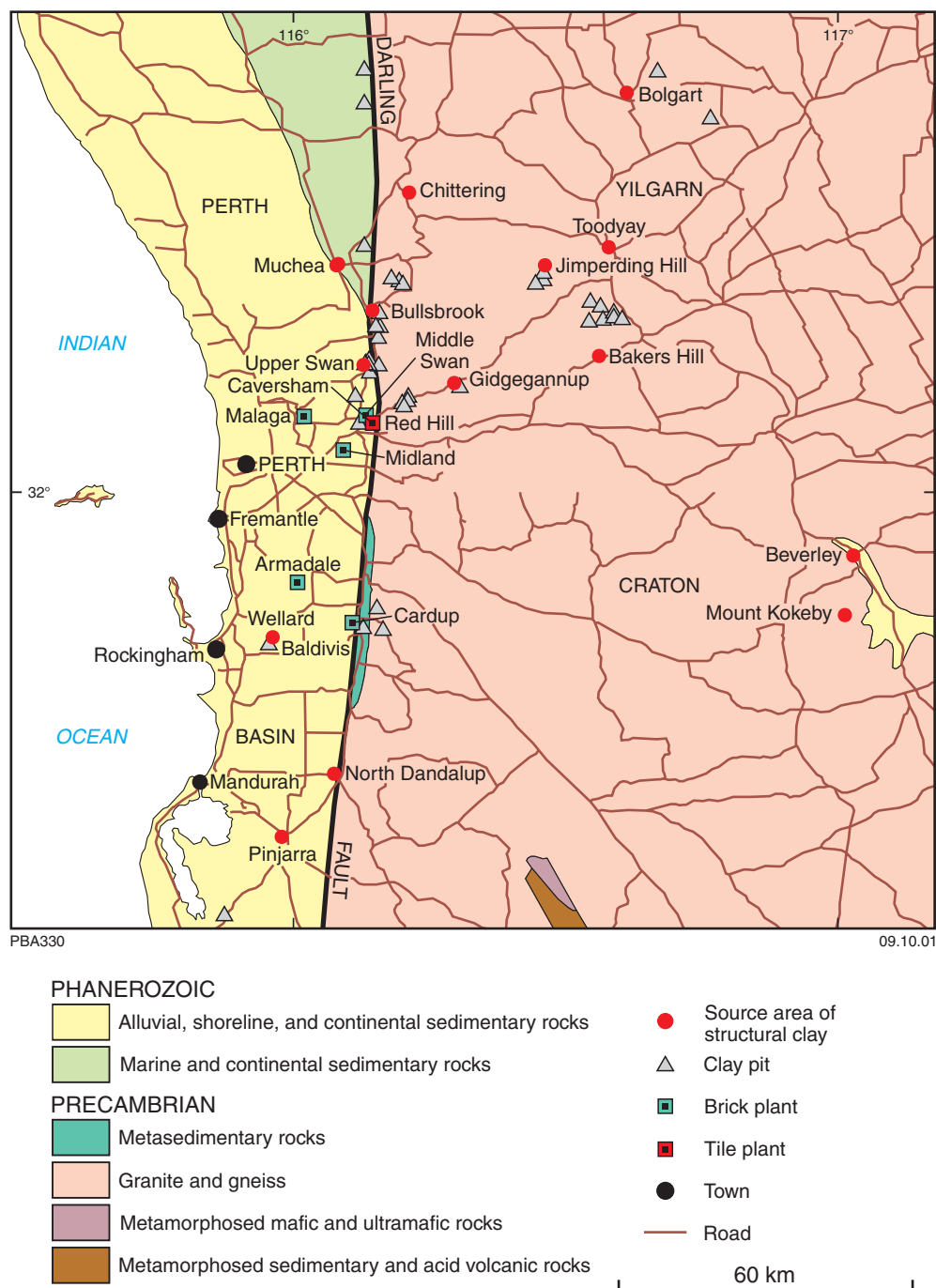


Figure 41. Source areas of structural clay for the brick and tile industries in Perth

Most of the clay deposits developed in ferruginous duricrusts are primary, and the type of minerals found in the clay mostly depends on the underlying rock type. For example, the weathering of granitic rocks generally produces clay rich in kaolinite, halloysite, and quartz, whereas weathering of mafic rocks can produce illite, kaolinite, chlorite, and smectite-rich clays. Residual clay deposits derived from mafic or ultramafic rocks can exhibit preferential layering of certain minerals such as chlorite or serpentine, depending on the layering and other textural characteristics of the source rocks.

Palaeodrainage deposits

These deposits are the products of chemical and mechanical weathering occurring continuously during landscape evolution in the interior of the State. Weathering processes have provided material for transport and deposition to form regolith in palaeochannels, playa lakes, and colluvial mantles. Many of these processes are continuing today. Clay deposits formed in such environments include those in lacustrine environments such as the Mount Kokeby deposit in the South West Terrane of the State, and palaeochannel deposits around Kalgoorlie (Abeyasinghe and Fetherston, 1999).

Alluvium

Construction industry clay suitable for brick, tile, and related industries is commonly found on alluvial or colluvial plains and in many weathered formations (other than sandstone or limestone) in Western Australia. These deposits commonly form terraces and low scarps along river courses above the present-day river level, and range in thickness from a few metres to more than 20 m. The sediments in these environments have formed by periodic alluvial deposition and sheet flooding over wide areas, followed by dessication giving rise to clay-rich and pedogenic layers accumulating alternately. The material commonly contains laterite and silcrete clasts with varying degrees of cementation, and partial calcretization is common (Hocking and Cockbain, 1990).

There are few major areas of active alluvial deposition in Western Australia. Unconsolidated to semi-consolidated, dominantly sandy alluvium is present along most of the drainages in the State. Alluvial deposits grade laterally into colluvial, diluvial, and residual deposits.

Construction industry clay in Western Australia

Construction industry clay can form as the result of surface weathering of almost any Precambrian to Holocene rock, with the exception of pure quartz sandstones and limestone. Therefore, construction industry clay is widely distributed in Western Australia (Figs 37 and 42). The type of clay produced depends on the source material, and the climatic and geochemical environments. Since construction industry clay is a low-

value commodity, it is extremely important that this resource is available close to towns and other population centres. Therefore, known resources of high-quality construction industry clay in the State are generally restricted to the Perth area.

The available data from various investigations in Perth are included in the discussion below. In addition, information gathered during the current study, primarily based on sampling carried out in many localities close to towns along the coastal region and the Kalgoorlie area, is discussed.

For the purpose of this discussion, the construction-industry clay resources in Western Australia are assigned to the following underlying major tectonic units and are discussed in order of economic significance:

- Perth Basin
- Yilgarn Craton
- Albany–Fraser Orogen and Bremer Basin
- Pilbara Craton
- Carnarvon Basin.

Deposits in the Perth Basin

Geological setting

The Perth Basin is an elongated trough of Phanerozoic sedimentary rocks extending for some 1000 km along the southwestern coastal belt of Western Australia (Fig. 36). It has a width of about 80–175 km onshore and covers an approximate area of 45 000 km² on land. The eastern margin of the basin is defined throughout most of its length by the Darling Fault, and the northern part is bordered to the west by the Ajana Ridge, which consists of shallow basement rocks. The western and southern margins of the Perth Basin extend to the continental – oceanic crust boundary (Playford et al., 1976; Hocking, 1994).

The basement rocks underlying the Perth Basin consist of Proterozoic rocks of the Pinjarra Orogen. These are exposed in the Northampton Complex, the Leeuwin Complex, and the Mullingar Inlier. Sedimentary rocks in the Perth Basin range in age from Ordovician to Quaternary.

The Perth Basin is a polycyclic basin and consists of an Ordovician to Lower Cretaceous sequence deposited in an interior-fracture setting, and is overlain by a middle Cretaceous to Quaternary sequence laid down in a marginal sag basin (Cockbain, 1990; Mory et al., 1998). The following summary of the geology of Perth Basin is extracted from Playford et al. (1976), Cockbain (1990), and Mory et al. (1998).

The Tumblagooda Sandstone, which is exposed in the valley of the Murchison River, is an Ordovician unit in the Perth Basin, and its thickness exceeds 3000 m. The colour of the sandstone varies from red, yellow, and brown to white. The sandstone is very fine to coarse grained and is commonly conglomeratic.

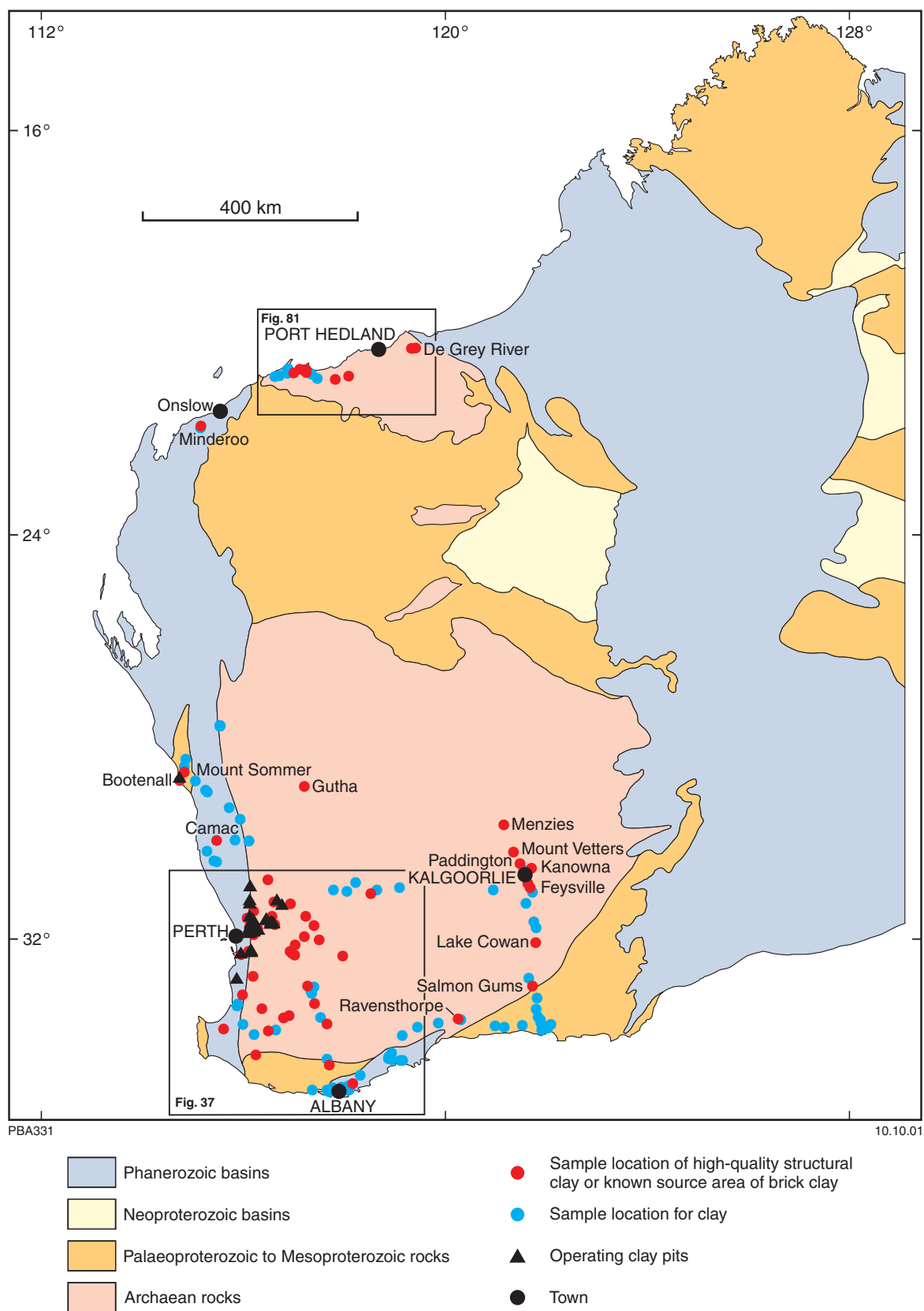


Figure 42. Sample localities for construction industry clay in Western Australia

The total thickness of Upper Carboniferous and Permian rocks in the Perth Basin probably exceeds 2600 m, and consists of a marine and continental sequence in the northern part of the basin and a continental sequence in the southern part. These rocks only outcrop in the northern part of the Perth Basin. The sequence consists of the Nangetty Formation, Holmwood Shale, High Cliff Sandstone, Irwin River Coal Measures, Carynginia Formation, Mingenew Formation, and Wagina Sandstone in the Dandaragan Trough; and the Sue Coal Measures and part of the Sabina Sandstone in the Bunbury Trough. Sandstone and siltstone are the commonest lithologies (Playford et al., 1976; Cockbain, 1990).

Outcrops of Triassic rocks are confined to the Geraldton and Hill River districts, but are present in the subsurface throughout most of the basin. The Triassic rocks may exceed 2500 m in thickness, and consist of marine and continental sequences in the northern part and a continental sequence in the southern part of the basin. The sequence comprises the upper part of the Sabina Sandstone, the Kokatea Shale, Woodada Formation, and Lesuer Sandstone. Shale and sandstone are the dominant lithologies. The shales, as typified by the Kokatea Shale, are grey to black in colour, although outcrops are generally white, yellow, red, purple, or brown.

The Jurassic to Lower Cretaceous sequence is mainly continental, with a thickness of at least 4200 m, and is widespread throughout the basin, with best exposures in the Geraldton and Hill River districts. The sequence comprises the Cockleshell Gully, Cadda, Yarragadee, and Parmelia Formations (Jurassic and Early Cretaceous), and the Chapman and Champion Bay Groups. The predominant lithologies are siliciclastic, with rare limestone. The Cockleshell Gully Formation is composed of fine- to coarse-grained sandstone, with interbedded claystone and siltstone. The sedimentary rocks of the lower Eneabba Member of the Cockleshell Gully Formation are characteristically multicoloured (red, brown, pink, and white), whereas the upper Cattamarra Member of this formation contains grey shale and coal. The Cadda Formation and Champion Bay Group are characterized by shale, siltstone, sandstone, and limestone, whereas the Yarragadee and Parmelia Formations essentially consist of sandstone, siltstone, and shale units. The Cockleshell Gully and Yarragadee Formations are present throughout the basin.

The main exposures of rocks of Cretaceous age are in the Gingin–Dandaragan area, and the total thickness is thought to be around 12 000 m. The Cretaceous sequence comprises the Warnbro and Coolyena Groups and their correlatives, the Donnybrook Sandstone, and the Bullsbrook Formation. The Bunbury Basalt, a vesicular porphyritic basalt, is present at the base of the sequence. The Lower Cretaceous Warnbro Group consists of the lower South Perth Shale and the upper Leederville Formation. The lower South Perth Shale consists of mainly grey and black shale and claystone, with sandstone at the base, whereas the Leederville Formation consists of interbedded sandstone, shale, siltstone, and claystone, with minor conglomerate. The Coolyena Group consists of mainly glauconitic sandstone, argillaceous rocks, and chalk. The Osborne Formation of the Coolyena Group

consists of interbedded sandstone, siltstone, and shale, and is characteristically glauconitic.

The Paleocene and lower Eocene rocks consist of predominantly carbonate rocks, which are best known in the central part of the basin and the adjacent offshore region. However, in the Perth region these rocks consist mainly of siltstone, shale, and some sandstone. The Eocene sequence comprises the Porpoise Bay and Challenger Formations. The Porpoise Bay Formation contains white chalk, calcarenite, and chert, whereas the Challenger Formation comprises brown calcareous shale and siltstone. The onshore sequence of Oligocene and Miocene rocks is confined to the Irwin and Coolcalaya Sub-basins, and comprises sandstone, siltstone, conglomerate, calcarenite, dolomite, and chert. The Pliocene to Holocene rocks are particularly well developed at the seaward edge of the Swan Coastal Plain, and consist of predominantly medium- to coarse-grained sand, commonly calcareous and with lenticular beds of clay and conglomerate.

Quaternary rocks are distributed in many areas of the Perth Basin, and consist of mainly Tamala Limestone (and other limestone units such as the Muchea and Rottne Limestones), Safety Bay Sand (and other sand units such as the Bassendean and Rockingham Sands), Ridge Hill Sandstone, and the Guildford Formation. The Guildford Formation consists of lenticular interbeds of sand, clay, and conglomerate, and is partly calcareous.

Potential geological units for structural clay

Potential sources of structural clay are associated with many geological units of the Perth Basin, and some of the more important units are given in Table 57. In addition, many areas in the Perth Basin are rich in alluvial clays that are suitable for the brickmaking industry. Important areas are found in the northern part of the Perth Basin, such as alluvial horizons around Geraldton, and also in the southern part of the basin, such as in the Dardanup area. In addition, kaolinitic clay suitable for use as structural clay is found in numerous localities of the Perth Basin. Such clays have formed as weathering products of granite, pegmatite, gneiss, or during laterization processes. For example, extensive kaolin deposits are associated with tin-bearing pegmatites in the Greenbushes area (Abeyasinghe and Fetherston, 1999).

Structural clay localities

More than 90% of structural clay in Western Australia is sourced from localities close to or within the Perth area. Many of these localities are within the Perth Basin, but clays from a number of localities in the Darling Range, just east of the Perth Basin and within the Yilgarn Craton, are also significant sources for the clay industry in Perth.

Lipple (1976) and Bowley (1941) have discussed structural clay resources in Western Australia, and Archer (1975) and Landvision (1996) have given descriptions of clay resources in the Perth region. Gozzard (1987a,b)

Table 57. Potential geological units for structural clay in the Perth Basin

Age	Geological unit	Localities	Commodity	Comment
Quaternary	Guildford Formation	Extends from Busselton in the south to Gingin in the north of the Perth Basin	Clay	Major unit currently mined. The formation underlies the coastal plain between the Bassendean Sand and the foot of the Darling Scarp, and consists of sands, sandy clays, and clays, with an occasional thin basal conglomerate, and unconformably overlies the Kings Park Shale, Osborne Formation, or Leederville Formation. The type section of the Guildford Formation is in the West Guildford artesian bore (Lat. 31°54'30"S, Long. 115°57'20"E) from the surface down to 32.99 m. The localities producing structural clay from the Guildford Formation include numerous areas in the Swan Valley in the Perth metropolitan region (Low, 1971; Fig. 40)
Late Cretaceous	Osborne Formation	Vicinity of Gingin and Bullsbrook East	Shale	Major unit currently mined. This formation is the lowermost unit of the Upper Cretaceous Coolyena Group. It consists of interbedded glauconitic sandstone, siltstone, shale, and claystone, and outcrops in weathered exposures in the Muchea–Bullsbrook area. It has been penetrated in a number of water bores in the Perth area and in Gingin No. 1 well, where it is 54.8 m thick. The formation is probably overlain by an Upper Cretaceous succession consisting of the Molecap Greensand, Gingin Chalk, and Poison Hill Greensand (Wilde and Low, 1978). Shale suitable for use in brick manufacture has been obtained from the Osborne Formation around Bullsbrook East (Fig. 39)
Early Cretaceous	Leederville Formation	East of Muchea	Clay	Important source of structural clay for Perth. This formation of the Lower Cretaceous Wanbro Group is exposed in a number of scattered outcrops along the eroded edge of the escarpment near Gingin. The formation comprises shale and siltstone, with minor conglomerate, and unconformably overlies the Yarragadee Formation and is unconformably overlain by the Dandaragan Sandstone or Osborne Formation. It has been penetrated to a maximum thickness of 1181.4 m (Wilde and Low, 1978; Fig. 39)
Jurassic	Yarragadee Formation	Around Greenough River, Geraldton area, 25 km southwest of Eneabba	Clay and shale	Used in the brick industry. This formation is an interbedded sequence of sandstone and siltstone, with lesser thicknesses of shale, claystone, and conglomerate. It is characterized by mottled red, yellow, and white colours, and the type section lies close to the Urella Fault (29°06'S, 115°25'E) on the Dongara – Hill River 1:250 000 geological map (Playford et al., 1970; Lowry, 1974; Lipple, 1976)
Proterozoic	Cardup Group	Between Kelmscott and Mundijong	Clay and shale	Important source of clay for the brick industry. After the Swan Valley area, the most important brick industry is located in the Armadale–Cardup area. However, many quarries in the Kelmscott and Armadale area are no longer in use. The Cardup Group (Figs 43 and 44) comprises three formations collectively containing weakly metamorphosed shale, sandstone, and minor conglomerate. The rocks commonly dip steeply or moderately westwards and have a pronounced slaty cleavage that is subparallel to bedding, and an associated intersection lineation. The thickness of the Cardup Group is about 500 m. These rocks are intruded by dolerite dykes and quartz veins (Myers, 1990b)
Archaean	Weathered profiles of gneissic and granitic rocks	Cardup, Roelands, Newlands	Clay	Currently mined. Weathering profiles of gneissic and granitic rocks are important sources of brick clay. Most of these clays are white and kaolinitic, and the white clays are used in the brick and tile industries to control colours

Table 58. Test results for structural clay samples from the Muchea – Bullsbrook – Swan Valley regions

<i>Locality</i> <i>Sample no. on Figs 39 and 40</i> <i>GSWA no.</i>	<i>Bullsbrook</i> <i>1</i> <i>2024</i>	<i>Muchea</i> <i>2</i> <i>71</i>	<i>Caversham</i> <i>3</i> <i>160</i>	<i>Bassendean</i> <i>4</i> <i>173</i>	<i>Middle Swan</i> <i>5</i> <i>158</i>	<i>Middle Swan</i> <i>6</i> <i>161</i>	<i>Herne Hill</i> <i>7</i> <i>162</i>
% Drying shrinkage	1.50	3.20	4.00	7.80	5.80	5.00	3.00
% Fired adsorption at 1120°C	–	34.80	14.10	13.20	13.60	16.60	13.40
at 1160°C	24.30	3.90	12.00	10.90	11.80	14.60	11.70
% Fired shrinkage at 1120°C	–	–	–	–	11.70	11.00	–
at 1160°C	3.70	9.40	9.50	14.50	12.50	15.70	6.10
Non-plastic content	–	–	–	62.25	–	–	–
Colour	pink	–	terracotta	terracotta	terracotta	terracotta	terracotta
Dried strength	weak	–	–	strong	–	–	–
Fired strength	–	–	good	good	good	good	good
Salt glaze	–	–	good	very good	good	good	good
Plasticity	nil	–	–	good	poor	very poor	–

<i>Locality</i> <i>Sample no. on Figs 39 and 40</i> <i>GSWA no.</i>	<i>Upper Swan</i> <i>8</i> <i>3026</i>	<i>Middle Swan</i> <i>9</i> <i>3106</i>	<i>Middle Swan</i> <i>10</i> <i>3107</i>	<i>Herne Hill</i> <i>11</i> <i>3109</i>	<i>Millendon</i> <i>12</i> <i>3110</i>	<i>Midland</i> <i>13</i> <i>2084</i>	<i>Midland</i> <i>14</i> <i>3112</i>
% Drying shrinkage	7.80	6.50	7.10	5.50	4.70	5.80	4.70
% Fired adsorption at 1120°C	6.10	15.50	15.00	12.50	12.40	14.00	13.90
at 1160°C	15.90	–	15.40	9.70	11.20	13.90	13.50
% Fired shrinkage at 1120°C	10.10	–	9.30	5.50	–	11.70	badly warped
at 1160°C	10.40	–	9.30	–	badly warped	11.70	badly warped
Non-plastic content	72.75	86.75	76.00	82.00	74.75	61.50	77.50
Colour	dark brown	light brown	light red	dark red	red	red	red
Dried strength	poor	good	medium	medium	fairly good	strong	poor
Fired strength	fair	fair	good	very strong	good	good	poor
Salt glaze	good	fair	good	very good	heavy	fair	heavy
Plasticity	poor	nil	poor	nil	low	plastic	poor

SOURCE: Gozzard (1987a)

documented test results of numerous samples of clay collected from the Perth area (Tables 58–60). Important localities for structural clay in the Perth Basin are discussed below.

Perth region

The important localities for clay deposits in the Perth Basin are given in Table 57 and shown on Figures 38–44. The source areas of clay for industries in the Perth metropolitan region at present are Upper Swan, Middle Swan, Herne Hill, Muchea, Bullsbrook East, Gidgegannup, Red Hill, and Cardup. In addition, clay is sourced from relatively more distant locations such as the Beverley and Pinjarra areas (located within the Perth Basin) and also from Toodyay and Jimperding Hill, which are located east of the Perth Basin, within the Yilgarn Craton (Fig. 41). In the past, important localities for structural clay for Perth were located in the valleys of the Swan, Helena, Canning, and Serpentine Rivers. There is

still some production from some of these river valleys, especially the Swan Valley. The following are brief descriptions of the important localities in the Perth region.

Muchea – Bullsbrook East

The siltstone of the Leederville Formation in the Muchea – Bullsbrook East region is at present a source of semi-plastic kaolinitic clay for the brick industry in the Perth region (Figs 39 and 45). The Osborne Formation, found in the same area, is also a source for this industry. The material from the Leederville Formation is white, thinly bedded, well laminated, and fine grained. It also contains some large, ferruginous concretions and laminae, which are locally micaceous. The material from the Osborne Formation is pale brownish-yellow, fine to medium grained, and contains quartz and feldspar in a siltstone matrix. The quartz–mica schist exposed in the area around Bullsbrook East (Fig. 39) is also a significant source of semi-plastic clay for brick manufacture. The schist is

Table 59. Test results for structural clay samples from the Canning Valley, Armadale, Cardup, and Byford regions

<i>Locality</i> <i>Sample no. on Fig. 43</i> <i>GSWA no.</i>	<i>Gosnells</i> <i>15</i> <i>3002</i>	<i>Kenwick</i> <i>16</i> <i>3004</i>	<i>Maddington</i> <i>17</i> <i>3011</i>	<i>Maddington</i> <i>18</i> <i>3012</i>	<i>Kenwick</i> <i>19</i> <i>4001</i>	<i>Kenwick</i> <i>20</i> <i>4002</i>	<i>Cardup</i> <i>21</i> <i>4017</i>	<i>Cardup</i> <i>22</i> <i>4018</i>
% Drying shrinkage	7.30	6.80	5.70	9.70	7.70	9.60	8.80	–
% Fired adsorption								
at 1120°C	13.50	15.70	14.70	5.90	14.50	5.20	11.00	–
at 1160°C	11.70	14.80	13.90	–	12.70	5.10	–	–
% Fired shrinkage								
at 1120°C	13.30	10.20	7.10	20.00	8.90	17.20	13.40	–
at 1160°C	14.80	9.50	7.40	–	9.30	17.20	14.10	–
Non-plastic content	78.70	73.75	63.50	67.60	62.75	63.60	56.25	–
Colour	reddish brown	dark brownish red	red	red	brownish red	red	red	–
Dried strength	good	good	very good	good	good	good	good	fair
Fired strength	good	–	–	excellent	–	strong	good	poor
Salt glaze	very good	fairly good	fair	fair	fairly good	good	good	–
Plasticity	good	good	fair	good	plastic	high	good	plastic

<i>Locality</i> <i>Sample no. on Fig. 43</i> <i>GSWA no.</i>	<i>Cardup</i> <i>23</i> <i>4019</i>	<i>Cardup</i> <i>24</i> <i>4020</i>	<i>Byford</i> <i>25</i> <i>4022</i>	<i>Byford</i> <i>26</i> <i>4023</i>	<i>Byford</i> <i>27</i> <i>1005</i>	<i>Lesmurdie</i> <i>28</i> <i>168</i>	<i>Lesmurdie</i> <i>29</i> <i>169</i>	<i>Kelmscott</i> <i>30</i> <i>2002</i>
% Drying shrinkage	9.10	7.80	6.30	2.50	6.30	4.70	3.00	10.75
% Fired adsorption								
at 1120°C	15.40	17.40	18.90	16.20	–	21.50	27.90	3.70
at 1160°C	14.40	16.20	16.70	14.30	8.60	18.60	27.00	3.30
% Fired shrinkage								
at 1120°C	10.20	7.80	6.30	0.70	–	9.70	–	3.70
at 1160°C	11.10	8.80	6.30	2.50	15.60	10.00	4.70	17.50
Non-plastic content	63.75	69.00	85.25	76.25	30.60	62.00	53.75	39.25
Colour	red	red	red	light brown	cream	white	white	dark reddish brown
Dried strength	good	good	good	poor	good	poor	weak	good
Fired strength	good	–	strong	–	–	poor	poor	very good
Salt glaze	fair	good	fairly good	poor	surface cracking	fair	heavy	excellent
Plasticity	good	good	fair	poor	fair	plastic	low	high

<i>Locality</i>	<i>Kelmscott</i>	<i>Kelmscott</i>	<i>Maddington</i>	<i>Gosnells</i>	<i>Maddington</i>	<i>Maddington</i>	<i>Maddington</i>	<i>Maddington</i>	<i>Bickley Brook</i>
<i>Sample no. on Fig. 43</i>	<i>31</i>	<i>31</i>	<i>32</i>	<i>33</i>	<i>34</i>	<i>35</i>	<i>36</i>	<i>37</i>	<i>38</i>
<i>GSWA no.</i>	<i>2004A</i>	<i>2004B</i>	<i>3001</i>	<i>3006</i>	<i>3007</i>	<i>3008</i>	<i>3009</i>	<i>3010</i>	<i>3019</i>
% Drying shrinkage	5.50	6.30	5.67	6.70	–	–	–	–	6.70
% Fired adsorption									
at 1120°C	16.30	18.00	–	20.00	–	–	–	–	–
at 1160°C	–	17.00	6.40	19.70	–	–	–	–	14.10
% Fired shrinkage									
at 1120°C	6.30	7.80	–	6.70	–	–	–	–	–
at 1160°C	–	–	13.90	6.90	–	–	–	–	17.60
Non-plastic content	57.25	–	40.00	88.75	–	–	–	–	15.60
Colour	light brown	dirty cream	light brown	dark red	–	–	–	–	cream
Dried strength	fair	fair	good	medium	good	very good	fair	good	good
Fired strength	fair	very poor	–	–	very poor	poor	poor	poor	–
Salt glaze	poor	poor	fair	poor	–	–	–	–	very good
Plasticity	fair	fair	high	fair	plastic	plastic	fair	plastic	fair

SOURCE: Gozzard (1987a,b)

Table 60. Test results for structural clay samples from the Mundijong and Rockingham regions

Locality	Mundijong	Mundijong	Mundijong	Mundijong	Mundijong	Mundijong	Mundijong	Mundijong	Mundijong
Sample no. on Fig. 44	39	40	41	42	43	44	45	46	47
GSWA no.	7	10	12	15	16	17	22	23	33
% Drying shrinkage	4.70	4.70	5.00	9.60	–	–	–	7.00	–
% Fired adsorption									
at 1120°C	17.10	15.60	14.50	11.10	–	–	–	10.70	–
at 1160°C	16.70	15.80	10.30	11.20	–	–	–	10.20	–
% Fired shrinkage									
at 1120°C	4.70	5.80	9.00	11.40	–	–	–	14.10	–
at 1160°C	4.70	7.10	badly warped	12.10	–	–	–	15.20	–
Non-plastic content	77.75	72.75	65.00	47.00	–	–	–	62.25	–
Colour	light grey	red	very dark red	medium red	–	–	–	brownish red	–
Dried strength	good	good	good	excellent	good	good	good	good	good
Fired strength	–	–	good	good	poor	poor	medium	–	poor
Salt glaze	poor	good	good	excellent	–	–	–	fair	–
Plasticity	good	fair	fairly good	high	plastic	plastic	plastic	plastic	plastic

Locality	Mundijong	Mundijong	Peel Estate	Peel Estate	Peel Estate	Peel Estate	Peel Estate	Peel Estate
Sample no. on Fig. 44	48	49	50	51	52	53	54	55
GSWA no.	4003	4004	4005	4012	4013	4014	4015	4016
% Drying shrinkage	8.70	7.80	6.30	7.70	10.50	7.30	8.20	8.40
% Fired adsorption								
at 1120°C	11.10	12.80	15.00	11.80	12.20	13.10	10.90	14.70
at 1160°C	11.00	13.00	14.70	11.30	11.20	10.40	9.80	14.70
% Fired shrinkage								
at 1120°C	12.20	10.30	7.00	12.80	14.80	10.90	10.20	9.50
at 1160°C	11.70	10.30	7.00	13.60	14.80	10.90	11.00	9.50
Non-plastic content	72.75	56.25	78.75	64.50	62.75	63.25	60.00	–
Colour	light red	red	terracotta	red	brown	red	red	red
Dried strength	good	good	good	good	good	good	good	good
Fired strength	–	–	–	–	strong	medium	fairly good	fair
Salt glaze	good	good	fair	fairly good	good	fair	fairly good	fair
Plasticity	good	good	plastic	good	high	good	good	good

Locality	Wellard	Wellard	Wellard	Wellard	Dog Hill	Dog Hill	Karnup	Karnup
Sample no. on Fig. 44	56	57	58	59	60	61	62	63
GSWA no.	18	19	24	25	26	27	50	51
% Drying shrinkage	8.70	9.20	8.90	9.30	10.60	9.70	12.50	10.00
% Fired adsorption								
at 1120°C	11.10	12.00	12.00	–	12.90	8.50	–	–
at 1160°C	11.00	11.90	11.20	–	13.10	8.50	10.30	10.70
% Fired shrinkage								
at 1120°C	11.80	11.40	11.00	10.20	13.60	12.80	–	–
at 1160°C	12.20	11.40	11.30	15.60	13.30	12.80	15.50	12.50
Non-plastic content	55.50	58.30	69.25	52.90	56.60	41.00	–	–
Colour	light reddish	light red	brownish	medium yellow	light red	brownish	deep red	deep red
	brown		red	brown		red		
Dried strength	good	good	good	fairly good	good	good	difficult to dry	–
Fired strength	–	–	–	fair	good	very good	–	–
Salt glaze	readily glazes	readily glazes	readily glazes	no glaze	–	readily glazes	–	–
Plasticity	high	high	high	plastic	plastic	plastic	good	–

Table 60. (continued)

Locality Sample no. on Fig. 44 GSWA no.	Dog Hill 64 52	Dog Hill 65 53	Dog Hill 66 54	Dog Hill 67 4006	Wellard 68 4007	Dog Hill 69 4008	Wellard 70 4009	Wellard 71 4044
% Drying shrinkage	10.90	13.20	3.40	8.40	—	13.30	11.70	11.30
% Fired adsorption at 1120°C	—	—	—	13.10	15.30	7.70	11.50	10.30
at 1160°C	14.80	8.00	46.50	12.10	—	7.00	—	10.00
% Fired shrinkage at 1120°C	—	—	8.00	11.70	—	18.00	15.60	15.70
at 1160°C	16.50	14.90	9.40	11.70	—	18.30	—	15.70
Non-plastic content	—	—	—	61.25	—	43.25	—	—
Colour	red	deep red	cream	terracotta	yellow brown	reddish brown	red	terracotta
Dried strength	fair	—	—	good	low	good	fair	good
Fired strength	good	very strong	medium	fair	strong	strong	—	good
Salt glaze	—	cracks	—	fair	none	excellent	none	—
Plasticity	—	—	—	high	plastic	plastic	good	high

Locality Sample no. on Fig. 44 GSWA no.	Wellard 71 4045	Wellard 71 4046	Wellard 71 4047	Wellard 71 4048	Wellard 71 4049	Mundijong 72 4	Mundijong 73 38	Mundijong 74 39
% Drying shrinkage	10.50	—	8.00	11.00	10.00	3.50	3.80	5.30
% Fired adsorption at 1120°C	12.40	10.90	17.10	16.40	13.60	16.60	23.80	16.40
at 1160°C	12.10	—	15.70	—	12.90	12.50	22.40	20.50
% Fired shrinkage at 1120°C	13.60	12.00	14.00	13.30	11.40	7.00	7.70	8.40
at 1160°C	14.00	—	—	—	13.70	badly warped	8.00	10.10
Non-plastic content	60.75	—	79.25	55.50	66.25	77.50	68.50	71.25
Colour	light reddish brown	—	—	dark brown	light brown	brownish red	pinkish cream	cream
Dried strength	very good	very strong	medium	very strong	good	not good	strong	strong
Fired strength	fair	good	weak	strong	—	not good	fair	—
Salt glaze	good	good	fair	fair	very good	readily glazes	fair	fair
Plasticity	plastic	plastic	low	fair	low	not plastic	fair	fair

SOURCE: Gozzard (1987b)

highly schistose and grey to pale grey. The homogeneous grey, micaceous, and silty clay associated with the quartz–mica schist, about 5 km east of Wandena, is also used as a source of semi-plastic clay for brick manufacture. Test results for samples collected from the Bullsbrook and Muchea regions are given in Table 58 (samples 1 and 2).

Swan Valley

The whole of the Swan Valley, extending from around Upper Swan in the north to around Maylands in the south, was previously the most important source of plastic alluvial clays in the Perth metropolitan region (Fig. 40). The Upper Swan, Middle Swan, and Herne Hill regions still continue to be important sources of plastic alluvial clay, although clays from the Maylands, Belmont, and Redcliffe regions are no longer available due to urban development. Clay from the Swan Valley area shows more sorting than clays from the other river valleys such as

Helena and Canning. This sorting has resulted in the formation of fine-grained, plastic clays with a low silica content. Therefore, clay from the Upper Swan, Middle Swan, and Herne Hill regions in the Swan Valley is currently the main source of plastic alluvial clay for the pipe, tile, and brick industries in Perth.

In the Swan Valley area, the Guildford Formation comprises small, irregular-shaped lenses of slightly silty, plastic clays surrounded by much coarser sandy clays and sands. Such rapid lateral variation and lack of persistent horizons are typical of sediments in the area due to the meandering nature of the river. The plastic alluvial clays from the Guildford Formation in the Upper Swan – Herne Hill area are used in the manufacture of bricks, pipes, and tiles, and the deposits have a maximum clay thickness of 8 m. The clays vary from slightly sandy, grey plastic clays mottled with yellow-brown iron oxide to pale-grey to yellowish-brown, very sandy clays. Patches of dark-grey to black, slightly sandy swampy clay are also present.

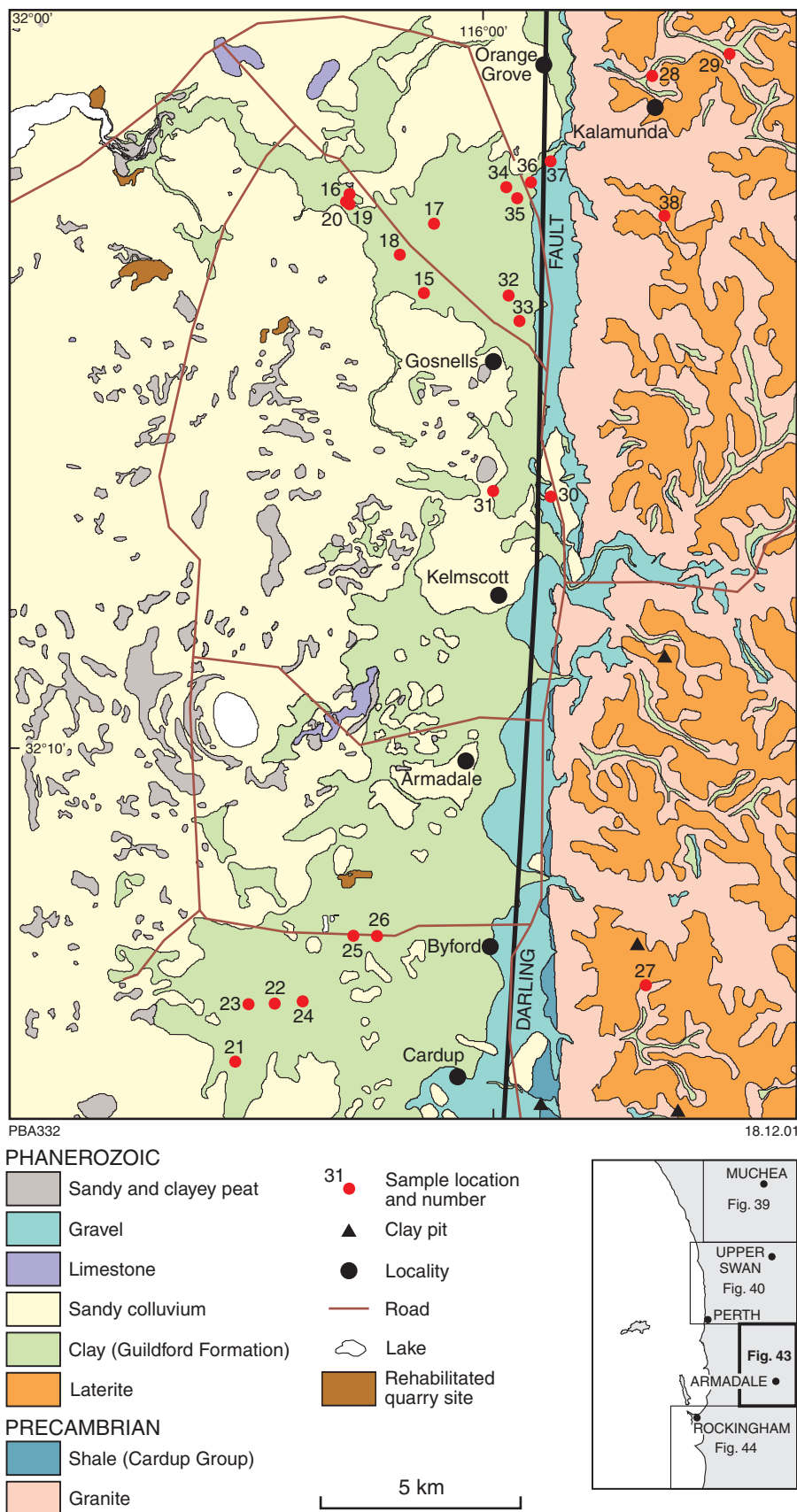


Figure 43. Geology of the area around Armadale (modified from Jordan, 1986a)

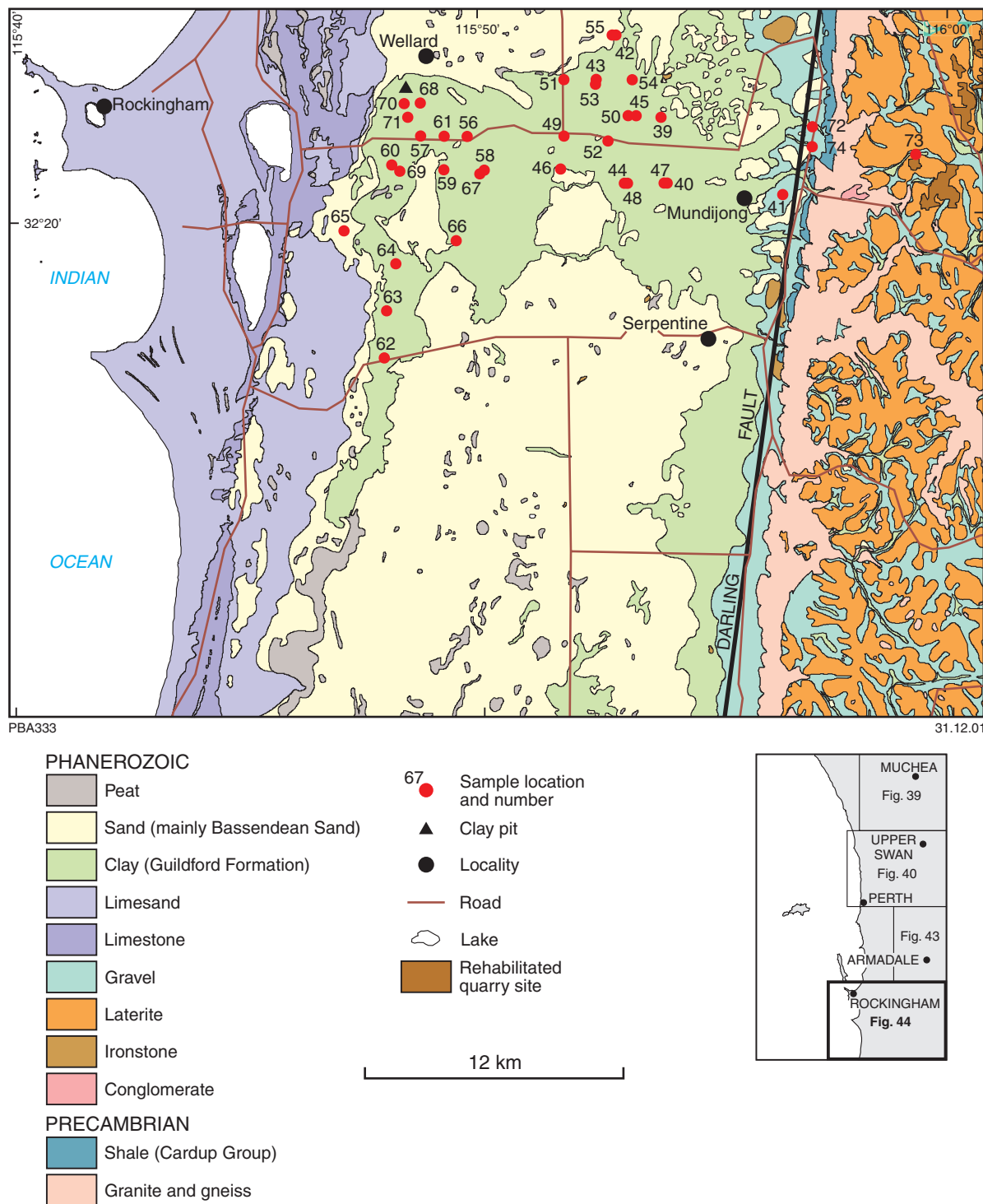


Figure 44. Geology of the area around Mundijong and Rockingham (modified from Gozzard, 1983 and Jordan, 1986b)



Figure 45. Kaolinitic clay in a quarry near Muchea (Lat. 31°31'S, Long. 116°18'E)

Clays from the Middle Swan area are also used in the brick industry. In this area, the upper clay layer is commonly about 3 m thick and the colour varies from pale grey to pale brown, yellow, brown, and mottled red. This upper clay horizon is commonly underlain by an approximately 2 m-thick sand layer, which again is underlain by another clay horizon approximately 3 m thick. This bottom layer typically contains bluish-grey, mottled clay and is more fine-grained and more plastic than the upper clay layer.

The area around and to the north of Caversham has been an important source of fine plastic clays for pipe and tile manufacture, but the area is now heavily urbanized and access to clay resources is severely restricted. The clay deposits were reported to have been shallow, with a maximum thickness of approximately 5 m, but indicated considerable lateral extent. Apart from the presence of fine-grained, almost chocolate-brown clay, the lithological characteristics of these clays are similar to those seen elsewhere. Test results for samples from the various localities of the Swan Valley region are given in Table 58 (samples 3–14).

Helena Valley

In the past, the clay of the Guildford Formation in the Helena Valley area (Fig. 40) has been used in the manufacture of bricks. The maximum thickness of the clay is approximately 6 m, and consists of pale-grey, coarse sand to clay loam with variable amounts of yellow, red, and brown oxide mottling throughout. There is considerable variation in mottling and grain size.

Canning Valley–Armada–Cardup–Byford

The clay from Orange Grove (Fig. 43) in the Canning Valley has been used as a source of brick and cement clays. The clay from this area is poorly sorted and similar to that in the Helena Valley area, and the variation in lithology is considerable. Test results for samples from various localities in the Canning Valley region are given in Table 59 (samples 15–38).

Shale from the Proterozoic Cardup Group is an important source of non-plastic clay for the brick industry. The Cardup Group outcrops as a narrow, steeply dipping band at the foot of the Darling Scarp between Kelmscott and Mundijong (Figs 43 and 44). These rocks are intruded by dolerite dykes and quartz veins. Only a few localities in the Cardup, Kelmscott, and Armadale areas are currently mined. The kaolinitic material produced during laterization and that associated with the weathered horizons of granite are also a source of clay for the brick industry. Some of this kaolinitic clay is extracted by brick manufacturers from a number of quarries located along the Darling Scarp, east of the Byford area.

Mundijong–Wellard

The alluvial clay of the Guildford Formation formed in a flat-lying area to the north of Serpentine and immediately west of Byford and Mundijong (Figs 43 and 44). The clay in this area is slightly plastic, but is invariably sandy and coarse, generally grey with dark brownish-red mottling, and local yellowish iron-oxide staining. The variation of colour is considerable, but generally appears red. The sand

is made up of angular quartz and feldspar grains. The maximum thickness of this clay horizon is about 3 m, but it extends over a large area. At present this material is not widely used as a source of clay for brick manufacture, except for some extraction from a quarry south of Wellard. The use of this material is restricted to the brick industry, but the coarseness of the material and low plasticity is considered to be a deterrent (Archer, 1975). Test results for samples from various localities in these areas are given in Table 60 (samples 39–74).

Test results for structural clay samples from the southeastern Perth metropolitan region examined by Bowley (1941) are given in Table 61.

Resources

The clay for brick and tile manufacturing plants in Perth is sourced from approximately 40 quarries, with about another 20 sites earmarked for future supplies (Fig. 41). Resources at these sites have been estimated by Landvision (1996), which reported resources separately for brick and tile, plastic, semi-plastic, and kaolinitic clays. The identified resources in the Perth metropolitan region (as estimated in 1996), on the basis of approved areas (by the Local Government bodies and relevant Government departments) for mining, amount to 37.1 Mt, and not-approved areas amount to 31.1 Mt (Table 62).

Of the total resources identified, the plastic clay resources within approved and not-yet approved areas of the outer Perth metropolitan region were estimated at 8.3 Mt. Of this, approximately 7.7 Mt (93%) are located in the Upper Swan region in a narrow 3 km-long strip and within one kilometre either side of the Great Northern Highway (Fig. 40). The remaining 600 000 t are located south of the Wellard and Pinjarra areas.

The total resources, within approved and not-approved areas, of semi-plastic clay within the Perth metropolitan region are 20.3 Mt. A total of 16.3 Mt (80.3%) of this are located along a northerly trending line some 5 km east of Muchea, and another 4 Mt (19.7%) are located in the area around Bullsbrook East (Fig. 39). An additional 700 000 t have been identified in the Beverley, Mount Kokeby, and Bolgart regions outside Perth (Fig. 41).

The known resources of non-plastic clay within approved and not-approved areas in Perth are estimated at 38.9 Mt. Of these, approximately 17.1 Mt (44%) are at Gidgegannup, 10.5 Mt (27%) at Toodyay, 6.6 Mt (17%) at Cardup, and the remaining 4.7 Mt (12%) at Bullsbrook East, Red Hill, and North Dandalup.

South of Perth

Stretches of land located east and west of the South Western Highway from Wokalup to Waterloo contain vast areas of alluvial clay from the Guildford Formation (Fig. 18). These alluvial deposits contain plastic and semi-plastic clay suitable for use in the ceramic or brick industry. Brief details of samples collected from some of the localities in this belt are presented below.

Wokalup

In the Wokalup area, an alluvial plain containing clay from the Guildford Formation extends over several kilometres from the town in a westerly and southerly direction (Fig. 18). The test results for sample GSWA 117816 (Tables 32, 63, and 64) collected from the bank (at a depth of about 2 m from the surface) of a small creek on the western side of Hocart Road indicate that this material could be used as a possible red-filler material in the manufacture of bricks. The raw sample was dark to very dark grey and reasonably plastic, but silty. The fired colour of the sample was dark red. Chemical analysis indicates that it has a composition suitable for use in brick manufacture. However, the sample contained a minor amount of smectite that may result in undesirable effects.

Benger

The area around Benger is a flat alluvial plain extending for more than 2 km in a northerly, westerly, and southerly direction, and contains clayey material of the Guildford Formation. The test results for a sample (GSWA 117817; Fig. 18) of dark-brown to grey, plastic clay from the wall of a bank (at a depth of about 2 m from the surface) of a small creek on the western side of Marriott Road indicate that it could be used as a possible filler material in the manufacture of bricks (Tables 32, 63, and 64). The fired colour of the sample was red to dark red, and the clay produced a soft bar when fired to 1160°C. The chemical composition indicates that it has a suitable composition for use in brick manufacture. However, the sample contained a major amount of smectite, and this may have undesirable effects when used as a structural clay.

Roelands

The Guildford Formation continues into the Roelands area from Benger, with the clayey material extending for more than 2 km in a northerly, westerly, and southerly direction from Roelands. Wilde and Walker (1982) stated that kaolinized material present in the weathering profiles over gneissic rocks, at a location 7 km east of Roelands, was possibly used in the ceramic industry. Test results for a sample (GSWA 117818; Fig. 18) of plastic, dark-grey clay from the western side of Raymond Road indicated that the material was silty and sandy, with some ironstone, and unsuitable for use in the manufacture of bricks (Tables 64 and 65). However, on the basis of surface geological features, the potential for clay in the area for use as a structural clay cannot be ruled out.

Waterloo

Clay from the Guildford Formation is used for brick-making in a factory at Waterloo. Wilde and Walker (1982) stated that clay suitable for ceramic and brick manufacture has been obtained from the Maxicar Beds, 1 km north of Maxicar. A firing test on a brown to grey, plastic clay sample (GSWA 117819; Fig. 18), collected from the Guildford Formation, produced a soft bar with a light-red to orange colour that appeared to be unsuitable for use in the manufacture of bricks (Tables 64 and 65). However, the results for this sample cannot be taken as conclusive

Table 61. Test results for structural clay samples from the southeastern Perth metropolitan region

<i>Locality</i>	<i>Cardup (west of brickworks)</i>	<i>Cardup Lot 47/244</i>	<i>Kalamunda (Piesse Gully)</i>	<i>Kalamunda (Piesse Gully)</i>	<i>Kalamunda (Piesse Gully)</i>	<i>Kalamunda (Woodlupine Brook)</i>	<i>Armadale Loc. 88 and 91</i>
<i>Sample no.</i>	<i>31</i>	<i>71</i>	<i>32</i>	<i>55</i>	<i>67</i>	<i>74</i>	<i>36</i>
Plasticity	69	76	40	4	40	104	53
Air shrinkage (%)	9.5	13.2	7.9	7.6	7.6	14.9	8.9
Fired shrinkage (%)							
at 1050°C	3.3	3.3	—	3.4	3.4	3.1	4.5
at 1150°C	4.4	3.3	—	3.3	3.3	7.8	5.6
at 1250°C	9.5	9.2	—	6.5	6.5	16.3	8.6
at 1350°C	11.5	9.6	12.7	10.6	10.6	16.9	12.2
Porosity (%)							
at 1050°C	31.1	35.6	—	29.5	29.5	29.6	39.1
at 1150°C	29.2	34.8	—	25.3	25.3	21.3	30.9
at 1250°C	18.2	22.1	—	20.7	20.7	6.3	24.3
at 1350°C	12.9	19.7	9.7	14.8	14.8	4.5	16.3
Colour							
at 1050°C	white	creamy white	—	white	white	grey white	white
at 1150°C	white	creamy white	—	white	white	creamy white	white
at 1250°C	creamy white	creamy white	—	creamy white	white	pale grey	white
at 1350°C	creamy white	creamy white	white	creamy white	creamy white	pale grey	creamy white
Vitrification							
at 1050°C	—	—	—	—	—	—	—
at 1150°C	incipient	incipient	—	—	incipient	incipient	—
at 1250°C	—	—	—	—	—	—	incipient
at 1350°C	—	—	incipient	incipient	—	advanced	—

SOURCE: Bowley (1941)

Table 62. Structural clay resources in the Perth region

<i>Clay type</i>	<i>Resources in approved areas (Mt)</i>	<i>Resources in not-approved areas (Mt)</i>
Plastic	6.195	2.100
Semi-plastic	6.470	14.500
Non-plastic fillers (e.g. granite, dolerite, ironstone)	24.442	14.500
Total	37.107	31.100

SOURCE: modified from Landvision (1996)

NOTE: Approved areas are approved for mining by the Local Government bodies and relevant Government departments

evidence of unsuitability because of the possibility of the presence of high-quality clay lenses in the Guildford Formation.

Dardanup

The clays from the Cretaceous Maxicar Beds, exposed about 6–8 km east of Dardanup at the western border of the Yilgarn Craton, have been used for the manufacture of bricks. These beds consist of about 9 m of poorly sorted, ferruginous feldspathic sandstone at the type locality, 6.5 km east of Dardanup. A sequence of white claystone, siltstone, and fine-grained sandstone with carbonaceous layers is exposed in a clay pit 1 km north of the type locality (Wilde and Walker, 1982).

North of Perth

The Quaternary alluvial and colluvial beds south of Geraldton, as well as in some areas east of Geraldton, contain clay suitable for brick manufacture. The kaolinitic material associated with lateritic horizons in some areas

south of Eneabba and north of Cooljarlo are also likely to contain pockets of good quality clay suitable for use as structural clay.

Bootenall

Quaternary alluvial deposits containing variable amounts of quartz, sand, clay, and loam are present in a south-easterly belt from the Geraldton area down to Walkaway (Fig. 46). This alluvial formation is bordered by the Tamala Limestone to the west and sedimentary rocks of the Champion Bay Group and granitic rocks to the east. The alluvial formations in the Bootenall area, within the above belt, contain horizons of good clay suitable for use in brick manufacture, and a factory at Bootenall uses this material to manufacture bricks on a commercial basis.

Mount Sommer

In the area around Mount Sommer, alluvial clay has formed in narrow valleys between weathered outcrops of granitic rocks. A sample of this alluvial clayey material from a road cutting (taken about 3 m below the surface) was tested for its suitability for use in the manufacture of bricks (Fig. 46). The sample (GSWA 145190) was a grey to brown silty clay and representative of appreciable quantities of clay found in the surrounding area. The fired sample of this material produced a soft red-coloured bar and would be suitable as a red filler in brickmaking (Table 64). The sample contained 78.5% SiO₂, 9.93% Al₂O₃, and 2.99% Fe₂O₃, and a major amount of feldspar (Tables 63 and 65).

Camac

Kaolinitic clay horizons are commonly found associated with the lateritic material outcropping on the gentle slopes of both sides of the road leading to Coorow from the Brand Highway (Fig. 47). A sample (GSWA 145174) of whitish kaolinitic clay from about 1.5 km east of Camac Homestead, by the side of the road leading to Coorow from Mill Roadhouse, produced a good strong, cream-coloured bar and is suitable for use in brick manufacture. The chemical analysis of the sample indicated 66.9% SiO₂, 18.30% Al₂O₃, and 1.92% Fe₂O₃, and the mineralogical studies showed kaolinite and feldspar to be major components of the sample (Tables 63 and 65).

Table 63. Chemical composition of structural clay samples from the Perth Basin

<i>Locality</i>	<i>Wokalup</i>	<i>Benger</i>	<i>Camac</i>	<i>Mount Sommer</i>
<i>GSWA no.</i>	<i>117816</i>	<i>117817</i>	<i>145174</i>	<i>145190</i>
Percentage				
SiO ₂	71.20	72.90	66.90	78.50
Al ₂ O ₃	11.80	10.60	18.30	9.93
TiO ₂	0.99	0.82	0.98	0.87
Fe ₂ O ₃	5.49	4.15	1.92	2.99
MnO	0.09	0.04	<0.01	0.02
CaO	1.05	0.73	0.06	0.34
K ₂ O	1.48	1.63	3.64	1.88
MgO	0.24	0.33	0.31	0.33
P ₂ O ₅	0.02	0.06	0.02	0.04
SO ₃	0.05	0.05	0.10	0.02
BaO	0.04	0.08	0.10	0.05
Na ₂ O	1.39	1.06	0.54	0.54
LOI	5.90	6.66	6.72	4.00
Total	99.74	99.11	99.59	99.51
H ₂ O ⁻	1.11	1.49	1.03	0.95

Table 64. Test results for structural clay samples from the Perth Basin

Locality GSWA no.	Wokalup 117816	Benger 117817	Roelands 117818	Waterloo 117819	Camac 145174	Mount Sommer 145190
Salt (ppm)	434	569	310	316	7 434	761
pH	6.3	6.5	6.4	6	5.7	7.7
>90 µm (%)	42.4	35	47	31.2	24.8	45.4
Shrinkage (%)						
Drying (110°C)	4	6	5	7.5	4	4
Firing	1.5	1	0.5	2.5	5	0.5
Total	5.5	7	5.5	10	9	4.5
Friability index	7	7	10	7	1	6–7
Fired temperature (°C)	1160	1160	1160	1160	1220	1160
Fired colour	Dark red	Red to dark red	Red	Light red to orange	Cream to light yellow	Red
C (%)	1.07	1.24	0.433	0.376	0.123	0.0384
S (%)	0.0163	0.0172	0.0059	0.0067	0.0295	0.0075
Comments	Sandy and silty material. Yields a soft bar at >1160°C. Possible use as a red filler (Appendix 3)	Silty material. Soft bar at >1160°C. Possible use as a red filler (Appendix 3)	Soft bar at >1160°C. Material is very silty and sandy, with some ironstone. Unsuitable for brickmaking (Appendix 3)	Material is sandy and yields a soft bar. Unsuitable for brickmaking (Appendix 3)	Material consists of schist and shale containing fine quartz, mica, and some ironstone. Yields a good strong bar and is a suitable clay for brickmaking (Appendix 3)	Yields a soft bar, but possible for use as a red filler (Appendix 3)

Table 65. Mineralogy of structural clay samples from the Perth Basin

<i>Locality GSWA no.</i>	<i>Roelands 117818</i>	<i>Waterloo 117819</i>	<i>Camac 145174</i>	<i>Mount Sommer 145190</i>
Kaolinite	minor	minor	major	minor
Smectite	—	—	—	—
Mica/illite	—	?minor	—	minor
Vermiculite	—	—	minor	minor
Attapulgite	—	—	—	—
Talc	—	—	—	—
Quartz	dominant	dominant	dominant	dominant
K-feldspar	minor	minor	major	major
Na-feldspar	—	—	—	—
Amphibole	—	—	—	—
Calcite	—	—	—	—
Dolomite/ankerite	—	—	—	—
Hematite	minor	minor	—	?minor
Anatase	—	?minor	—	?minor
Goethite	?minor	minor	—	—
Gibbsite	—	—	—	—
Halite	—	—	—	—

NOTE: Dominant: >50%; subdominant: 40–50%; major: 10–40%; minor: 2–0%

Other areas

Samples were collected by the author from a number of localities in the northern areas of the Perth Basin that appeared to contain clays suitable for use as structural clay. However, testing of these samples revealed that the clays were not suitable for use in the brick industry. On the basis of surface geological indications, these localities appear to have potential for good clay pockets, and therefore more sampling and testing are warranted. These localities and their test results are given in Tables 66 and 67. Bowley (1941) cited test results for two samples of clay from the Ferguson and Busselton areas, and these samples were considered to be of good quality for brick and tile manufacture (Table 68).

Deposits on the Yilgarn Craton

Geological setting

The geology of the Yilgarn Craton is favourable for significant deposits of residual and alluvial clay as extensive deep-weathering profiles are developed on granite and granitic gneiss. The mature drainage systems and palaeochannels in the Southwest Drainage Division (Fig. 48) are also potential areas for thick horizons of transported clay. The pallid zones of these weathering profiles and palaeochannels commonly contain thick sequences of variable-grade clay.

Large deposits of clay (including kaolin), of both residual and transported origin, are already known in the southwestern region of the State. The important kaolin deposits of both residual and transported origin have been discussed in a Bulletin on kaolin resources in Western Australia (Abeyasinghe and Fetherston, 1999). Residual kaolin deposits have formed as

weathered profiles on granitic bodies and gneisses of Precambrian age. Transported deposits have formed in areas of palaeodrainages and lacustrine environments. Construction-industry clay deposits are also found on vast areas of the Yilgarn Craton, but there have not been many investigations to assess the resource available because of their remoteness from markets.

The Yilgarn Craton has been subdivided into the following tectonic units (Tyler and Hocking, 2001a,b):

- South West Terrane
- Murchison Granite–Greenstone and Narryer Terranes
- Southern Cross Granite–Greenstone Terrane
- Eastern Goldfields Granite–Greenstone Terrane.

South West Terrane

The South West Terrane is bounded by the Albany–Fraser Orogen to the south, the Southern Cross Granite–Greenstone Terrane to the east, the Murchison Granite–Greenstone Terrane to the north, and the Perth Basin to the west (Fig. 49).

The main geological units within the South West Terrane are granite, and the Jimperding and Balingup Gneiss Complexes. Granite is the most widespread rock type that intrudes the Jimperding and Balingup Gneiss Complexes. The granitic rocks are partly recrystallized to greenschist facies, and have been mapped as even-grained, seriate, or porphyritic granites.

The Jimperding Gneiss Complex consists of metasedimentary rocks, ultramafic rocks, and banded quartzofeldspathic orthogneiss. Metasedimentary rocks are mainly fuchsite-bearing quartzite, quartz–feldspar–biotite–garnet gneiss, andalusite and sillimanite schist, banded iron-formation (BIF), and minor calc-silicate rocks.

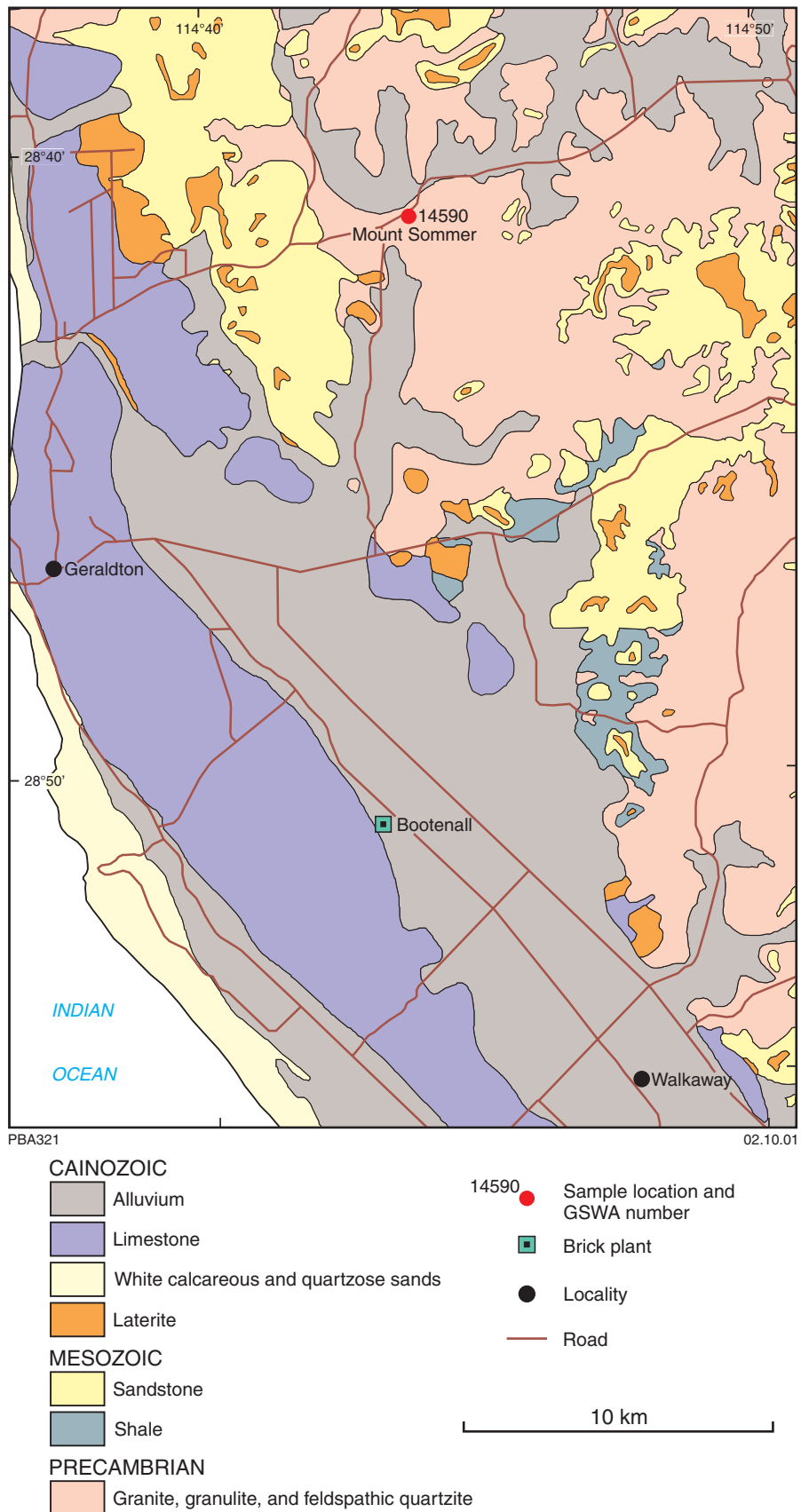


Figure 46. Geology of the area around Bootenall and Mount Sommer (modified from Playford et al., 1971)

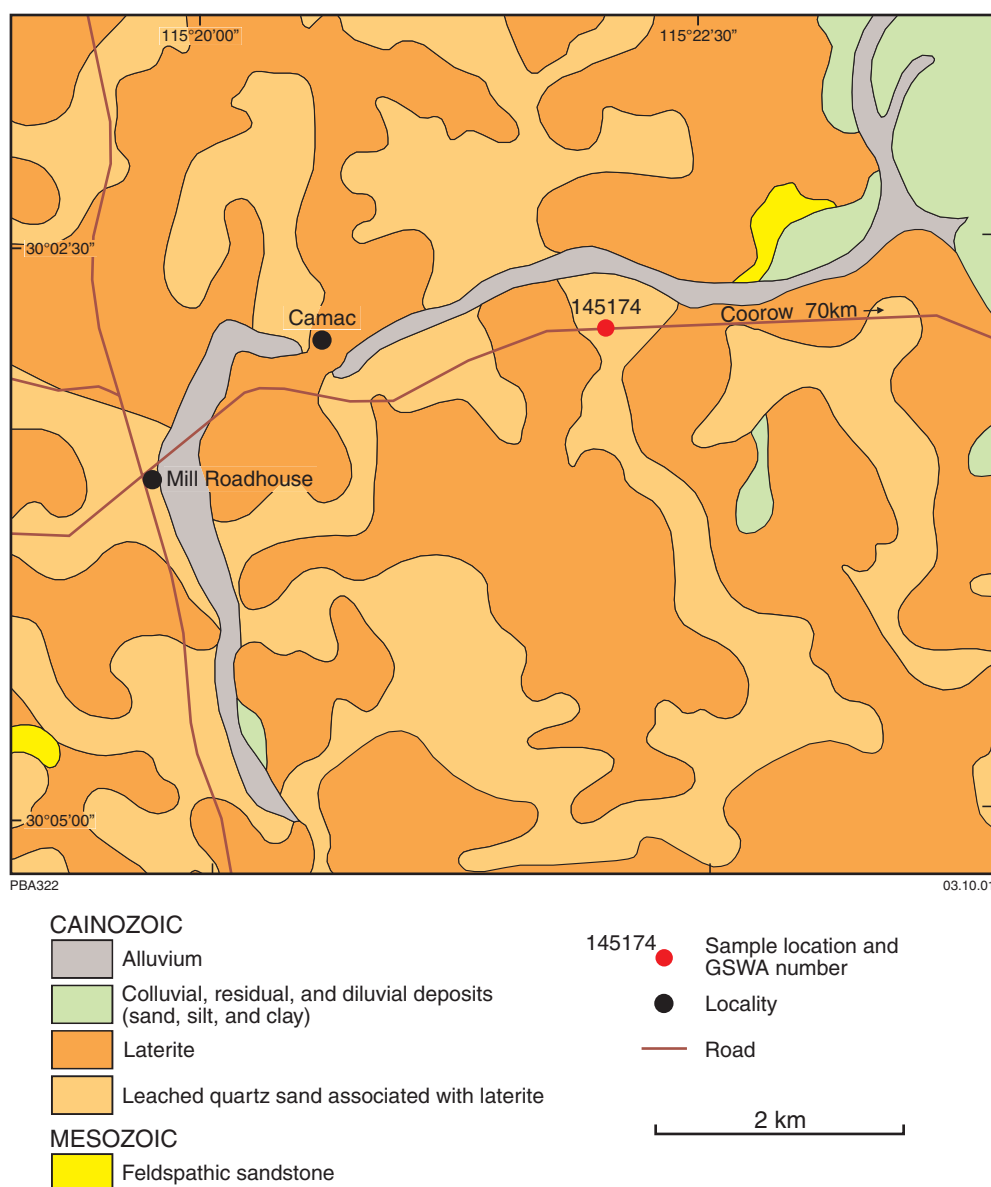


Figure 47. Regional geology of the area around Camac (modified from Mory et al., 1994)

The Balingup Gneiss Complex consists mainly of metasedimentary rocks, quartzofeldspathic gneisses, amphibolites, calc-silicate gneiss, and ultramafic rocks (Wilde, 1980). The metasedimentary rocks are mainly interlayered quartzite, quartz–mica schist, quartz–feldspar–biotite–garnet gneiss, and BIF. The Balingup Gneiss Complex has been metamorphosed to amphibolite facies, although localized assemblages of granulite-facies metamorphism are also present.

The Saddleback greenstone belt in the south-western sector of the South West Terrane consists of metamorphosed siltstones, felsic lava, pyroclastic rocks, and basalt (Wilde and Pidgeon, 1986).

Weathered profiles of the granitic, gneissic, and mafic rocks discussed above are likely to contain regolith material suitable for use as industrial clay.

Murchison Granite–Greenstone Terrane

The Murchison Granite–Greenstone Terrane is in the northwestern sector of the Yilgarn Craton. It is bounded by the Perth Basin to the west, the Narryer Terrane to the northwest, the Bryah and Yerrida Basins to the north, the Southern Cross Granite–Greenstone Terrane to the east, and the South West Terrane to the south. The following summary of the geology of the Murchison Granite–Greenstone Terrane is extracted from Watkins (1990).

The greenstone sequences in this terrane consist of the Luke Creek Group (Fig. 50) and the overlying Mount Farmer Group, which together form the Murchison Supergroup (Watkins, 1990). The Luke Creek Group is divided into lower and upper volcanic sequences. The lower sequence contains a thick pile of tholeiitic and high-Mg basalt (Murrouli Basalt) capped by the much thinner

Table 66. Test results for clay samples from the northern Perth Basin

<i>Locality GSWA no.</i>	<i>Bibby Road^(a) 145171</i>	<i>Bibby Road^(a) 145172</i>	<i>Gairdner Range 145173</i>	<i>Pinjarrega Lake 145175</i>	<i>Three Springs 145176</i>	<i>Yandanooka 145179</i>
Salt (ppm)	262	325	458	272	8 555	12 213
pH	7	6.8	7.2	6.9	8.5	8.7
>90 µm (%)	37.6	51.8	62.2	63.6	32.8	56.2
Shrinkage (%)						
Drying (110°C)	2.5	3.5	4	2	5	2.5
Firing	9	2	1.5	0.5	2	0.5
Total	11.5	5.5	5.5	2.5	7	3
Friability index	5–6	8	10	10	8	2
Fired temperature (°C)	1220	1160	1160	1220	1160	1160
Fired colour	Light orange	Pink to light red	Off white	Off white to light cream	Red to dark red	Very dark red to cherry red
C (%)	0.238	0.0988	0.0528	0.0535	0.358	0.214
S (%)	0.0211	0.0208	0.0112	0.0037	0.0189	0.027
Comments	Yields a soft bar and is unsuitable for brick-making (Appendix 3)	Yields a soft bar and is not very suitable for brickmaking (Appendix 3)	Yields a very soft bar and is unsuitable for brickmaking (Appendix 3)	Sandy material. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)	Sandy material with some gravel and limestone. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)	Sandy material with limestone. Unsuitable for brickmaking (Appendix 3)

<i>Locality GSWA no.</i>	<i>Mount Horner 145180</i>	<i>Mount Hill 145181</i>	<i>Ellendale Bluffs 145182</i>	<i>Nanson 145191</i>	<i>Nabawa 145192</i>
Salt (ppm)	557	478	21 299	556	5 623
pH	8.9	6.9	7.7	6.6	8.9
>90 µm (%)	46.4	56.6	46.8	69.2	47.6
Shrinkage (%)					
Drying (110°C)	4	3	4	1.5	3
Firing	2.5	1	1	5	1.5
Total	6.5	4	5	6.5	4.5
Friability index	10	9	10	10	6
Fired temperature (°C)	1220	1220	1220	1160	1160
Fired colour	Light yellow	Light yellow	Dark yellow to orange	Red	Dark red
C (%)	0.95	0.957	0.0818	0.148	2.36
S (%)	0.0048	0.003	0.0643	0.006	0.0599
Comments	Sandy material. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)	Sandy material. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)	Sandy material. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)	Red sandy material that contains coarse ironstone. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)	Material contains sand, silt, and limestone. Unsuitable for brickmaking (Appendix 3)

NOTE: (a) Approximately 30 km southeast of Jurien

Table 67. Mineralogy of clay samples from the northern Perth Basin

Locality	Bibby Road ^(a)	Bibby Road ^(a)	Gairdner Range	Pinjarrega Lake	Three Springs	Yandanooka	Mount Horner	Mount Hill	Ellendale Bluffs	Nanson	Nabawa
GSWA no.	145171	145172	145173	145175	145176	145179	145180	145181	145182	145191	145192
Kaolinite	dominant	major	major	major	major	minor	major	major	major	dominant	minor
Halloysite	?minor	—	—	—	—	—	—	—	—	—	—
Smectite	—	—	—	—	?minor	?minor	—	—	?minor	—	—
Mica/illite	?minor	?minor	—	—	—	?minor	minor	minor	minor	minor	minor
Vermiculite	—	—	—	—	—	—	—	—	—	—	—
Attapulgite	—	—	—	—	—	—	—	—	—	—	—
Talc	—	—	—	—	—	—	—	—	—	—	—
Quartz	major	dominant	dominant	dominant	dominant	dominant	dominant	dominant	dominant	major	dominant
K-feldspar	minor	minor	—	—	major	minor	—	—	minor	minor	major
Na-feldspar	—	—	—	—	—	—	—	—	—	—	—
Amphibole	—	—	—	—	—	—	—	—	—	—	—
Calcite	—	?minor	—	—	minor	—	—	?minor	?minor	—	minor
Dolomite/ankerite	—	—	—	—	?minor	—	—	—	?minor	—	—
Hematite	minor	minor	—	?minor	?minor	—	?minor	—	—	minor	minor
Anatase	?minor	—	?minor	?minor	—	—	?minor	?minor	?minor	?minor	?minor
Goethite	minor	minor	—	—	—	—	—	—	—	?minor	—
Gibbsite	?minor	—	—	—	—	—	—	—	—	—	—
Halite	—	—	—	—	—	?minor	—	—	minor	—	—

NOTE: Dominant: >50%; subdominant: 40–50%; major: 10–40%; minor: 2–0%
(a) Approximately 30 km southeast of Jurien

Table 68. Test results for structural clay samples from the Ferguson and Busselton areas

Locality	Ferguson Loc. 1983	Busselton (22 km southeast)
Sample no.	28	63
Plasticity	40	154
Air shrinkage (%)	4.2	14.9
Fired shrinkage (%)		
at 1050°C	—	4.9
at 1150°C	0.5	9.0
at 1250°C	2.0	12.7
at 1350°C	2.8	15.2
Porosity (%)		
at 1050°C	22.8	42.8
at 1150°C	23.4	32.7
at 1250°C	21.2	21.9
at 1350°C	18.8	18.5
Colour		
at 1050°C	white	white
at 1150°C	white	white
at 1250°C	creamy white	creamy white
at 1350°C	creamy white	cream
Vitrification		
at 1050°C	—	—
at 1150°C	—	—
at 1250°C	—	incipient
at 1350°C	incipient	—

SOURCE: Bowley (1941)

Golconda Formation, which consists of BIF and inter-layered mafic rocks. The upper sequence, comprising the Gabanintha and Windaning Formations, appears to be a classic greenstone sequence. A thick succession of interlayered high-Mg and tholeiitic basalts overlying the Gabanintha Formation is widespread throughout the Murchison Granite–Greenstone Terrane. These basalts are successively overlain by a mixture of mafic and felsic volcanics and their sedimentary derivatives. The Windaning Formation is uppermost and consists of regionally extensive jaspilitic BIF interlayered with volcanoclastic sedimentary rocks, felsic tuff, and minor volcanic rocks. In the Mount Farmer Group, there are nine distinct volcanic complexes and one sedimentary sequence. The sedimentary sequence is known as the Mougoodera Formation and comprises an upward-fining sequence of clastic sedimentary rocks unconformably overlying the Luke Creek Group. The compositional spread of the Mount Farmer and Luke Creek Group rocks is similar. However, in the Luke Creek Group rocks, iron-rich tholeiites are more abundant. In the Mount Farmer Group, there is a higher proportion of felsic rocks.

Four suites of granitoid rocks have been identified in the Murchison Granite–Greenstone Terrane. These are pegmatite-banded gneiss, recrystallized monzogranite, and two compositionally diverse suites of post-folding granitoids. These suites were emplaced into the Murchison Supergroup, in the order mentioned, during three phases of granitoid magmatism. The two suites of post-folding granitoids were broadly contemporaneous.

Pegmatite-banded gneiss is particularly abundant near the western margin of the Murchison Granite–Greenstone Terrane (Fig. 50), and commonly forms large enclaves, rafts, and partially absorbed remnants in recrystallized monzogranite. The western outcrops of pegmatite-banded gneiss are known as the Murgoo Gneiss Complex, which is heterogeneous both in composition and deformation state. Elsewhere, the gneiss consists of subparallel pegmatite bands, up to several centimetres thick, inter-layered with compositionally banded, medium-grained monzogranite and granodiorite up to 10 cm thick. The pegmatite bands intrude the gneiss and are more abundant in the central part of the Murchison Granite–Greenstone Terrane than in the western part. The pegmatite-banded gneiss essentially contains quartz, oligoclase, K-feldspar, and biotite, with accessory white mica, epidote, sphene, apatite, zircon, and opaque minerals. The pegmatite bands contain coarse-grained quartz, microcline, and oligoclase, with less than 1% mica phases.

The recrystallized monzogranite, the pegmatite-banded gneiss, and the Murchison Supergroup have all been thoroughly recrystallized during regional metamorphism, and as a result igneous textures were obliterated. The textures of these rocks are now mainly granoblastic and lepidoblastic in unfoliated and foliated rocks respectively. Protomylonitic textures, which have now partially or completely recrystallized into mortar textures, have developed in some regions of high strain. Mineral assemblages of the recrystallized monzogranite are similar to those in the pegmatite-banded gneiss.

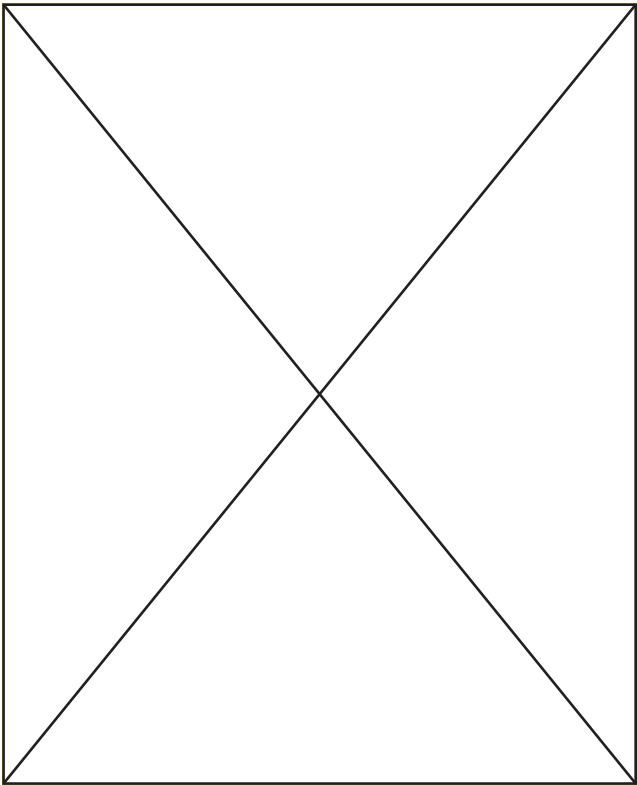


Figure 48. The Southwest Drainage Division showing the extent of young, mature, and old drainage (after Bettenay and Mulcahy, 1972)

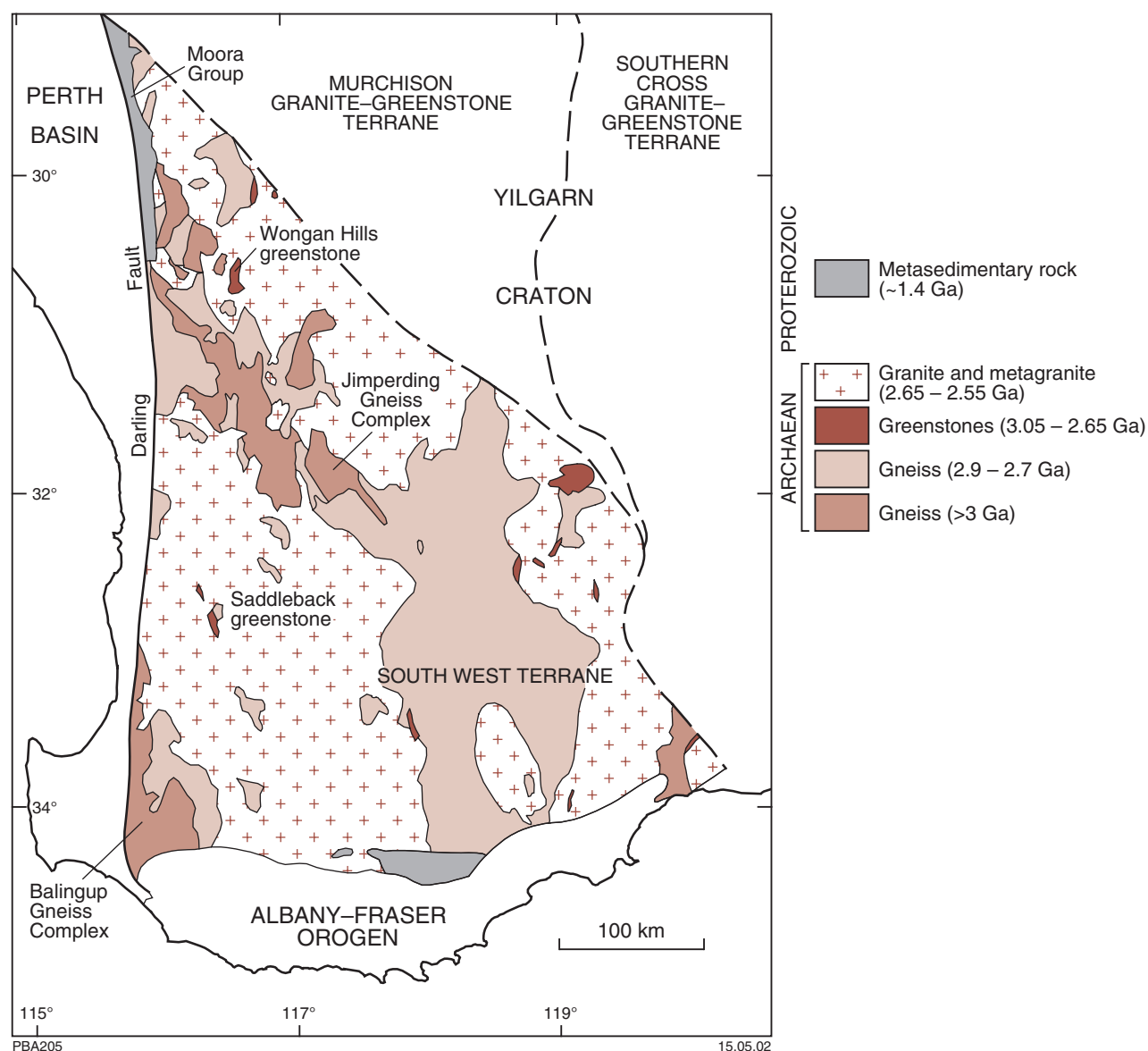


Figure 49. Regional geology of the South West Terrane, Yilgarn Craton (after Abeysinghe and Fetherston, 1999)

Fifty-seven plutons of post-folding granitoid have been recognized in the Murchison Granite–Greenstone Terrane. These have been divided into two suites (I and II) on the basis of petrology and geochemistry (Watkins, 1990). Suite I plutons are mainly confined to the northeastern half of the Murchison Granite–Greenstone Terrane and suite II to the southwestern half. Suite I consists of predominantly tonalite and monzogranite, whereas suite II consists of syenogranite. Mineral assemblages of both suites may contain any of the following principal phases: quartz, plagioclase, K-feldspar, biotite, hornblende, and muscovite, with minor opaque minerals, apatite, sphene, zircon, fluorite, chlorite, epidote, sericite, and carbonates. In general, the post-folding granitoids contain a higher proportion of ferromagnesian phases than either the recrystallized monzogranite or pegmatite-banded gneiss.

Weathered profiles of granitic, gneissic, pegmatitic, and greenstone rocks discussed above are likely to contain material suitable for use as industrial clay.

Southern Cross Granite–Greenstone Terrane

The Southern Cross Granite–Greenstone Terrane is unconformably overlain by the Yerrida Basin to the north and is in tectonic contact with the Albany–Fraser Orogen to the south (Fig. 51). It is bounded to the east by the Eastern Goldfields Granite–Greenstone Terrane and to the west by the South West and Murchison Granite–Greenstone Terranes. The following summary of the geology of Southern Cross Granite–Greenstone Terrane has been extracted from Griffin (1990a).

Granitoid and gneiss dominate the Southern Cross Granite–Greenstone Terrane, but are poorly exposed and



Figure 50. Simplified geology of the area north of Mount Gibson in the Murchison Granite–Greenstone Terrane, Yilgarn Craton (modified from Watkins, 1990)

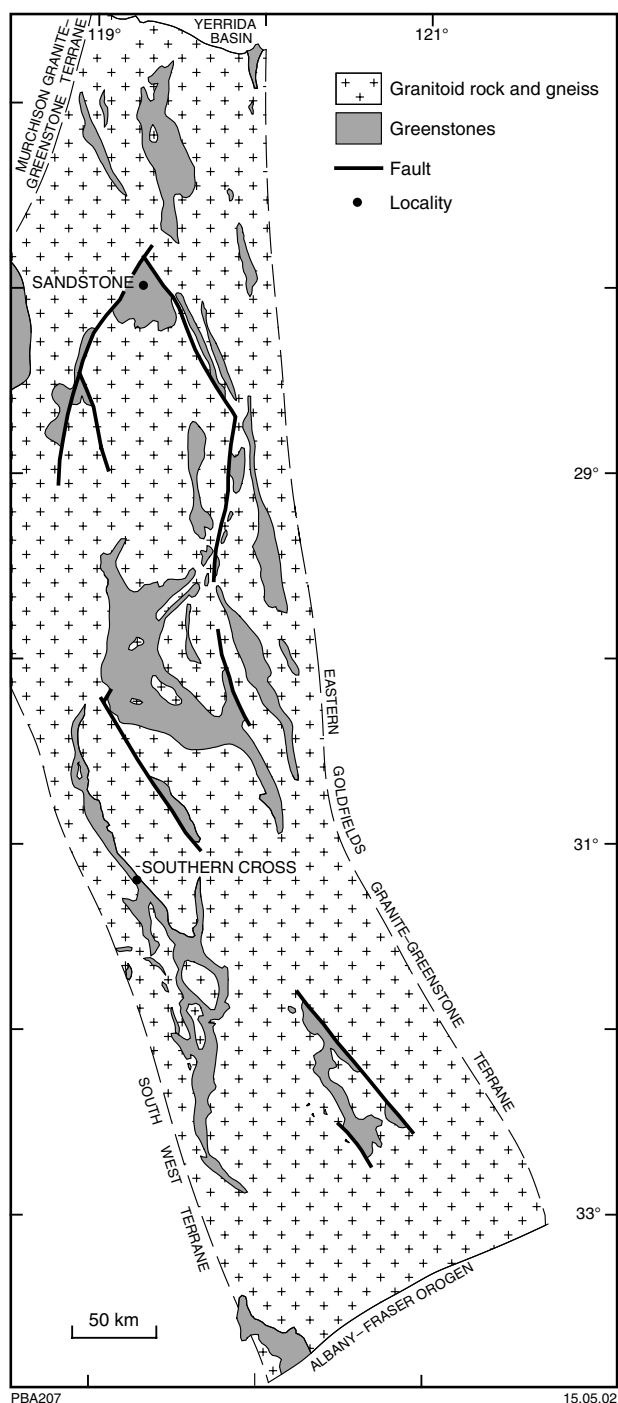


Figure 51. Geology of the Southern Cross Granite–Greenstone Terrane, Yilgarn Craton (modified from Griffin, 1990a)

form isolated pavements within extensive areas of sandy soil. Gneiss appears to be restricted to elongated zones adjacent to greenstone belts and as enclaves within large areas of granitoid. The southwestern part of the Southern Cross Granite–Greenstone Terrane contains gneiss and granitoid metamorphosed to granulite facies. The contacts between gneiss or granitoid and greenstone are commonly sheared or strongly foliated (Walker and Blight, 1983;

Stewart et al., 1983). Gneissic rocks are of two types: foliated gneiss and massive gneiss. Both rock types are predominantly feldspar–quartz–biotite rocks ranging in composition from tonalite to syenogranite. Foliated to weakly foliated granitoid dominates large areas between the greenstone belts. The predominant textures of the granitic rocks are medium to coarse grained and porphyritic to seriate, although fine-grained and non-porphyritic phases are locally significant. The granitoids are composed of microcline, zoned plagioclase, quartz, biotite, hornblende (rarely), chlorite, and accessory muscovite, zircon, apatite, sphene, allanite, epidote, and opaque minerals. Microcline phenocrysts, biotite, and recrystallized lenses of quartz and feldspar are aligned along the foliations, and biotite-rich mafic xenoliths are widespread. Discrete plutons of foliated and undeformed granitoid intrude older granitoid, gneiss, and greenstone, and have narrow contact-metamorphic aureoles. Xenoliths in these plutons define an igneous foliation. All these phases are intruded by veins and small masses of granitoid, pegmatite, and aplite.

The greenstones consist of an upper and lower sequence separated by a major unconformity. The lower sequence consists of a quartzite unit at the base overlain by dominantly mafic and ultramafic volcanic rocks. Clastic sedimentary and minor felsic volcanic rocks are present near and at the top of this lower sequence. The upper sequence is present only in the centre of the region and consists of clastic sedimentary rocks and felsic volcanic rocks that unconformably overlie the lower sequence.

Both granitoids and greenstones are strongly deformed, with evidence of polyphase deformation, and have a dominant north-northwesterly trend similar to that of the Eastern Goldfields Granite–Greenstone Terrane. Their ages range from 3.1 to 2.5 Ga.

Weathered profiles of granitoids, and gneissic and mafic rocks discussed above are likely to contain material suitable for use as industrial clay.

Eastern Goldfields Granite–Greenstone Terrane

The Eastern Goldfields Granite–Greenstone Terrane is a typical Archaean granite–greenstone terrane, and occupies the eastern part of the Yilgarn Craton. It consists of large areas of granitic rocks and linear to arcuate belts of greenstone, mainly with a north-northwesterly trend (Fig. 52). The greenstones exhibit various degrees of deformation, and have mainly undergone greenschist-facies metamorphism (Griffin, 1990b). The Eastern Goldfields Granite–Greenstone Terrane is unconformably overlain by sedimentary rocks of the Earahedy Basin to the north and northeast, and by sedimentary rocks of the Gunbarrel Basin in the east. In the south, the Archaean rocks are truncated by the Albany–Fraser Orogen. In general, granitoid rocks are more poorly exposed than the greenstone belts, and the main granitoid varieties recognized are granitic gneiss, foliated and unfoliated granites, and small discordant granitoid stocks. In the greenstone belts, the lowest parts of the sequence are mostly mafic to ultramafic volcanic rocks overlain by felsic volcanic rocks and clastic sedimentary rocks. The

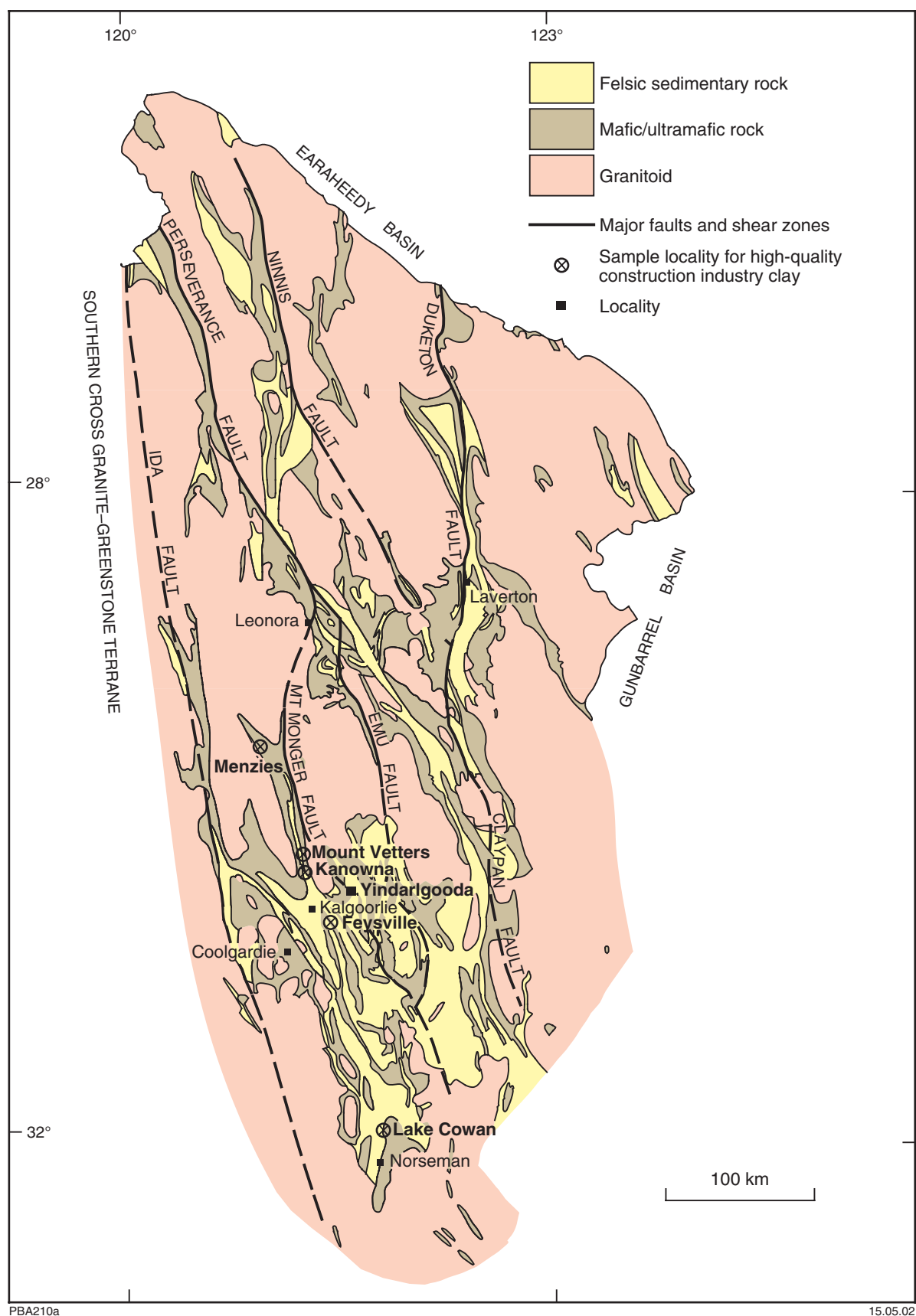


Figure 52. Main lithological units of the Eastern Goldfields Granite–Greenstone Terrane, Yilgarn Craton (after Griffin, 1990b)

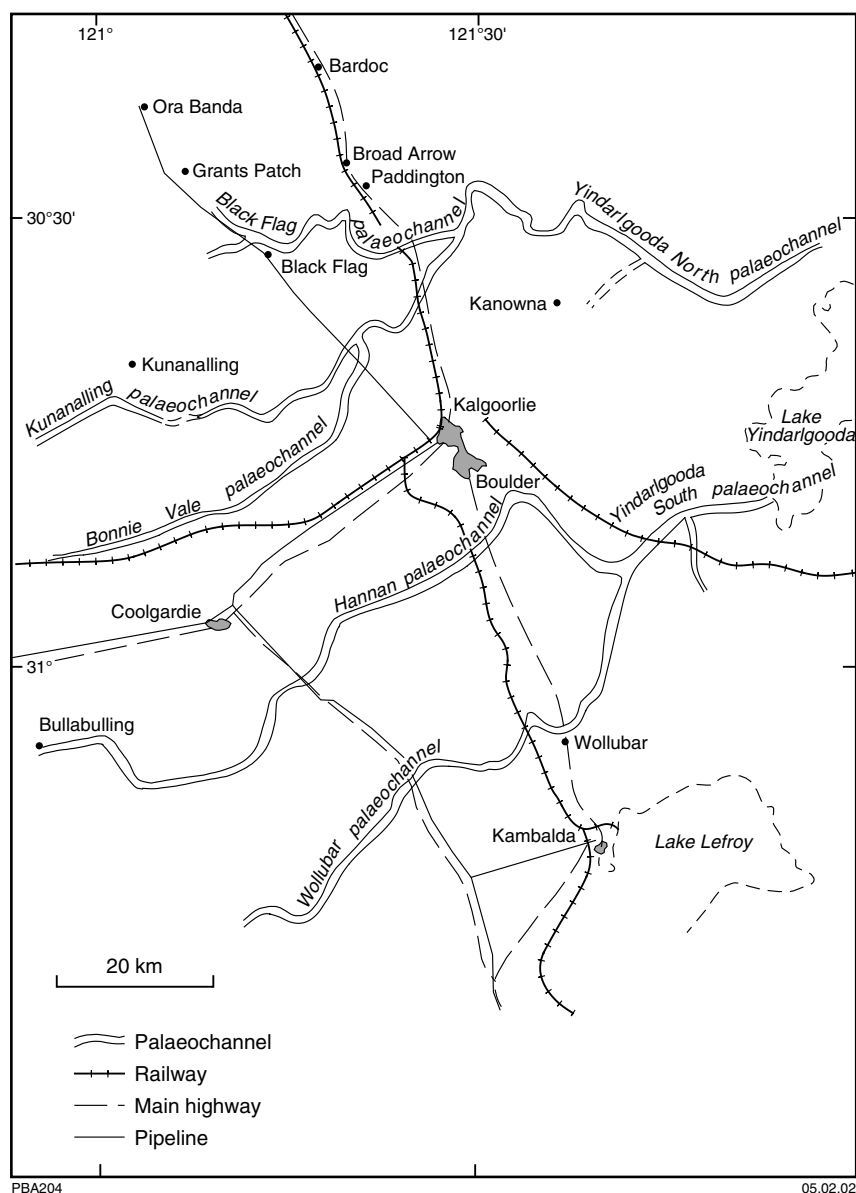


Figure 53. Palaeochannels in the Kalgoorlie region (after Commander et al., 1992)

age of the granite–greenstone rocks in the region is 2720–2630 Ma (Nelson, 1997).

Weathered profiles of granitic, gneissic, and mafic rocks discussed above are likely to contain material suitable for use as industrial clay.

Potential clay areas

The most significant kaolin deposits in Western Australia are found on the Yilgarn Craton. These include Greenbushes, Jubuk, Ockley–Wickepin, Kerrigan, Gabbin, Tambellup, Mullewa, Mount Gibson, Goomalling, Mount Kokeby, and Brookton.

In the Kalgoorlie region, between Kambalda and Broad Arrow, there are a number of palaeochannels

extending in an approximately northeasterly direction. Some of these palaeochannels pass through Black Flag, Yindarlgooda North, Kunanalling, Bonnie Vale, Bullabulling, Yindarlgooda South, and Wollubar (Fig. 53). Hydrogeological drilling in these regions has indicated that most of these palaeochannels contain kaolin horizons. Drillholes indicate that the kaolin horizons are mainly confined to the Perkolilli Shale, which is conformably underlain by the Wollubar Sandstone (Commander et al., 1992). Lithologically, the Perkolilli Shale correlates with the Eocene Pallinup Siltstone of the Plantagenet Group and the lacustrine facies containing clay and siltstone of the lower unnamed unit of the Eocene Eundynie Group (Griffin, 1989).

The kaolin occurrences on the Yilgarn Craton have been discussed in detail in Abeysinghe and Fetherston

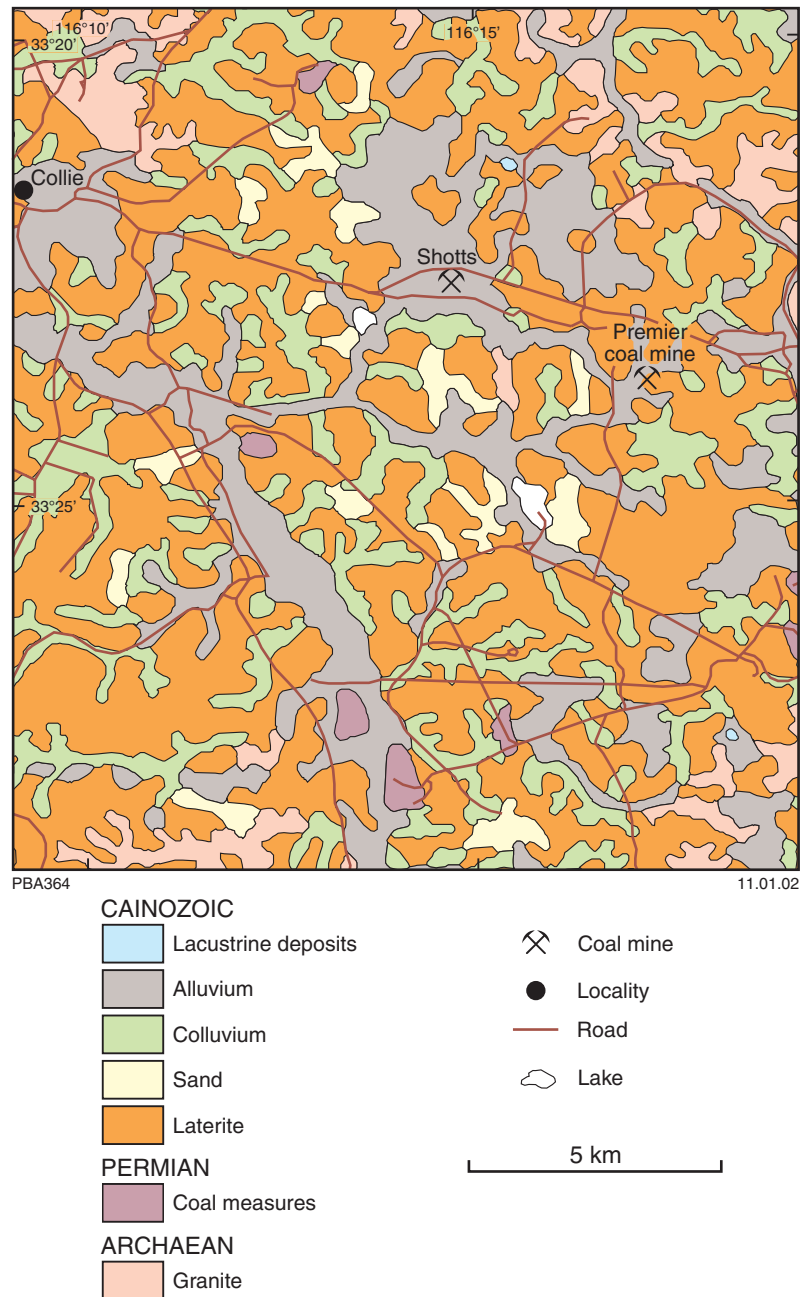


Figure 54. Geology of the area around Shotts (modified from Lowry et al., 1983)

(1999), and hence will be not discussed here. However, some of the above localities, where test results for use of the material as structural clays are available, will be described in the following section, in addition to test results from other localities.

Collie

Collie is located within the Collie Basin, which is an outlier of the southern Perth Basin within the Yilgarn Craton (Fig. 37). The Collie Basin contains two principal grabens: the Cardiff Sub-basin and Premier Sub-basin. The sediments in the Collie Basin consist of weakly folded, westerly dipping Permian strata that include the Collie

Coal Measures (Playford et al., 1975; Wilson, 1990; Hocking, 1994).

High-quality clays have been produced from the Collie Coal Measures, particularly in the vicinity of Shotts (Fig. 54; Lord, 1952). Simpson (1952) stated that clays associated with these coal measures could be used in the manufacture of a wide range of ceramic products. Two chemical analyses of this material (samples 13 and 14) indicated kaolinite compositions with 28.32 and 29.58% Al_2O_3 and 54.31 and 51.95% SiO_2 (Table 69). Six samples from a number of locations in the Collie area burnt to good white at a temperature of 1050°C and to creamy white and light cream at 1350°C (Table 70).

Table 69. Chemical analyses of potential structural clay samples from the Yilgarn Craton

Locality	Collie	Collie	Glen Forrest	Glen Forrest	Mount Kokeby Loc. 16114	Bolgart Lot 7	Goomalling (Stinking Well)	Wagin Loc. 3533
Sample no.	13	14	3	43	7	39	45	8
Percentage								
Al ₂ O ₃	29.58	28.32	37.93	34.18	33.94	39.56	35.96	38.28
SiO ₂	51.95	54.31	47.57	52.19	51.43	43.10	48.07	45.57
TiO ₂	—	0.56	0.22	0.34	0.54	0.44	1.26	0.30
Fe ₂ O ₃	3.40	1.23	0.31	0.64	0.93	0.69	1.00	0.56
FeO	—	—	—	—	—	—	—	0.14
MnO	tr	0.58	—	—	—	—	0.01	—
CaO	tr	—	—	—	—	—	0.13	—
K ₂ O	0.63	0.39	0.58	0.51	0.74	0.64	0.54	0.91
MgO	1.01	0.33	—	—	—	—	0.28	0.14
P ₂ O ₅	—	—	—	—	—	—	0.05	0.14
Na ₂ O	1.09	0.11	0.11	0.10	0.26	0.17	0.06	0.20
NaCl	—	0.69	—	0.15	tr	0.13	0.08	0.27
CO ₂	—	—	—	—	—	—	—	0.02
SO ₃	—	—	—	—	0.24	—	—	0.01
H ₂ O ⁺	11.23	9.61	11.38	12.31	11.32	14.49	12.31	13.11
H ₂ O ⁻	0.54	2.90	0.50	1.02	0.78	1.03	1.02	0.56
Total	99.43	99.03	98.60	101.44	100.18	100.25	100.77	100.21

SOURCE: Bowley (1941)

NOTE: tr: trace

Table 70. Firing tests for structural clay samples from the Yilgarn Craton

Locality	Collie CML 245	Collie CML 245	Collie Loc. 1382	Between Collie and Wellington Mill	Collie–Cardiff Lot 283	Collie CML 245
Sample no.	2	11	26	50	64	73
Plasticity	52	64	24	80	53	14
Air shrinkage (%)	6.6	7.2	3.6	7.5	6.2	5.3
Fired shrinkage (%)						
at 1050°C	0.5	3.2	0.2	3.6	0.7	1.1
at 1150°C	5.1	5.4	0.3	5.5	3.4	3.9
at 1250°C	5.6	7.6	1.4	14.3	6.9	7.7
at 1350°C	9.9	10.0	1.5	16.7	7.2	9.7
Porosity (%)						
at 1050°C	54.5	25.4	22.1	30.6	24.1	34.4
at 1150°C	44.5	20.8	21.5	26.0	20.3	29.5
at 1250°C	45.4	18.1	19.1	9.1	14.1	21.3
at 1350°C	34.1	12.2	18.1	5.1	13.4	18.2
Colour						
at 1050°C	white	white	white	white	white	light pink
at 1150°C	white	white	white	white	white	creamy white
at 1250°C	creamy white	white	creamy white	creamy white	creamy white	creamy white
at 1350°C	creamy white	creamy white	creamy white	creamy white	creamy white	creamy white
Vitrification						
at 1050°C	—	—	—	—	—	—
at 1150°C	—	—	—	—	—	—
at 1250°C	—	incipient	—	incipient	incipient	—
at 1350°C	incipient	—	no vitrification	advanced	—	—

Table 70. (continued)

Locality	Collie Premier coal mine	Glen Forrest (Statham's Pit)	Glen Forrest (Statham's Pit)	Clackline	Clackline adjacent Loc. 19453	Mount Kokeby Loc. 16114
Sample no.	25	3	43	1	10	7
Plasticity	50	28	25	17	22	50
Air shrinkage (%)	8.1	7.1	4.5	5.2	8.2	5.5
Fired shrinkage (%)						
at 1050°C	2.6	5.3	3.0	3.4	5.0	8.6
at 1150°C	3.5	—	3.8	5.4	4.7	9.9
at 1250°C	13.2	—	6.0	6.6	8.5	13.4
at 1350°C	14.4	—	10.0	10.7	15.1	11.8
Porosity (%)						
at 1050°C	32.1	23.1	37.1	27.2	42.7	28.6
at 1150°C	31.3	—	36.7	25.8	41.9	24.7
at 1250°C	13.2	—	29.6	22.3	33.1	17.0
at 1350°C	10.2	—	22.7	13.5	19.7	11.3
Colour						
at 1050°C	white	white	white	white	white	white
at 1150°C	white	—	white	white	white	white
at 1250°C	light cream	—	creamy white	white	white	white
at 1350°C	light cream	—	light cream	white	white	white
Vitrification						
at 1050°C	—	no vitrification	—	—	—	—
at 1150°C	—	—	—	—	—	—
at 1250°C	incipient	—	—	—	—	incipient
at 1350°C	—	—	incipient	incipient	incipient	—

Locality	Mount Kokeby Loc. 16114	Mount Kokeby Loc. 16114	Youraling Loc. 7454	Brookton Loc. 10138	Beverley Loc. 5784	Goomalling Loc. 17248
Sample no.	47	48	49	40	70	12
Plasticity	57	54	50	65	23	30
Air shrinkage (%)	5.3	14.6	9.5	7.9	10.5	4.2
Fired shrinkage (%)						
at 1050°C	2.8	5.0	2.7	6.6	3.9	3.5
at 1150°C	5.6	7.6	8.6	7.0	7.6	3.8
at 1250°C	9.7	15.1	9.7	11.5	7.7	7.2
at 1350°C	11.3	19.0	16.3	15.2	12.3	9.0
Porosity (%)						
at 1050°C	29.1	35.5	31.2	25.5	34.6	38.4
at 1150°C	24.1	31.3	20.6	24.4	24.0	37.3
at 1250°C	15.7	14.7	13.9	15.1	24.0	29.9
at 1350°C	12.2	6.9	6.9	8.3	16.6	25.5
Colour						
at 1050°C	white	white	white	white	creamy white	white
at 1150°C	white	white	white	white	creamy white	white
at 1250°C	white	creamy white	creamy white	creamy white	creamy white	white
at 1350°C	creamy white	cream	cream	creamy white	creamy white	white
Vitrification						
at 1050°C	—	—	—	—	—	—
at 1150°C	—	—	—	incipient	—	—
at 1250°C	incipient	incipient	incipient	—	—	—
at 1350°C	—	—	—	—	incipient	no vitrification

Table 70. (continued)

Locality	Goomalling (Stinking Well)	Goomalling (Stinking Well)	Goomalling (Stinking Well)	Bolgart	Balkuling	Wagin
Sample no.	45	46	53	Lot 7 39	Loc. 11008 37	Loc. 3533 8
Plasticity	59	75	66	73	46	21
Air shrinkage (%)	8.3	8.6	5.0	11.1	7.6	4.2
Fired shrinkage (%)						
at 1050°C	3.9	4.4	1.5	5.4	2.2	2.8
at 1150°C	7.3	7.0	5.5	5.0	3.1	4.5
at 1250°C	14.4	14.1	6.7	10.9	9.1	10.4
at 1350°C	15.9	15.1	9.2	16.8	13.3	16.2
Porosity (%)						
at 1050°C	28.1	24.5	26.0	30.7	37.4	40.3
at 1150°C	20.1	19.0	19.0	31.6	34.1	35.5
at 1250°C	8.7	4.9	15.5	19.1	20.5	17.0
at 1350°C	5.7	3.9	11.9	6.2	11.8	12.6
Colour						
at 1050°C	white	white	white	white	white	white
at 1150°C	white	white	white	white	white	white
at 1250°C	creamy white	cream	creamy white	white	creamy white	white
at 1350°C	creamy white	cream	light grey	light cream	creamy white	white
Vitrification						
at 1050°C	—	—	—	—	—	—
at 1150°C	incipient	incipient	incipient	—	—	—
at 1250°C	—	—	—	incipient	incipient	incipient
at 1350°C	—	advanced	—	—	—	—

Locality	Wagin	Piawanning	Quairading	Manjimup	Cunderdin	Gutha
Sample no.	Loc. 3533 17	Loc. 39 78	Loc. 11008 29	Loc. 48/2034 77	(11 km southeast) 33	Loc. 5523 65
Plasticity	30	47	34	54	22	22
Air shrinkage (%)	3.7	7.3	2.8	11.8	3.8	4.7
Fired shrinkage (%)						
at 1050°C	3.4	3.5	3.1	4.5	4.0	1.7
at 1150°C	4.3	5.1	3.4	4.7	4.7	4.4
at 1250°C	9.7	13.1	12.1	17.4	9.3	6.4
at 1350°C	14.7	13.7	13.2	17.4	12.8	7.8
Porosity (%)						
at 1050°C	37.1	30.1	32.8	38.9	48.1	59.2
at 1150°C	34.6	24.1	31.3	37.6	47.2	32.2
at 1250°C	24.0	12.9	15.6	11.9	35.2	27.2
at 1350°C	14.5	7.9	11.5	10.1	28.2	24.5
Colour						
at 1050°C	white	white	white	creamy white	white	white
at 1150°C	white	creamy white	white	creamy white	white	white
at 1250°C	white	creamy white	creamy white	buff	white	white
at 1350°C	white	creamy white	creamy white	buff	white	white
Vitrification						
at 1050°C	—	—	—	—	—	—
at 1150°C	—	incipient	—	—	—	—
at 1250°C	incipient	—	incipient	incipient	no vitrification	—
at 1350°C	—	—	—	—	—	no vitrification

Table 70. (continued)

Locality	Meckering Loc. 22233	Capercup Loc. 3198	Duranillin MC 10	Kanowna ML 47	Kanowna ^(a) PA 506	Kanowna PA 506
Sample no.	6	9	51	60	68	76
Plasticity	78	75	98	9	8	3
Air shrinkage (%)	8.3	9.2	9.6	2.7	0.8	2.6
Fired shrinkage (%)						
at 1050°C	2.2	2.7	3.9	4.0	0.5	0.0
at 1150°C	3.6	4.7	6.6	3.3	2.2	8.1
at 1250°C	12.0	11.7	11.5	10.1	9.6	13.6
at 1350°C	13.6	11.8	14.9	14.7	13.3	11.3
Porosity (%)						
at 1050°C	31.6	28.6	30.4	34.8	33.7	26.6
at 1150°C	28.8	25.2	25.1	26.8	25.4	12.3
at 1250°C	14.2	12.0	13.9	13.2	14.9	1.1
at 1350°C	10.1	9.8	11.4	1.0	4.1	0.7
Colour						
at 1050°C	white	white	white	white	white	white
at 1150°C	white	white	white	white	white	creamy white
at 1250°C	creamy white	white	creamy white	creamy white	creamy white	white
at 1350°C	cream	creamy white	cream	creamy white	light green	white
Vitrification						
at 1050°C	–	–	–	–	–	–
at 1150°C	–	–	–	–	–	incipient
at 1250°C	incipient	–	incipient	incipient	incipient	advanced
at 1350°C	–	incipient	–	advanced	advanced	–

Locality	Kanowna PA 506	Kanowna MC 6	Kanowna	Jimperding (Yinniding Creek)	Mokine Loc. 41485
Sample no.	4	30	59	54	14
Plasticity	20	40	4	28	26
Air shrinkage (%)	2.6	3.6	0.7	4.7	6.2
Fired shrinkage (%)					
at 1050°C	0.9	0.1	0.2	4.9	4.1
at 1150°C	2.2	0.3	5.6	5.2	4.3
at 1250°C	5.1	5.1	16.5	7.3	7.0
at 1350°C	6.0	–	16.7	12.7	12.3
Porosity (%)					
at 1050°C	29.72	31.2	–	38.9	41.4
at 1150°C	27.32	31.5	21.1	38.3	40.5
at 1250°C	20.52	12.4	0.8	33.5	34.0
at 1350°C	14.75	–	0.5	21.9	24.0
Colour					
at 1050°C	white	white	white	white	white
at 1150°C	white	white	white	white	white
at 1250°C	white	white	grey white	white	white
at 1350°C	creamy white	–	creamy white	white	white
Vitrification					
at 1050°C	–	–	–	–	–
at 1150°C	–	–	incipient (1200°C)	–	–
at 1250°C	incipient	–	advanced	–	–
at 1350°C	–	incipient	–	incipient	incipient

Table 70. (continued)

Locality	Capercup (11 km south)	Jimperding (Yinniding Creek)	Wilga Coal PA 263	Burabadji adjoining Loc. 7807	Dwellingup Loc. 1121
Sample no.	72	13	23	24	52
Plasticity	92	—	54	12	48
Air shrinkage (%)	11.2	3.9	7.4	3.9	9.8
Fired shrinkage (%)					
at 1050°C	3.5	—	0.4	3.9	3.7
at 1150°C	4.3	5.0	3.2	6.0	4.3
at 1250°C	10.1	—	6.9	11.9	13.3
at 1350°C	10.7	—	8.4	15.6	13.6
Porosity (%)					
at 1050°C	24.9	—	30.8	39.0	37.9
at 1150°C	22.5	—	29.3	34.2	34.5
at 1250°C	14.5	—	21.6	21.0	18.3
at 1350°C	11.7	—	16.6	12.1	17.8
Colour					
at 1050°C	white	—	white	white	white
at 1150°C	creamy white	white	white	white	white
at 1250°C	creamy white	—	white	white	creamy white
at 1350°C	creamy white	—	white	white spotted	creamy white
Vitrification					
at 1050°C	incipient	—	—	—	—
at 1150°C	—	—	—	—	—
at 1250°C	—	—	—	incipient	incipient
at 1350°C	—	—	no vitrification	—	—

SOURCE: Bowley (1941)

NOTE: (a) Contains alunite

Kaolinitic clay, with some fine-grained quartz and illite, is also found at the Premier coal mine approximately 4 km southeast of Shotts. During 1994–97, 154 074 t of construction industry-grade kaolinitic clay was produced as a byproduct from this mine for use in the cement industry.

Glen Forrest – Red Hill

In a number of localities east of the Darling Fault, non-plastic clay has been extracted from the pallid zone formed during lateritic weathering of granitic rocks. These areas include Glen Forrest and Red Hill (Fig. 38). At present there is no reported production from Glen Forrest, but some localities are currently being explored for clay in the Red Hill region. Tables 69 and 70 show chemical analyses and firing test results for two samples of kaolinitic clay from the Glen Forrest area.

Gidgegannup

The Gidgegannup area is an important region for non-plastic clay for use in the brickmaking industry in Perth. Forty-four percent of the 38.9 Mt of non-plastic clay identified in the Perth region is from the Gidgegannup area. The clay is present in the kaolinitic horizons of the lateritic material associated with granitic and gneissic rocks in the area (Fig. 55). At present, clay quarries are operating within 15 km of Gidgegannup.

Toodyay–Clackline

Weathered quartz–mica schists and gneisses in the Toodyay and Clackline areas have been found to contain clay suitable for use as structural clay (Figs 56–59). The non-plastic clay from the Toodyay area is a significant source for the manufacturing industries in Perth. At present, clay is mined from a number of quarries around Clackline, Jimperding Hill, and Gabidine Hill, southwest of Toodyay. Approximately 27% of the 38.9 Mt of non-plastic clay identified in the Perth region is found in the Toodyay area.

Clackline, located about 80 km east-northeast of Perth, has a reputation for one of the best deposits of refractory clay in Western Australia (Fig. 56). The clay is extracted from kaolinized mica schist, sillimanite schist, garnet schist, pegmatite, and dolerite dykes. Kaolinization has extended at least 15 m below the surface. The schist belt has a strike length of about 1 km and is bounded by quartzite to the east, intruded by Archaean hornblende granite to the south and west, and overlain by laterite to the north (Abeyasinghe and Fetherston, 1999). The clay is white and grit-free, and an analysis of the kaolinized sillimanite schist indicates 26.2% Al₂O₃, 63.8% SiO₂, 0.6% Fe₂O₃, 0.22% MgO, 0.09% Na₂O, 1.76% K₂O, and 0.58% TiO₂ (Lipple, 1976; Geological Survey of Western Australia, 1980). Two samples from Clackline burnt to a good white colour at 1350°C (Table 70).

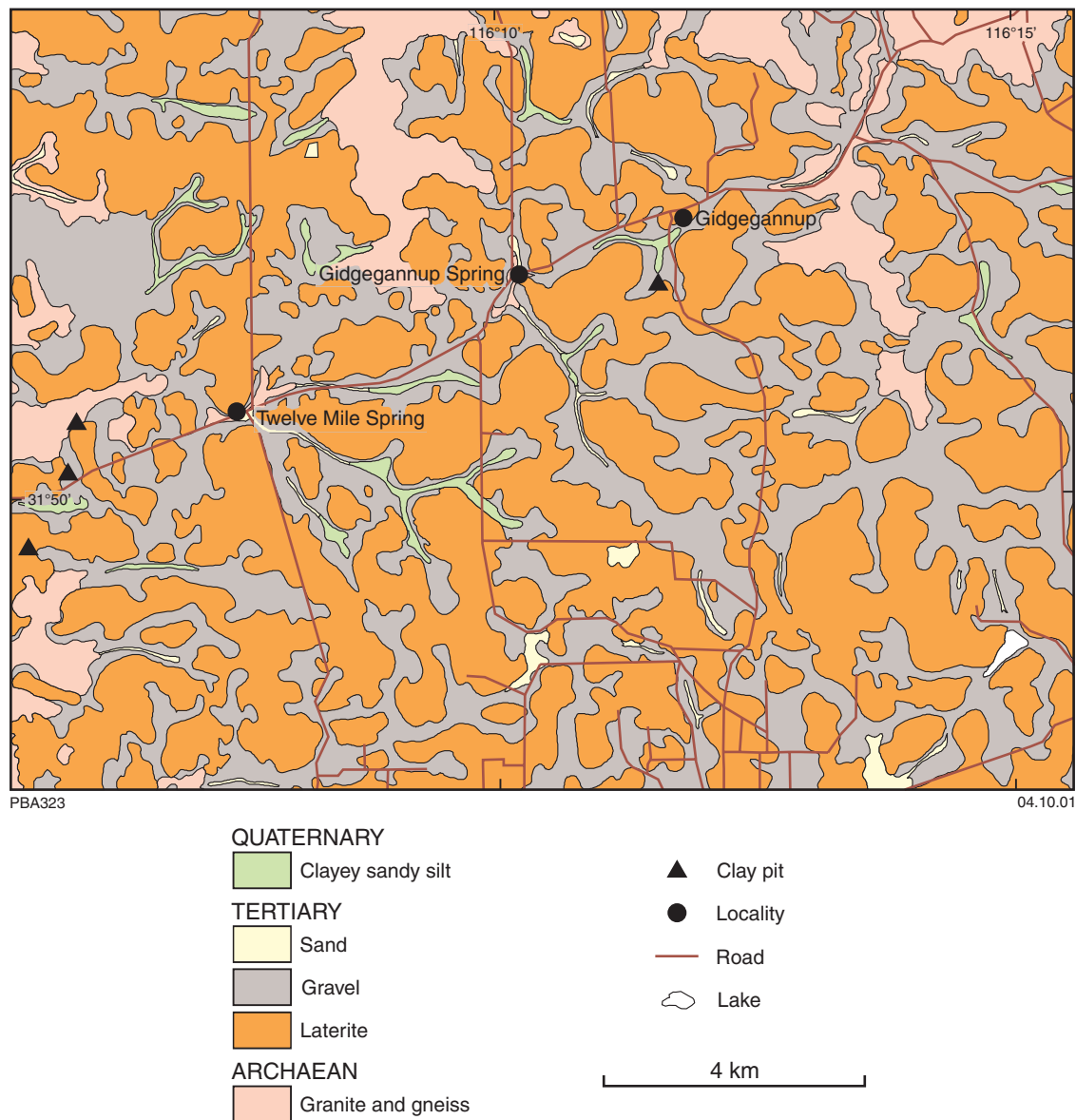


Figure 55. Geology of the area around Gidgegannup (modified from Smurthwaite, 1986)

Mount Kokeby – Brookton

In the area around Mount Kokeby, transported deposits of kaolinitic clay are present in palaeodrainages and lacustrine environments. The clay deposits in this area are an important source for semi-plastic clay for the brick and tile industry in Perth.

A considerable quantity of semi-ball clay has been obtained from Locations 16114 and 7454 about 13 km southwest of the Mount Kokeby townsite (Fig. 60). The clay in this area is interbedded with shale and sandstone. The thickness of the best clay horizon is about 5 m and it is located 3–7 m below the surface. The overburden consists of sand, laterite, and gritty clay. Chemical analysis of a sample from Location 16114 gave 33.94% Al_2O_3 and 51.43% SiO_2 , indicating that the material is good quality kaolin (Table 69). This sample

(sample no. 7) burnt to white at 1350°C, and two other samples (sample nos 47 and 48) from the same location burnt to creamy white and cream at temperatures above 1250°C (Bowley, 1941; Simpson, 1952). A sample from Location 7454 (Youraling) also burnt to cream at 1350°C (Table 70).

A sample from Location 10138 (Fig. 60) in the Brookton area burnt to a good white at temperatures up to 1150°C (Table 70). It contained 98% clay of fairly high plasticity, and the material was thought to be suitable for use as structural clay. The Brookton area is known for high-quality kaolin deposits, which are discussed in Abeyasinghe and Fetherston (1999).

Kaolin with minor quartz (approximately 2%) and minor iron oxide is known to be present in the Dale River area (Fig. 60; Lipple, 1976).

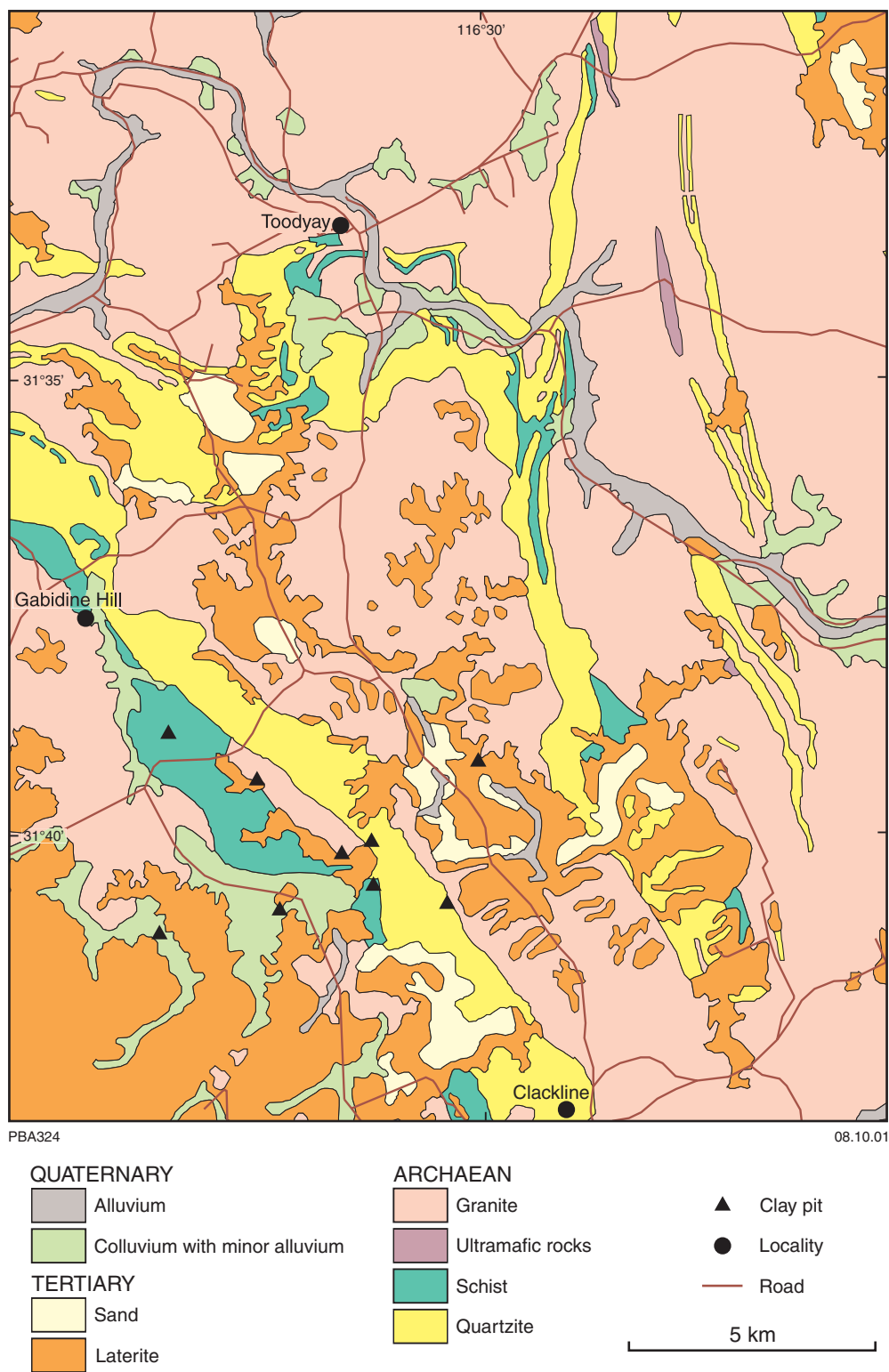


Figure 56. Geology of the area around Toodyay (modified from Low et al., 1978)

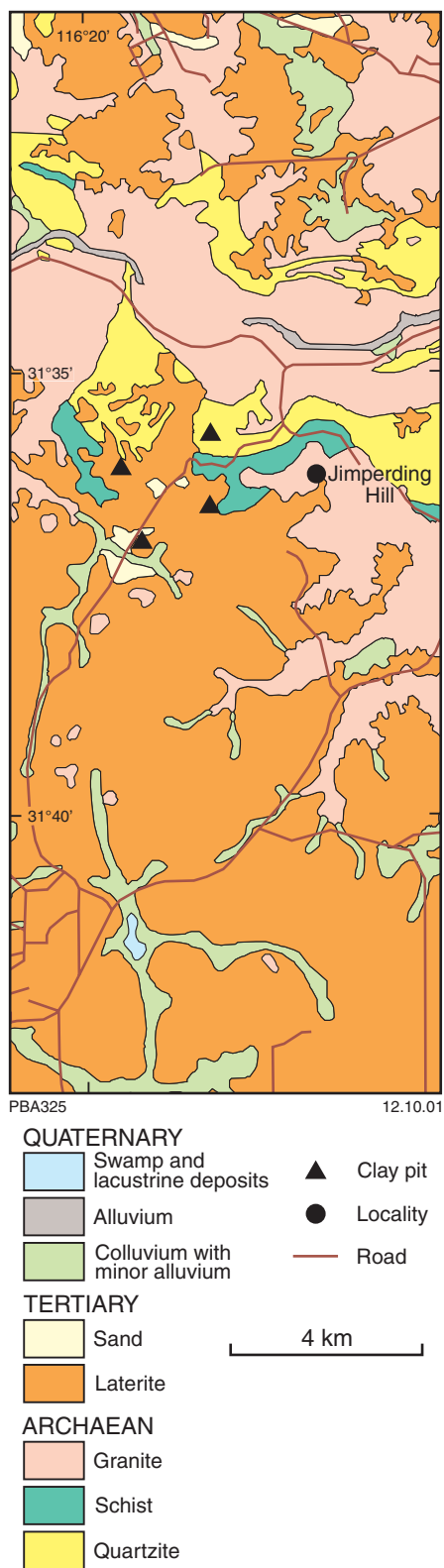


Figure 57. Geology of the area around Jimperding Hill (modified from Low et al., 1978)

Beverley

A clay sample (sample no. 70) from Location 5784 at Beverley (east of the town) burnt to creamy white at a temperature of 1350°C (Table 70). The sample contained 96% clay and had low plasticity (Bowley, 1941; Simpson, 1952).

Bolgart–Goomalling

A number of claypans between Goomalling and Bolgart are potential sources of ball and semi-plastic ceramic clay (Wilde and Low, 1978). The clay deposits in the Goomalling region have been deposited in a lacustrine environment associated with former tributaries of the Matlock River (Lipple, 1977). At present, clay deposits in the Bolgart area are an important source of semi-plastic clay for industries in Perth. Test results for one sample (sample no. 12) from Location 17248, three (sample nos 45, 46, and 53) from Stinking Well in the Goomalling area (Fig. 61), and one (sample no. 39) from Lot 7 in the Bolgart area (Fig. 62) are given in Table 70. All the samples contained 85–95% clay and burnt to a good white colour at 1150°C. The chemical analysis of sample no. 45 from Stinking Well in the Goomalling area contained 35.96% Al_2O_3 and 48.07% SiO_2 , indicating that the material has the composition of high-quality kaolin (Table 69). The sample from Bolgart contained 39.56% Al_2O_3 and 43.1% SiO_2 and also indicated a high-quality kaolin composition. This clay bed is approximately 15 m from the surface (Bowley, 1941; Simpson, 1952).

Balkuling

Simpson (1952) described completely kaolinized dykes, as well as kaolinized granite, at Location 11008 near Balkuling (Fig. 63). The dyke-derived clay burns to creamy white at a temperature of 1350°C. The granite-derived clay is also said to be highly refractory. Test results for a sample (sample no. 37) from a dyke at this location are given in Table 70. The sample contained 70–80% clay and fine grit (Bowley, 1941).

Boyup Brook

The predominant rock types in the Boyup Brook area are granite, gneiss, and migmatite (Fig. 64). The surface material of most of these formations is weathered, and has resulted in clays of variable quality. A sample (GSWA 117823) of white kaolinitic clay with patches of red lateritic material, from a road cutting approximately 2 km northeast of Boyup Brook, contained more than 50% kaolinite (Table 71). The sample contained 22.5% Al_2O_3 and 64.3% SiO_2 , which confirms its kaolinitic composition (Table 72). The material yielded a strong bar at 1220°C and appears to be suitable for brickmaking (Table 73). Clay sample GSWA 117824, collected from a farm dam near Dinninup, was found to be too sandy and produced a soft bar when fired (Fig. 64; Tables 71 and 73).

Corrigin

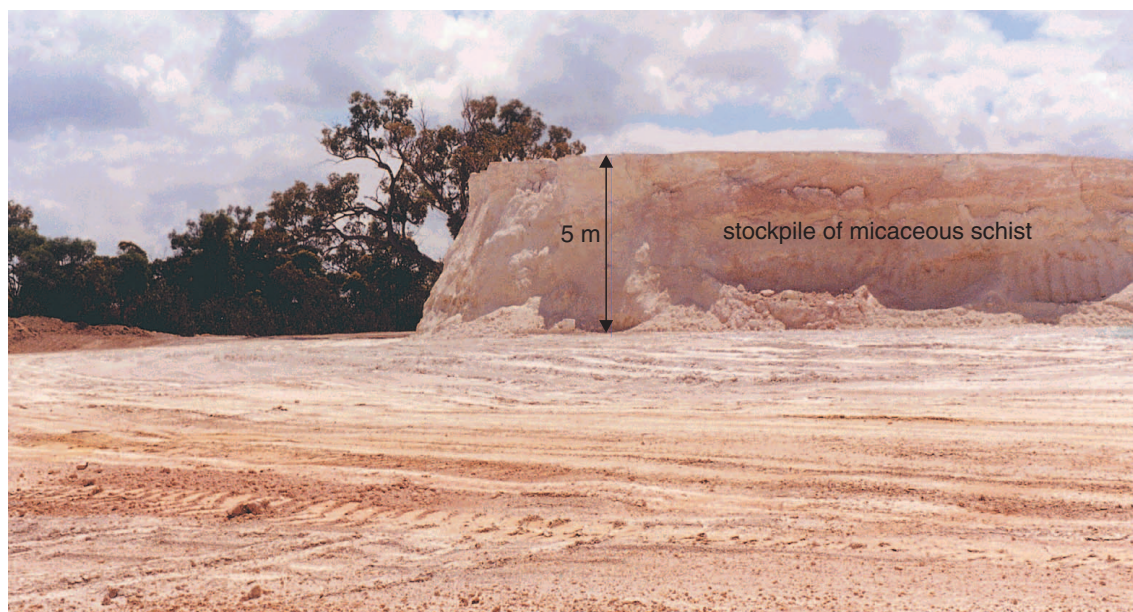
Clay from the Corrigin area has been used to manufacture bricks, but the exact locations of this material are unknown



PBA354

20.12.01

Figure 58. Micaceous schist in the Wandel Park quarry near Toodyay (Lat. 31°35'S, Long. 116°01'E)



PBA355

20.12.01

Figure 59. Stockpiles of micaceous schist in the Wandel Park quarry near Toodyay (Lat. 31°35', Long. 116°00'E)

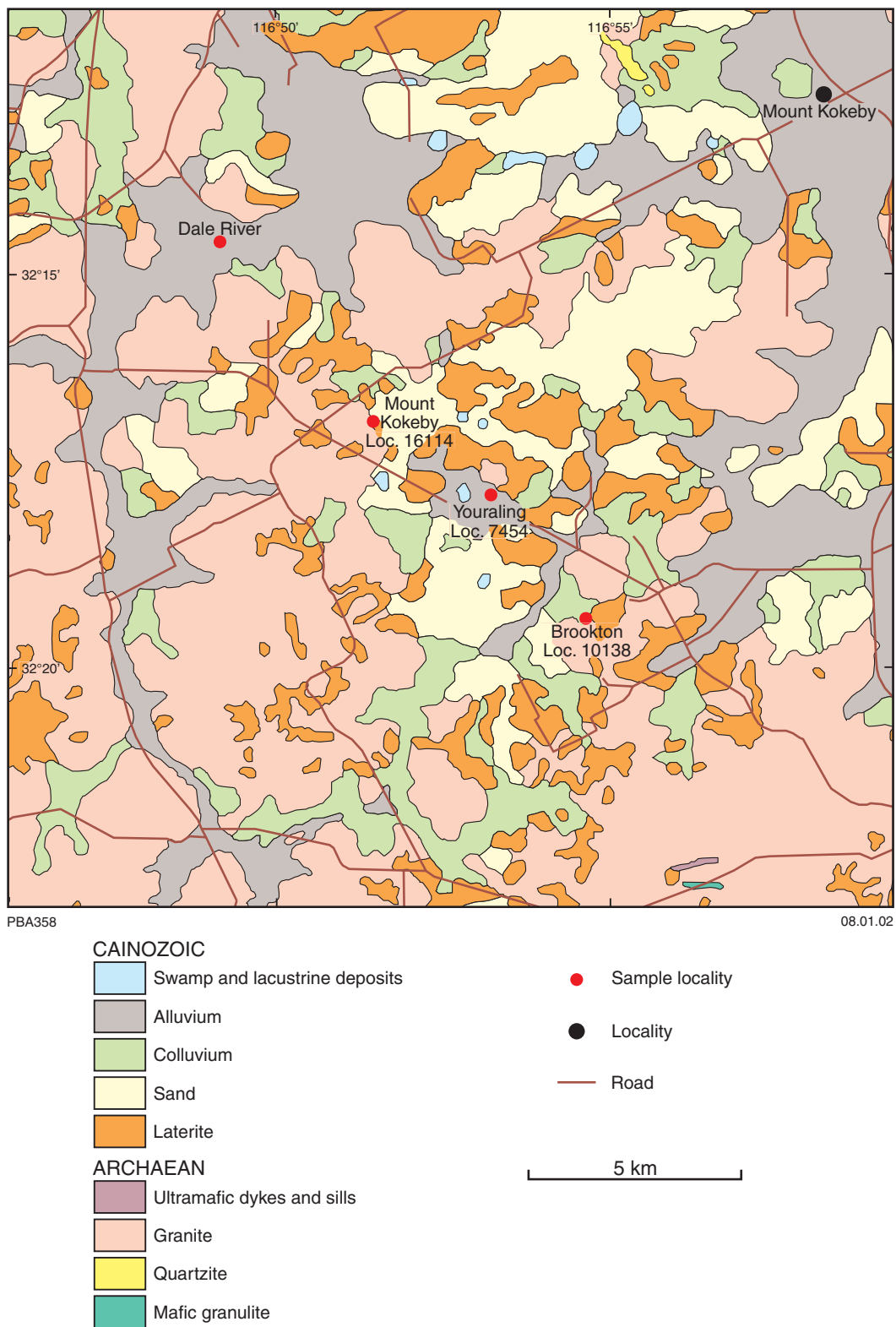


Figure 60. Geology of the area around Mount Kokeby (modified from Low et al., 1980)

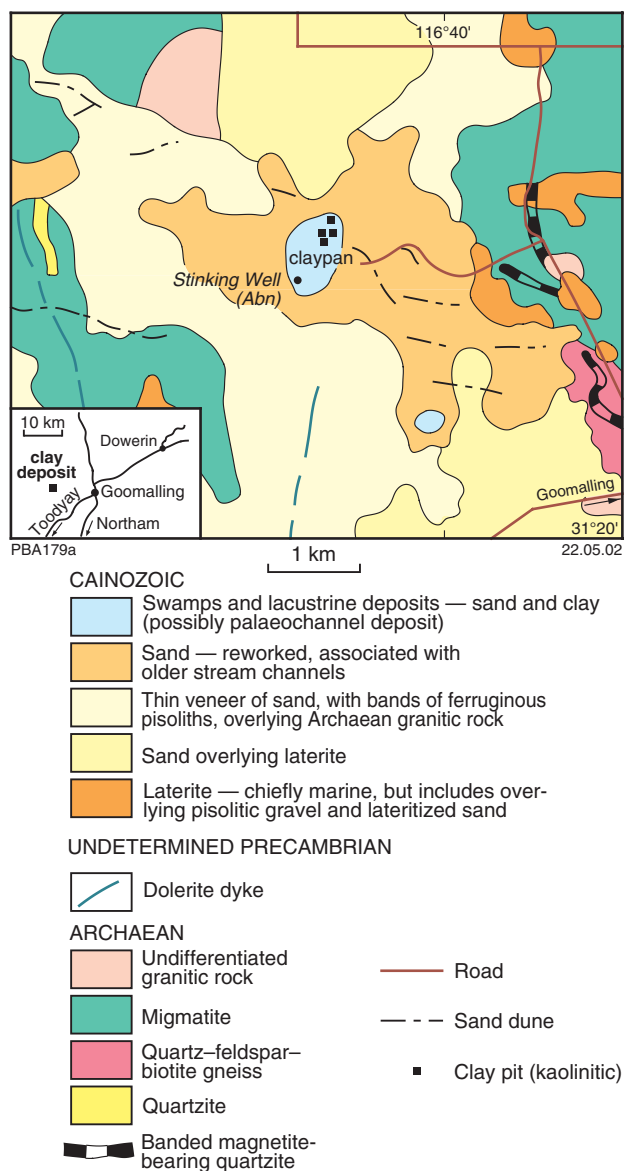


Figure 61. Geology of the area around the Goomalling kaolin deposit (after Abeysinghe and Fetherston, 1999)

(Chin, 1986). The area contains poorly exposed Archaean granite and adamellite that are deformed and recrystallized (Fig. 65). Fresh granite and adamellite outcrop in a number of localities, and in other areas granite is variably weathered to depths in excess of 30 m. Many low-level ridges in the area are covered by a remnant duricrust of massive and nodular, orange, iron-rich laterite and silcrete, which grades at depth into a variably coloured pallid kaolinized zone, and then into saprolite and weathered bedrock. The Jubuk kaolin deposit, located 20 km southwest of Corrigin, is a large deposit of high-quality kaolin and has been discussed in Abeysinghe and Fetherston (1999).

Wagin-Katanning

Clay deposits have been worked in the Wagin and Katanning areas for the manufacture of bricks. The clay

consists mainly of kaolin from a deeply weathered and leached zone of the laterite profile developed over easterly trending dolerite dykes (Chin and Brakel, 1986). Simpson (1952) referred to high-quality clay at Location 3533, about 5 km northwest of Wagin (Fig. 66). A sample from this location contained 38.28% Al_2O_3 and 45.57% SiO_2 , thus indicating it is of kaolinitic composition. This sample and another from the same location burnt to good white at a temperature of 1350°C (Tables 69–70).

Piawanning

A sample of construction industry clay from Location 39 in the Piawanning area burnt to creamy white at a temperature of 1350°C (Table 70). The area is well known for kaolin, which occurs at a location 2 km southwest of Piawanning (Fig. 37) and overlies weathered porphyritic granite. In 1943, there was recorded production of 406 t of kaolin from this location that was used as filler. In 1985–89, 4294 t of fireclay was produced from M 70/240.

Quairading

White kaolinitic clay derived from weathered granitic gneiss is known to be present at Quairading (Fig. 37). A sample from Location 11008 in the area contained 55% clay material and 38% grit less than 90 mesh, and burnt to pure white at 1150°C (Table 70). At 1350°C, it was still heat resistant, but was shrinking rapidly. Vanadium stains appeared after wetting the burnt briquettes (Simpson, 1952).

Manjimup

In the Manjimup area, clays derived from weathered Archaean gneissic and schistose rocks have been used for the manufacture of bricks (Wilde and Walker, 1984). A sample from Location 48/2034 burnt to a creamy white at 1150°C, but above this temperature the material shrank considerably and produced a buff colour (Table 70). A sample (GSWA 117822; Fig. 67) of wet, brown, semi-plastic clay collected from a farm dam about 2 km east along Middlesex Road (a few kilometres south of Manjimup along the South Western Highway) was tested for its mineralogy, chemical composition, and firing strengths (Tables 71–73). It contained a major amount of kaolinite, and contained 27.5% Al_2O_3 and 45.6% SiO_2 . The firing test results indicated that the material is suitable for use as a filler in the manufacture of bricks.

Narrogin-Boundain

Clay from pits around Narrogin is used for the manufacture of bricks. The clay is extracted from a deeply weathered lateritic zone overlying large Proterozoic mafic dykes. During the current project, the surrounding area was investigated to see whether any alternative clay resources are available. Test results of a sample (GSWA 117826; Fig. 68) collected from a location 10.5 km east of Narrogin, near Boundain, along the road parallel to the railway line, are given in Tables 71 and 73. The sample consisted of gritty, whitish-brown clay with quartz, and was collected from diggings at a lake dam. The

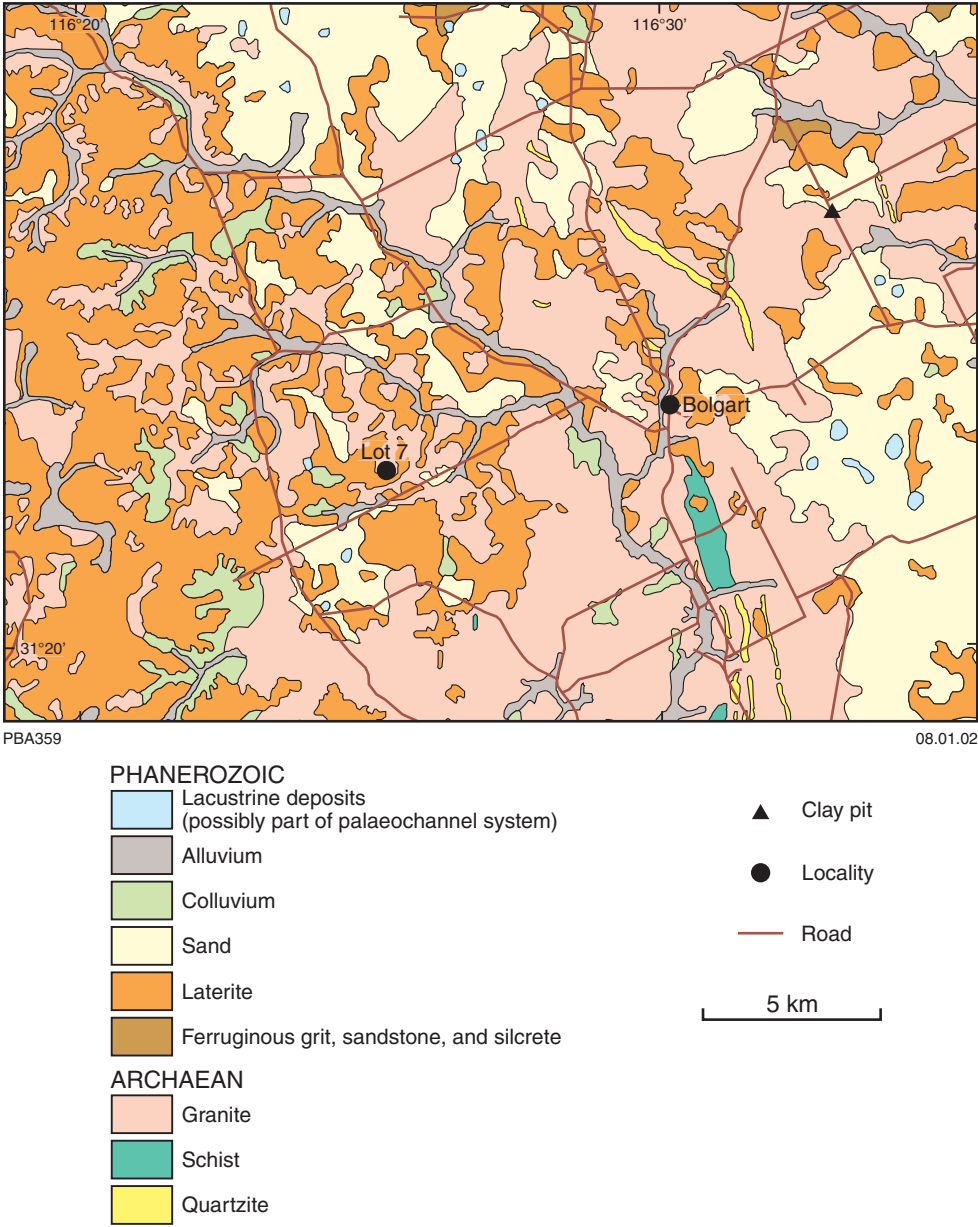


Figure 62. Geology of the area around Bolgart (modified from Low et al., 1978)

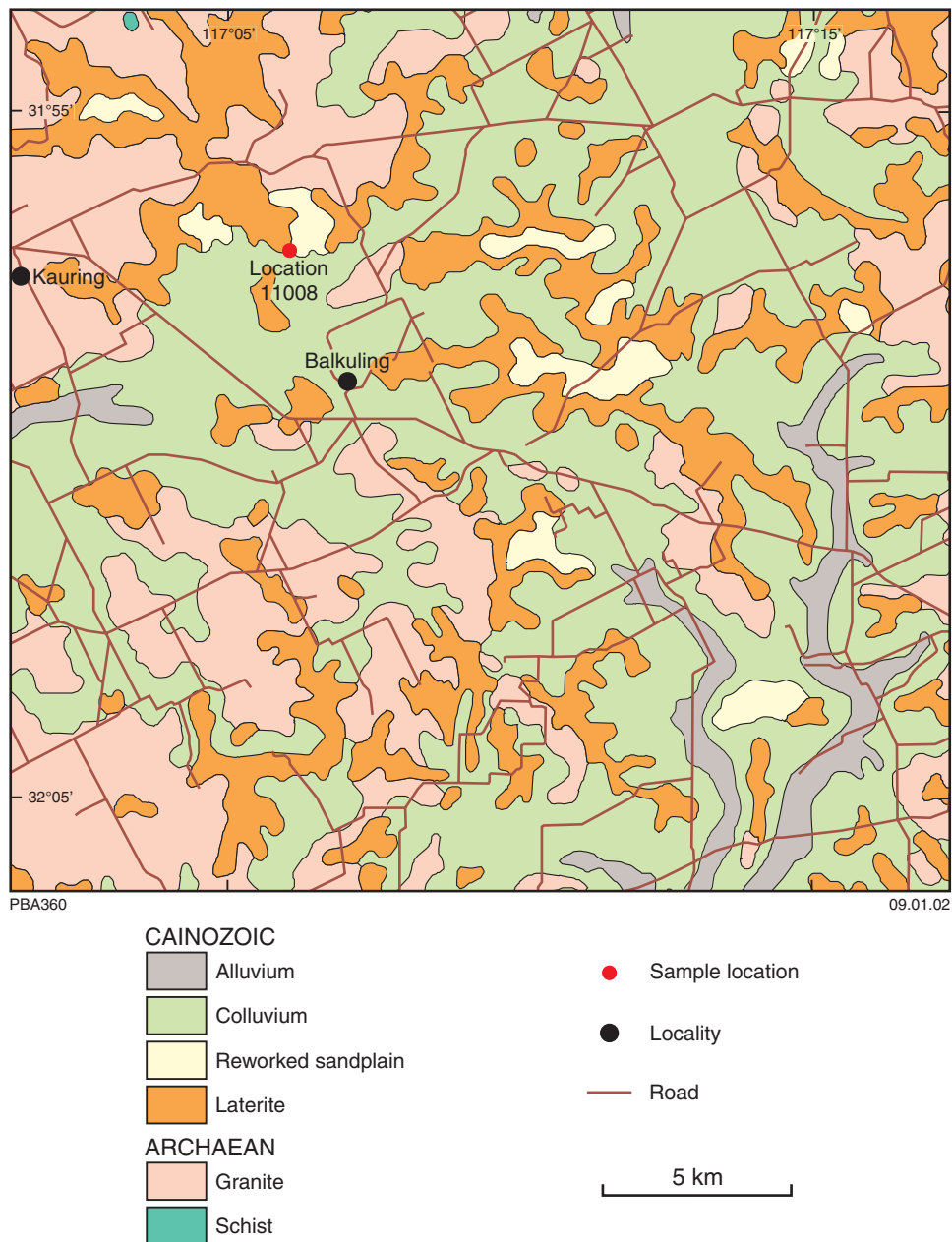


Figure 63. Geology of the area around Balkuling (modified from Muhling and Thom, 1985a,b)

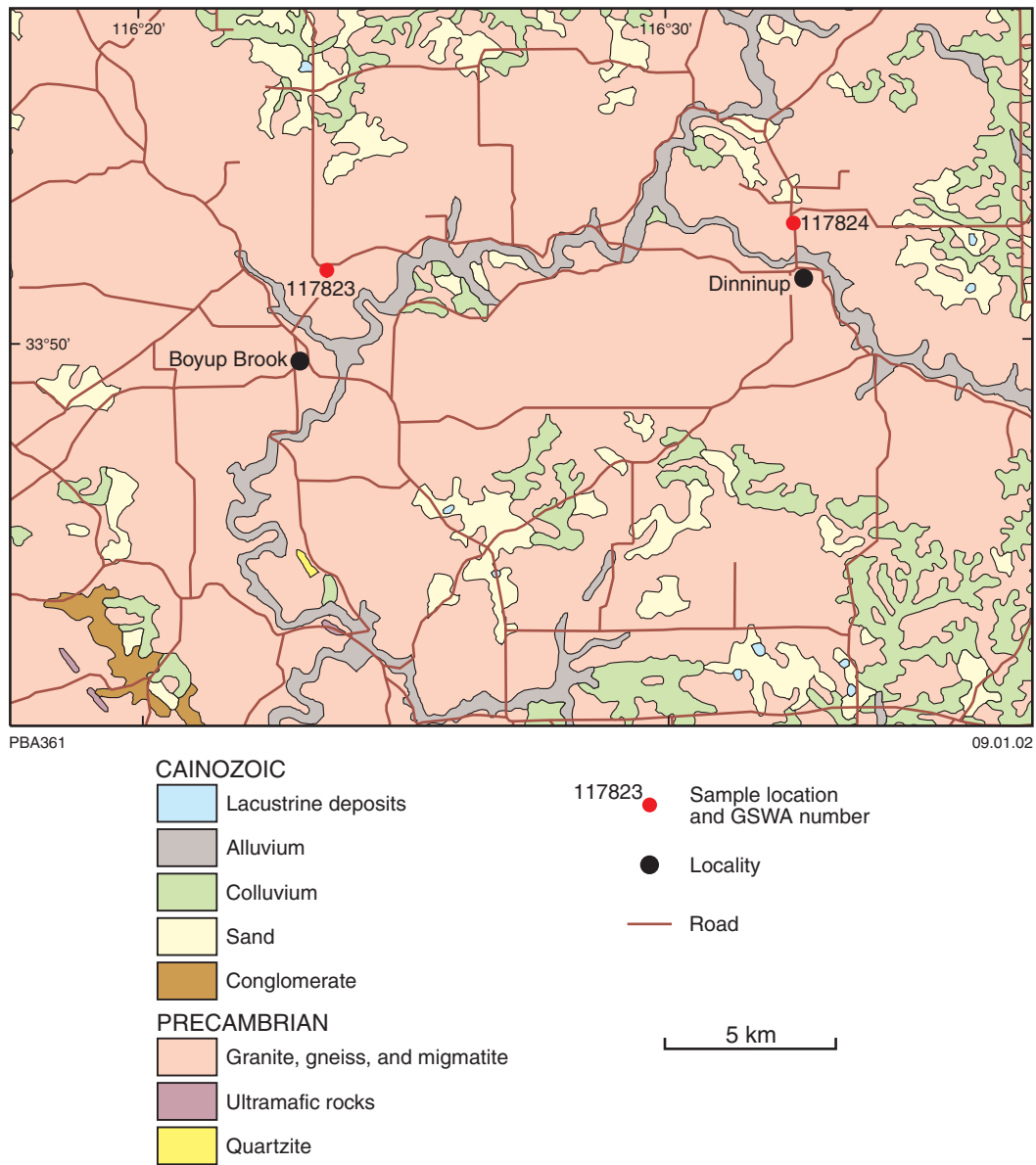


Figure 64. Regional geology of the area around Boyup Brook and Dinninup (modified from Lowry et al., 1983)

Table 71. Minerology of structural clay samples from the Yilgarn Craton

<i>Locality GSWA no.</i>	<i>Newlands 117820</i>	<i>Greenbushes 117821</i>	<i>Manjimup 117822</i>	<i>Boyup Brook 117823</i>	<i>Dinninup 117824</i>	<i>Boundain 117826</i>
Kaolinite	minor	major	major	dominant	minor	minor
Halloysite	—	—	—	—	—	—
Smectite	—	?minor	—	—	—	—
Mica/illite	minor	—	—	?minor	minor	minor
Vermiculite	?minor	—	—	—	—	—
Attapulgite	—	—	—	—	—	—
Talc	—	—	—	—	—	—
Quartz	dominant	dominant	dominant	major	dominant	dominant
K-feldspar	major	minor	?minor	—	major	major
Na-feldspar	—	—	—	—	—	—
Amphibole	—	—	—	—	—	—
Calcite	—	—	—	—	—	—
Dolomite/ankerite	—	—	—	—	—	—
Hematite	—	minor	—	minor	minor	—
Anatase	—	—	—	—	—	?minor
Goethite	—	?minor	minor	—	—	—
Gibbsite	minor	—	minor	—	—	—
Halite	—	—	—	—	—	—
Ilmenite	—	minor	—	—	—	—
Interstratified clay	—	—	—	—	—	—

<i>Locality GSWA no.</i>	<i>Highbury 117827</i>	<i>Tenterden 117829</i>	<i>Jerramungup 117849</i>	<i>Fitzgerald River 117850</i>	<i>West River 117851</i>	<i>Ravensthorpe 117852</i>
Kaolinite	major	major	major	subdominant	dominant	minor
Halloysite	—	—	—	—	—	—
Smectite	—	—	—	—	—	—
Mica/illite	minor	major	minor	—	—	minor
Vermiculite	—	—	—	—	—	?minor
Attapulgite	—	—	—	—	—	—
Talc	—	—	—	—	—	minor
Quartz	dominant	major	dominant	dominant	subdominant	dominant
K-feldspar	—	major	major	minor	minor	—
Na-feldspar	—	?minor	?minor	—	—	major
Amphibole	—	—	—	—	—	minor
Calcite	?minor	—	?minor	—	—	—
Dolomite/ankerite	—	—	—	—	—	—
Hematite	—	—	—	—	—	—
Anatase	—	—	—	—	—	—
Goethite	minor	—	—	—	?minor	?minor
Gibbsite	—	—	—	—	—	—
Halite	—	—	—	—	—	—
Ilmenite	—	—	—	—	—	—
Interstratified clay	—	—	—	—	—	—

Table 71. (continued)

<i>Locality GSWA no.</i>	<i>Salmon Gums 117867</i>	<i>Kumarl 117868</i>	<i>Lake Cowan 117869</i>	<i>Higginsville 117870</i>	<i>Widgiemooltha 117871</i>	<i>Mandilla 117872</i>
Kaolinite	major	?minor	minor	minor	minor	major
Halloysite	?subdominant	?subdominant	—	—	—	—
Smectite	—	—	major	?minor	—	—
Mica/illite	—	—	—	—	—	?minor
Vermiculite	—	—	—	—	subdominant	major
Attapulgitite	—	—	—	—	—	—
Talc	—	—	?minor	—	—	—
Quartz	subdominant	dominant	major	major	—	?minor
K-feldspar	?minor	?minor	?minor	minor	minor	—
Na-feldspar	—	—	major	minor	major	major
Amphibole	—	—	major	minor	minor	minor
Calcite	—	—	—	major	—	major
Dolomite/ankerite	—	—	major	—	major	—
Hematite	?minor	?minor	—	major	—	—
Anatase	?minor	—	—	—	—	—
Goethite	—	—	—	—	—	—
Gibbsite	?minor	—	—	—	—	—
Halite	—	—	—	—	—	—
Ilmenite	—	—	—	—	—	—
Interstratified clay	—	minor	—	—	—	—

<i>Locality GSWA no.</i>	<i>Kambalda 117873</i>	<i>Feysville 117874</i>	<i>Feysville 117875</i>	<i>Kalgoorlie 117876</i>	<i>Paddington 117877</i>	<i>Mount Veters 117878</i>
Kaolinite	minor	dominant	—	major	dominant	dominant
Halloysite	—	—	—	—	—	—
Smectite	?minor	major	—	?minor	—	—
Mica/illite	—	minor	—	minor	minor	—
Vermiculite	?minor	—	—	—	?minor	—
Attapulgitite	?minor	—	—	—	—	—
Talc	?minor	?minor	subdominant	—	—	—
Quartz	subdominant	major	minor	dominant	major	major
K-feldspar	minor	—	—	—	?minor	—
Na-feldspar	major	—	—	minor	—	—
Amphibole	major	—	—	—	—	—
Calcite	major	—	—	minor	—	—
Dolomite/ankerite	—	—	—	—	—	—
Hematite	?minor	—	—	?minor	—	?minor
Anatase	—	—	—	—	—	—
Goethite	—	minor	—	—	?minor	major
Gibbsite	—	—	—	—	—	—
Halite	—	—	—	—	minor	—
Ilmenite	—	—	—	—	—	—
Interstratified clay	—	—	subdominant	—	—	—

Table 71. (continued)

Locality GSWA no.	Menzies 117879	Bullabulling 117880	Bullfinch 117881	Warralakin 117882	Kununoppin 117884	Yelbeni 117885
Kaolinite	subdominant	dominant	major	—	minor	major
Halloysite	—	—	—	major	—	—
Smectite	major	?minor	—	—	—	—
Mica/illite	minor	minor	?minor	—	—	—
Vermiculite	—	—	—	—	—	—
Attapulgite	—	—	—	—	—	—
Talc	—	—	—	—	—	—
Quartz	major	major	dominant	dominant	dominant	dominant
K-feldspar	—	—	major	major	major	?minor
Na-feldspar	—	—	minor	minor	minor	—
Amphibole	—	—	—	—	—	—
Calcite	—	—	—	—	—	—
Dolomite/ankerite	—	—	—	—	—	—
Hematite	—	—	?minor	—	—	—
Anatase	—	—	—	—	—	—
Goethite	—	?minor	—	—	—	—
Gibbsite	—	—	—	—	—	—
Halite	—	—	—	—	—	—
Ilmenite	—	—	—	—	—	—
Interstratified clay	major	—	—	—	—	—

NOTE: Dominant: >50%; subdominant: 40–50%; major: 10–40%; minor: 2–0%

material produced a soft bar at temperatures greater than 1220°C and is unsuitable for use in brick manufacturing.

Cunderdin

Simpson (1952) recorded the occurrence of highly refractory white clay at Cunderdin (Fig. 37). A clay sample from this location contained 67% clay and 22% grit less than 90 mesh. It burnt to a pure white mass at 1050–1350°C, but showed no signs of vitrification at these temperatures (Table 70).

Gutha

Simpson (1952) recorded that a sample of clay from Gutha containing 70% clay and 27% grit less than 90 mesh was found to be a good fireclay, and burnt to a good white at 1350°C, with no sign of vitrification at this temperature (Fig. 42; Table 70).

Chandler

Lipple (1976) stated that alluvial clay from Chandler (Fig. 37), approximately 50 km north of Merredin, has been used in brickmaking.

Meckering

Simpson (1952) stated that fine-grained refractory ball clay, possibly derived from a kaolinized dolerite dyke, occurs at Location 22233, 14 km northeast of Meckering (Fig. 37). The clay contained 90% clay, 10% grit less than 90 mesh, burnt to pure white at a temperature of 1150°C, and reached incipient vitrification at 1250°C (Table 70).

Capercup

Simpson (1952) stated that white clay, probably kaolinized dolerite, is present at Location 3198 near Capercup (Fig. 37). This clay burnt to a creamy white colour at 1350°C and showed incipient vitrification at this temperature (Table 70). The sample contained 89% clay. Another clay sample from 11 km south of Capercup burnt to a creamy white at 1350°C, but showed incipient vitrification at 1050°C.

Duranillin

A sample of kaolinized greenstone from Duranillin (Fig. 37) containing 83% clay burnt to a cream colour at 1350°C, but showed incipient vitrification at 1250°C (Simpson, 1952; Table 70).

Ravensthorpe

Greenish-brown alluvial clay is present in a narrow valley about 10 km east of Ravensthorpe (Fig. 69). As viewed from the banks of the current stream, the clay bed is about 2.5 m thick, but the volume of clay available in this locality may not be very large due to the narrowness of the valley. Firing tests of a sample (GSWA 117852) from this location produced a strong bar with a good deep-red colour, and the material appeared to be suitable for use as a filler in the brickmaking industry (Table 73). The mineralogy and chemical composition of the sample are given in Tables 71 and 72. Another clay sample (GSWA 117853), from approximately 6 km east of the previous sample and also collected from an alluvial clay bed, was found to be too sandy, produced a soft bar when fired, and appeared to be unsuitable for use in brick manufacture (Table 73). This sample contained major

Table 72. Chemical analyses of structural clay samples from the Yilgarn Craton

<i>Locality GSWA no.</i>	<i>Manjimup 117822</i>	<i>Boyup Brook 117823</i>	<i>Ravensthorpe 117852</i>	<i>Salmon Gums 117867</i>	<i>Lake Cowan 117869</i>	<i>Feysville 117874</i>	<i>Feysville 117875</i>	<i>Paddington 117877</i>	<i>Menzies 117879</i>
					Percentage				
SiO ₂	45.60	64.30	69.90	57.60	48.10	61.70	50.40	51.00	53.10
Al ₂ O ₃	27.50	22.50	11.20	23.30	10.60	17.30	6.06	22.10	17.20
TiO ₂	0.78	0.63	0.48	0.58	0.60	0.64	0.30	1.42	1.03
Fe ₂ O ₃	10.10	2.48	5.87	5.44	7.33	9.14	11.90	8.78	13.20
MnO	0.01	<0.01	0.03	<0.01	0.09	0.01	0.14	0.01	0.33
CaO	0.10	0.01	0.93	0.12	6.11	0.03	0.01	0.15	0.12
K ₂ O	0.08	0.08	0.75	0.80	0.82	0.18	0.01	0.33	1.00
MgO	0.20	0.08	1.44	0.58	7.37	1.26	21.20	0.38	2.47
P ₂ O ₅	0.03	0.00	0.01	<0.01	0.01	0.02	0.01	0.01	0.03
SO ₃	0.06	0.10	0.19	0.12	0.47	0.15	0.19	0.53	0.05
BaO	0.01	0.01	0.03	0.02	0.03	0.01	0.04	0.01	0.02
Na ₂ O	0.11	0.16	3.11	0.49	1.89	0.44	1.07	2.50	1.22
LOI	15.60	9.90	5.49	11.20	16.20	9.07	8.18	12.90	9.72
Total	100.18	100.25	99.43	100.25	99.62	99.95	99.51	100.12	99.49
H ₂ O ⁻	2.57	0.96	1.26	2.10	2.92	1.29	1.53	1.29	2.18

Table 73. Evaluation of structural clay samples from the Yilgarn Craton

Locality GSWA no.	Newlands 117820	Greenbushes 117821	Manjimup 117822	Boyup Brook 117823	Dinninup 117824	Highbury 117825
Salt (ppm)	357	522	496	3 581	402	3 386
pH	6.1	6.3	6.7	5.5	6.2	7.3
>90 mm (%)	66	60.3	38.6	34	51.8	68.8
Shrinkage (%)						
Drying (110°C)	2	0.5	7.5	5	1.5	2
Firing	1.5	Does not yield a bar as the material exfoliated after firing	8.5	6	2	1
Total	3.5		16	11	3.5	3
Friability index	10		3–4	2	10	10
Fired temperature (°C)	1160	1160	1160	1220	1160	1220
Fired colour	Light red	Red	Red to light red	Off white	Red and some white specks	Cream to pink to orange
C (%)	3.61	2.32	1.02	0.128	0.24	0.0898
S (%)	0.0187	0.0288	0.0216	0.047	0.0107	0.0142
Comments	Material is sandy and silty with some organic material. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)	Does not contain appreciable clay. The red colour is due to the presence of ironstone. The material is not suitable for brickmaking	Contains ironstone and gravel. Yields a soft bar >1160°C. Possible use as red filler (Appendix 3)	Yields a strong bar at >1220°C. Suitable clay for brickmaking (Appendix 3)	Material is too sandy for use in brickmaking (Appendix 3)	Material is very sandy and contains some ironstone and shale. Yields a soft and multi- coloured bar, and is unsuitable for brickmaking (Appendix 3)

Locality GSWA no.	Boundain 117826	Highbury 117827	Woodanilling 117828	Tenterden 117829	Kendenup 117830	Jerramungup 117849
Salt (ppm)	234	1 575	5 711	236	5 233	6 797
pH	7.2	7	5.9	6.7	7.1	8.5
>90 mm (%)	63.2	48.6	43.6	70.8	30	49.4
Shrinkage (%)						
Drying (110°C)	1	1.5	4.5	2	6	3
Firing	2	0	1	1.5	4	1
Total	3	1.5	5.5	3.5	10	4
Friability index	8	8	8	8	2	8
Fired temperature (°C)	1160	1160	1160	1220	1160	1160
Fired colour	Light red	Red	Red	Off white	Red	Red
C (%)	0.112	0.139	0.322	0.279	0.268	0.152
S (%)	0.0045	0.0096	0.0204	0.0022	0.109	0.0224
Comments	Contains coarse quartz and some shale. Yields a soft bar at >1220°C, and is unsuitable for brickmaking (Appendix 3)	Yields a soft bar. Contains very sandy material and is unsuitable for brickmaking (Appendix 3)	Good colour, but yields a soft bar. Unsuitable for brickmaking (Appendix 3)	Soft bar at >1220°C. Not suitable for brick- making (Appendix 3)	Suitable for red filler (Appendix 3)	High content of salt and white sand. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)

Table 73. (continued)

Locality GSWA no.	Fitzgerald River 117850	West River 117851	Ravensthorpe 117852	Ravensthorpe 117853	Salmon Gums 117867	Kumarl 117868
Salt (ppm)	1 032	3 587	30 090	5 274	4 153	9 263
pH	7.4	7.6	7.9	9.5	7.1	8.1
>90 mm (%)	56.6	38	60.2	40	21.4	48
Shrinkage (%)						
Drying (110°C)	3	3.5	3.5	6	5	6
Firing	0	3.5	3	3	5.5	3
Total	3	7	6.5	9	10.5	9
Friability index	6–7	10	1	5	10	8
Fired temperature (°C)	1160	1160	1160	1160	1160	1160
Fired colour	Light orange	Orange	Deep red	Dark red with white spots	Red	Red
C (%)	0.4	0.242	0.155	1.17	0.196	0.199
S (%)	0.0126	0.0191	0.0911	0.0277	0.0343	0.493
Comments	Yields a soft bar and is unsuitable for brick-making (Appendix 3)	Yields a soft bar and is unsuitable for brick-making (Appendix 3)	Contains fine shale and silt. Good deep-red colour and yields a strong bar, but has a high salt content. Suitable for red filler (Appendix 3)	Contains sandy material with some limestone. Unsuitable for brick-making (Appendix 3)	Good red colour and is suitable for red filler. However, the material is silty with some sand and is sensitive to fast drying (Appendix 3)	Yields a soft bar and is unsuitable for brickmaking (Appendix 3)
Locality GSWA no.	Lake Cowan 117869	Higginsville 117870	Widgiemooltha 117871	Mandilla 117872	Kambalda 117873	Feysville 117874
Salt (ppm)	26 550	678	10 325	14 160	11 387	5 021
pH	8.8	8.2	9.2	8.7	8.7	6.7
>90 mm (%)	20.8	55.2	58.2	31	48.2	15.4
Shrinkage (%)						
Drying (110°C)	7	2	2	6.5	3	2.5
Firing	4	1.5	<0.5	2	2	2.5
Total	11	3.5	1.5	8.5	5	5
Friability index	3	10	10	2	8	6
Fired temperature (°C)	1160	1160	1160	1160	1160	1220
Fired colour	Red and cream	Dark red with cream spots	Off white	Red	Cream and red	Dark red with cream spots
C (%)	2.11	1.31	2.16	2.3	1.97	0.0426
S (%)	0.184	0.0204	0.0532	0.104	0.048	0.055
Comments	Contains ironstone and some creamy shale. Yields a multicoloured bar. Possible use as a filler (Appendix 3)	Contains gravel and limestone. Unsuitable for brickmaking	Material contains excessive sand for brick-making (Appendix 3)	Yields a multicoloured bar. Contains high salt and is unsuitable for brickmaking (Appendix 3)	Contains excessive sand and high salt. Unsuitable for brickmaking (Appendix 3)	Yields a soft bar at >1220°C, but possible filler for higher firing temperature products (Appendix 3)

Table 73. (continued)

Locality GSWA no.	Feysville 117875	Kalgoorlie 117876	Paddington 117877	Mount Vettors 117878	Menzies 117879	Bullabulling 117880
Salt (ppm)	12 862	2 873	7 434	1 664	3 870	1 858
pH	6.8	8.4	5.8	4.2	7.4	8.9
>90 mm (%)	46.2	50	18	35	6.6	56.4
Shrinkage (%)						
Drying (110°C)	2.5	3	2	1	10.5	1
Firing	3.5	<0.5	4	2.5	5.5	1
Total	6	2.5	6	3.5	16	2
Friability index	2	Exfoliated	16	0		10
Fired temperature (°C)	1220	1160	1160	1160	1160	1220
Fired colour	Light brown	Dark red with white spots	Dark brown	Light red with cream spots	Red to dark red	Light cream
C (%)	0.0134	1.15	0.0516	0.127	0.0264	0.135
S (%)	0.0802	0.043	0.199	0.11	0.0131	0.0138
Comments	Contains soft shale and fine biotite. Although it contains high salt it could be suitable for filler (Appendix 3)	Material is very sandy, with some limestone and gravel. Unsuitable for brickmaking (Appendix 3)	Some glaze at >1160°C. Some cracks during drying, but suitable for filler (Appendix 3)	Yields a soft bar. Suitable filler for fast-drying material at slightly higher firing temperatures (Appendix 3)	Yields a very strong bar at >1160°C. Suitable for red filler (Appendix 3)	Yields a very soft bar at >1220°C and is unsuitable for brickmaking (Appendix 3)

Locality GSWA no.	Bullfinch 117881	Warralakin 117882	Mukinbudin 117883	Kununoppin 117884	Yelbeni 117885
Salt (ppm)	6 325	18 762	637	1 557	2 124
pH	8	6.9	6.2	9	7
>90 mm (%)	38.4	29.6	52.6	46.8	74.8
Shrinkage (%)					
Drying (110°C)	4.5	6.5	3.5	3.5	0.5
Firing	0.5	1.5	0	0.5	<0.5
Total	5	8	3.5	4	0
Friability index	10	8	10	10	10
Fired temperature (°C)	1160	1160	1160	1160	1160
Fired colour	Red	Red	Red	Red	Orange
C (%)	0.177	0.239	0.126	0.393	0.146
S (%)	0.0656	0.172	0.0077	0.0074	0.0132
Comments	Sandy material. Yields a soft bar and is unsuitable for brick-making (Appendix 3)	Sandy material. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)	Very sandy material. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)	Material contains coarse sand and limestone, and is contaminated with organic matter. Unsuitable for brickmaking (Appendix 3)	Sandy material and is unsuitable for brickmaking (Appendix 3)

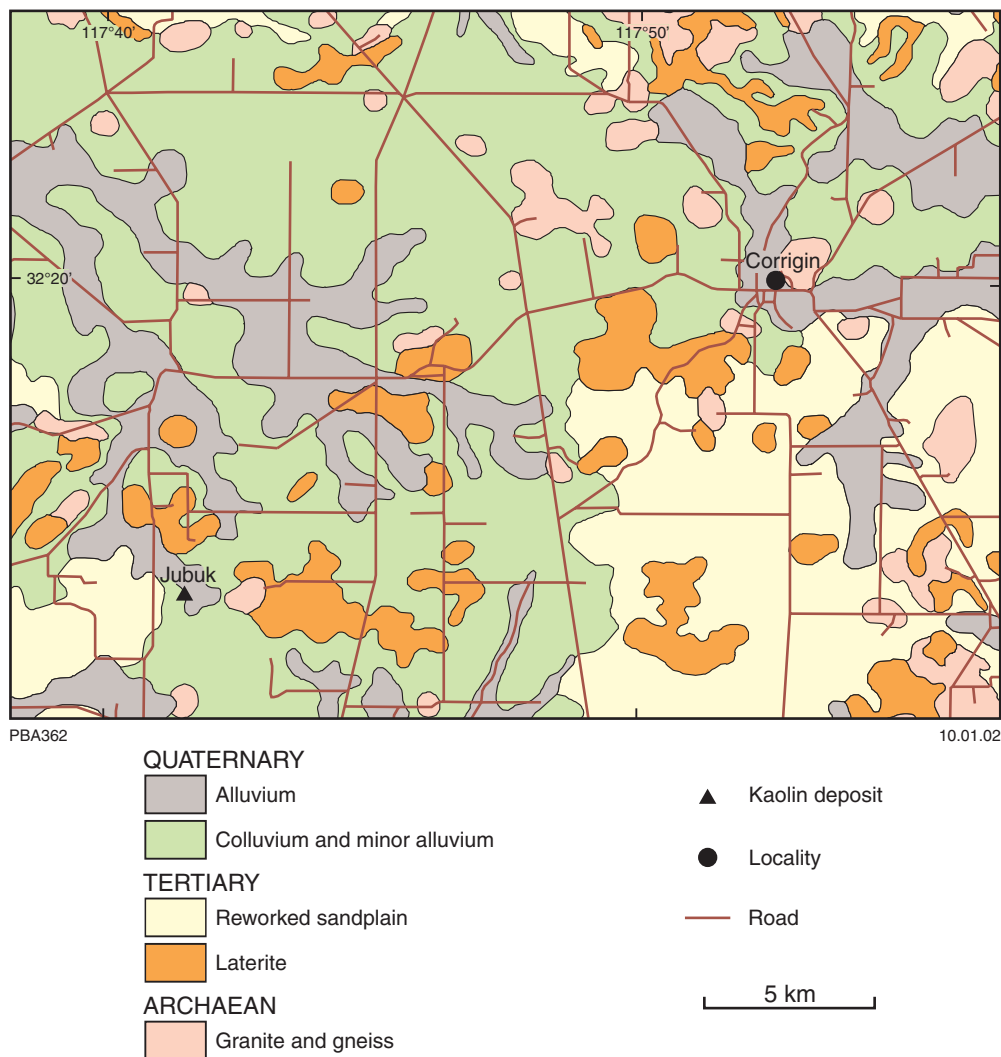


Figure 65. Geology of the area around Corrigin (modified from Muhling and Thom, 1985a)

smectite and was discussed in the chapter on **Bentonite**. The surface geological features suggest that the locality could be prospective for structural clay.

Simpson (1952) reported test results of a sample containing 65% clay from a kaolinized granite about 5 km south of Ravensthorpe. This sample burnt to a creamy white colour at 1150°C.

Salmon Gums

The area around Salmon Gums is an extensive flat terrain containing alluvial and residual clays (Fig. 70). A sample of chocolate-brown to red clay from diggings of a lake dam (GSWA 117867) was tested for mineralogy, chemical composition, and firing properties (Tables 71–73). The clay was found to be sensitive to fast drying, but the good red colour on firing indicated that the material could possibly be used as a red filler in the brick industry. The sample contained a major amount of kaolinite and 40–50% halloysite. The chemical analysis of the sample gave 23.3% Al_2O_3 and 57.6% SiO_2 , indicating an average composition of kaolin. A sample of sandy clay (GSWA

117868), collected from an abandoned reservoir dam near Kumarl and about 25 km northwest of Salmon Gums, was considered to be representative of the alluvium beneath the thin veneer of eolian sand, but was found to be too sandy and produced a soft bar when fired (Tables 71 and 73).

Lake Cowan

In the area between Lake Cowan and Norseman there are large areas of colluvial and alluvial horizons consisting of chocolate-brown to reddish clay. The clays in these horizons appear to have accumulated from weathered Precambrian granite, mafic–ultramafic rocks, and sedimentary rocks (Fig. 71). A sample (GSWA 117869) of chocolate-brown clay, collected from a road cutting (about 1.5 m high) approximately 17 km north of Norseman, produced a red and cream multicoloured bar on firing. The test results indicated that the material could be used as a red filler in the manufacture of bricks (Table 73). The sample contained 10.6% Al_2O_3 , 48.1% SiO_2 , and 7.33% Fe_2O_3 (Table 72) and hence is acceptable for use as a filler. The material contained a major amount of smectite (Table 71).

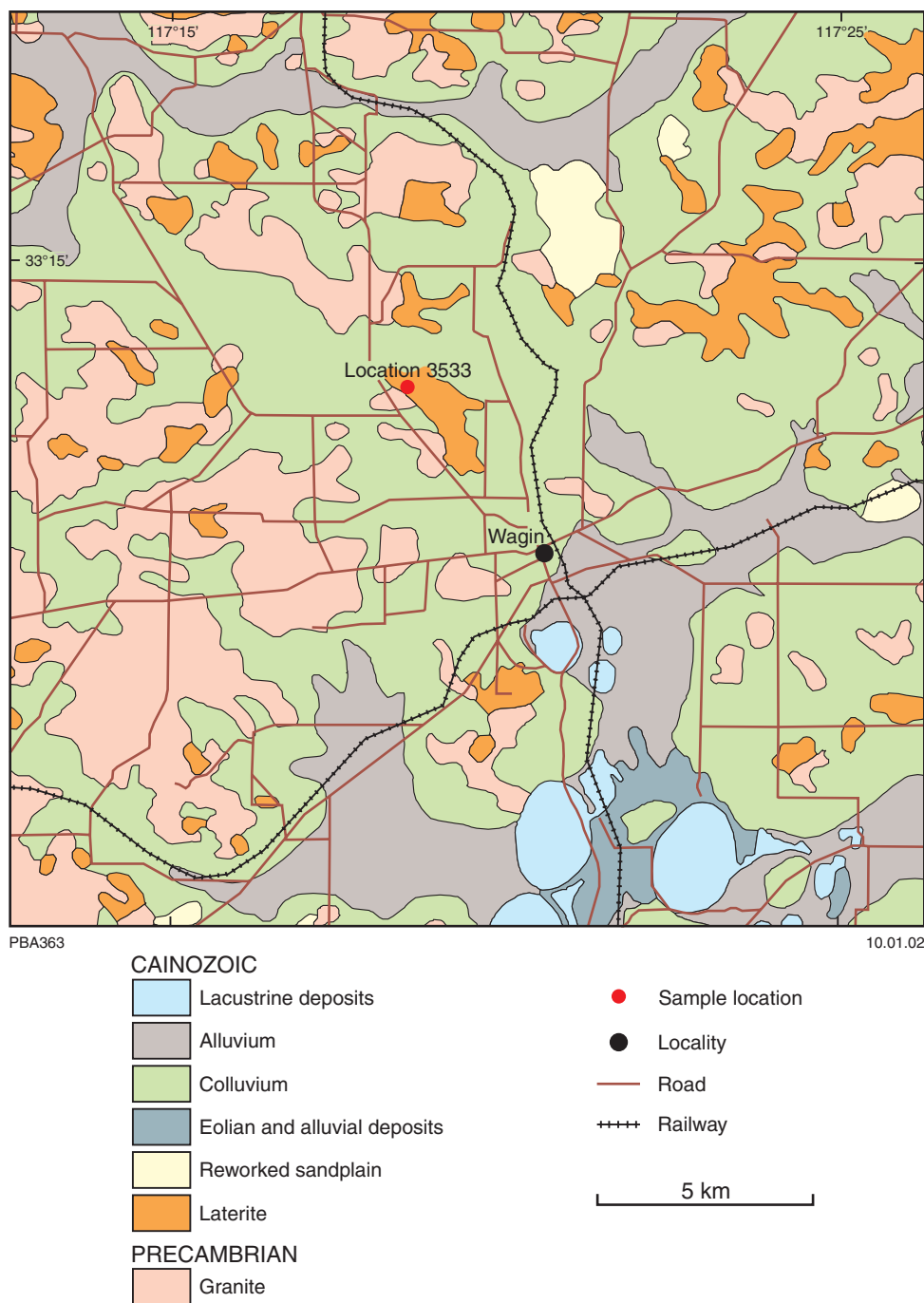


Figure 66. Geology of the area around Wagin (modified from Brakel et al., 1985)

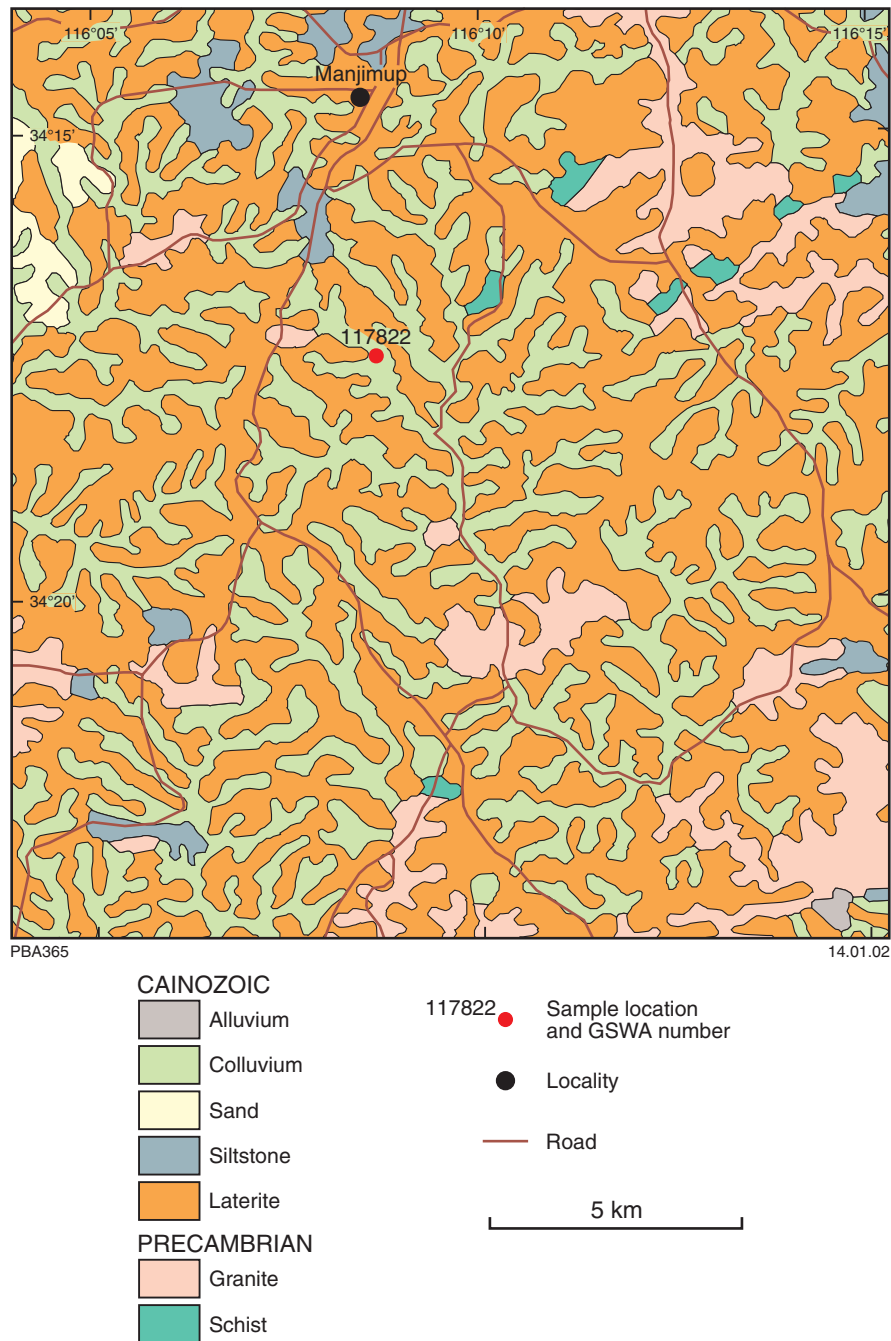


Figure 67. Geology of the area around Manjimup (modified from Wilde and Walker, 1984)

Feysville

The region around Feysville has large areas covered with colluvial and alluvial horizons of brown to reddish-brown clays that appear to be weathered products of Archaean mafic, ultramafic, and sedimentary rocks (Fig. 72). A creamy brown clay sample (GSWA 117874) from the dumps of a shaft, which appeared to be more than 10 m deep (bottom not visible), was collected for testing. The shaft is located on the western side of the highway. The creamy brown clay seen from the wall of the shaft formed at a depth of about 5 m below the surface. The sample contained more than 50% kaolinite and major smectite

(Table 71). The material yielded a soft bar at 1220°C that was a strong dark-red colour with creamy spots. The test results suggest that the material could possibly be used as a red filler for products fired at higher temperatures (Table 73). The chemical composition of the sample indicated 17.30% Al_2O_3 and is acceptable for use as a filler (Table 72).

A sample (GSWA 117875) of greenish-grey to whitish micaceous schist was collected from a location approximately 10 km northwest of the above sample, along the highway (Fig. 72). This sample contained 40–50% talc and 40–50% interstratified clay (Table 71),

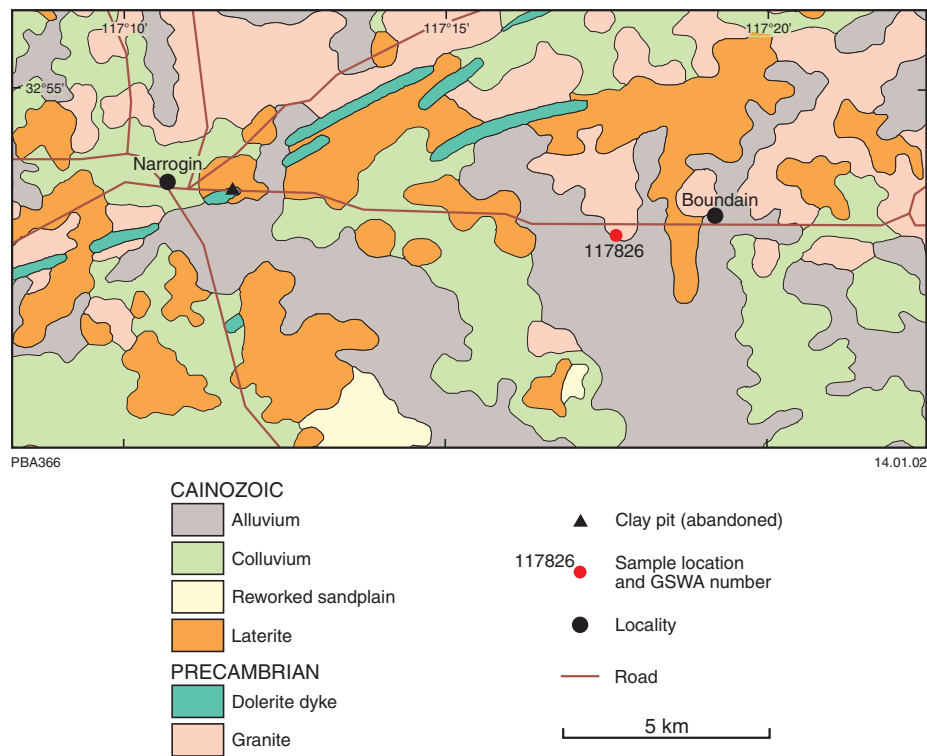


Figure 68. Geology of the area around Narrogin and Boundain (modified from Muhling and Thom, 1985a)

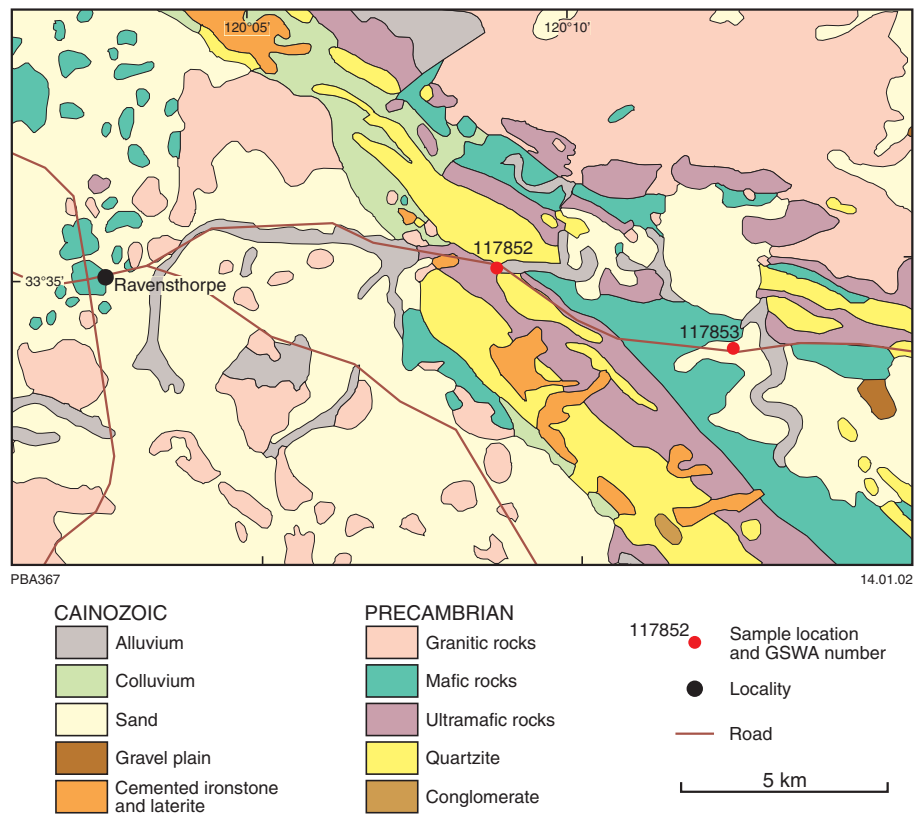


Figure 69. Geology of the area around Ravensthorpe (modified from Thom and Lipple, 1974)

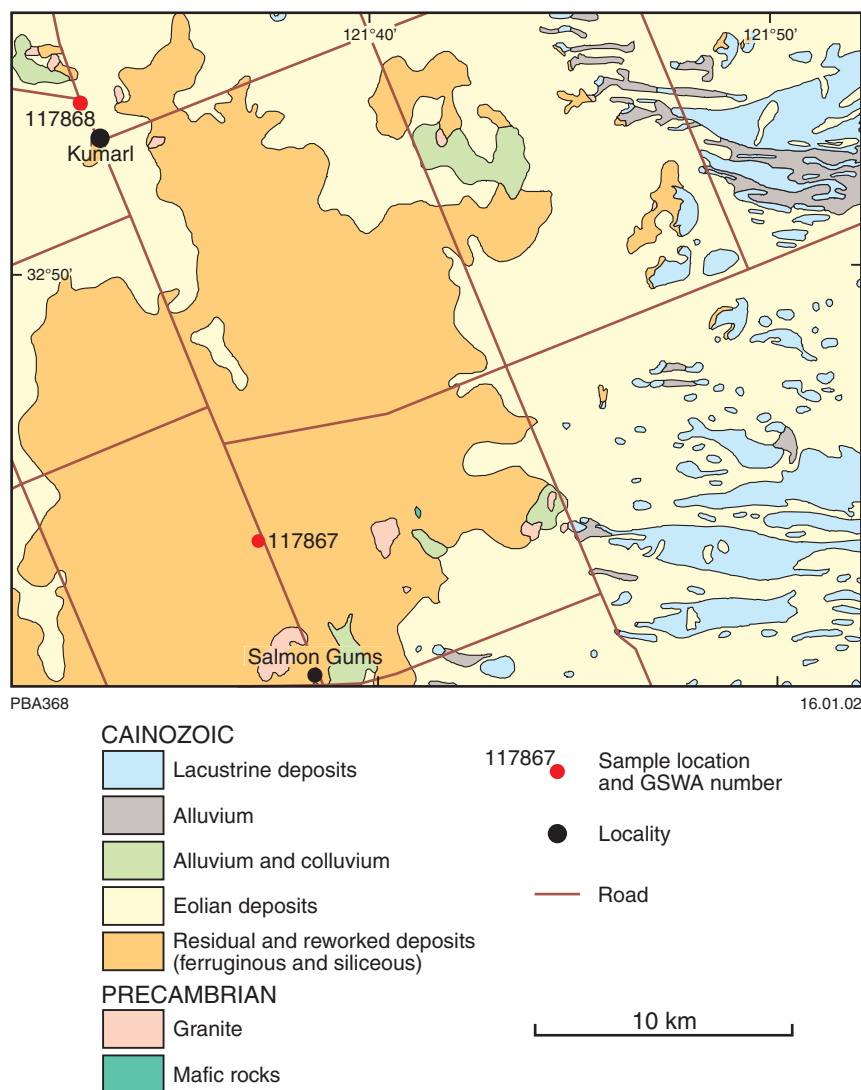


Figure 70. Geology of the area around Salmon Gums (modified from Doepel et al., 1972)

and had a chemical composition of 50.40% SiO_2 , 21.20% MgO , and 6.06% Al_2O_3 (Table 72). The firing tests for the sample suggested that the material could be used as a good red filler (Table 73).

Paddington

A chocolate-brown clay (Fig. 73; GSWA 117877), collected from dump material of a small, shallow shaft (about 7 m deep) in the Paddington area, contained more than 50% kaolinite (Table 71). On chemical analysis, the sample contained 22.1% Al_2O_3 , 51% SiO_2 , and 8.78% Fe_2O_3 (Table 72). Firing tests for this sample gave a dark-brown colour at greater than 1160°C and suggested that it could be used as good red filler (Table 73).

Kanowna

Simpson (1952) stated that attempts to obtain refractory clays from various geological formations in the Kanowna

area, approximately 20 km northeast of Kalgoorlie (Fig. 42), were hampered due to the presence of alunite and high sodium chloride values. The most appropriate use of this material was considered to be as a substitute for 'cornish stone' (a white, low-shrinking flux) for other more refractory clays. The chemical composition of a sample of alunite-bearing clay from PA 506 indicated 21.96% Al_2O_3 and 66.94% SiO_2 . Firing test results of a number of samples (from tenements PA 506, ML 47, MC 6, and MC 10) are given in Table 70, with most firing white to creamy white at 1150–1350°C and incipient vitrification occurring at temperatures above 1150°C.

Mount Vettters

The area around Mount Vettters, about 60 km north of Kalgoorlie along the Menzies road, has regolith material rich in chocolate-brown clay mixed with reddish-brown pisolite. The lithological units distinguished in the area include Archaean granite, mafic, and ultramafic rocks, and

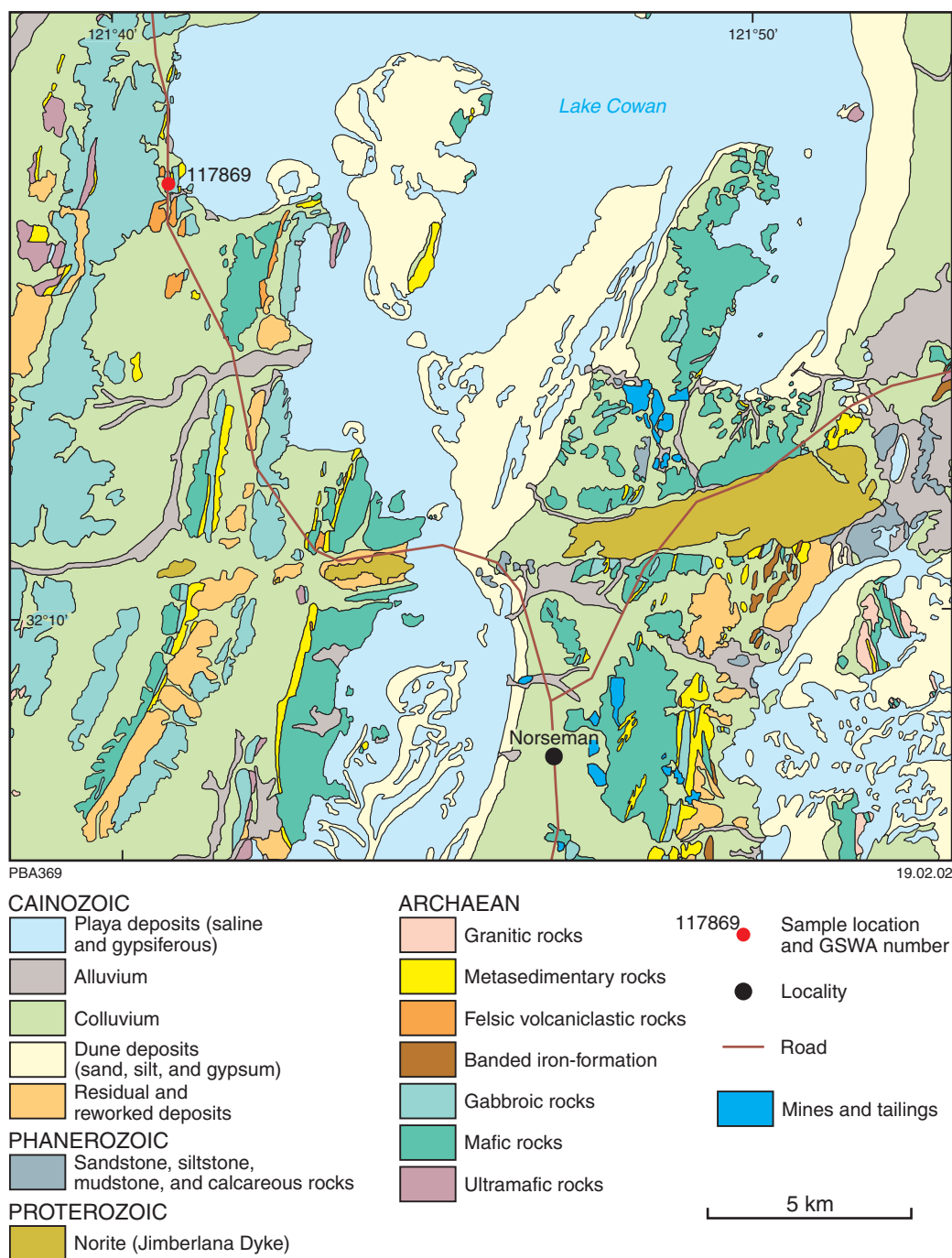


Figure 71. Geology of the area around Lake Cowan (modified from Doepel et al., 1972)

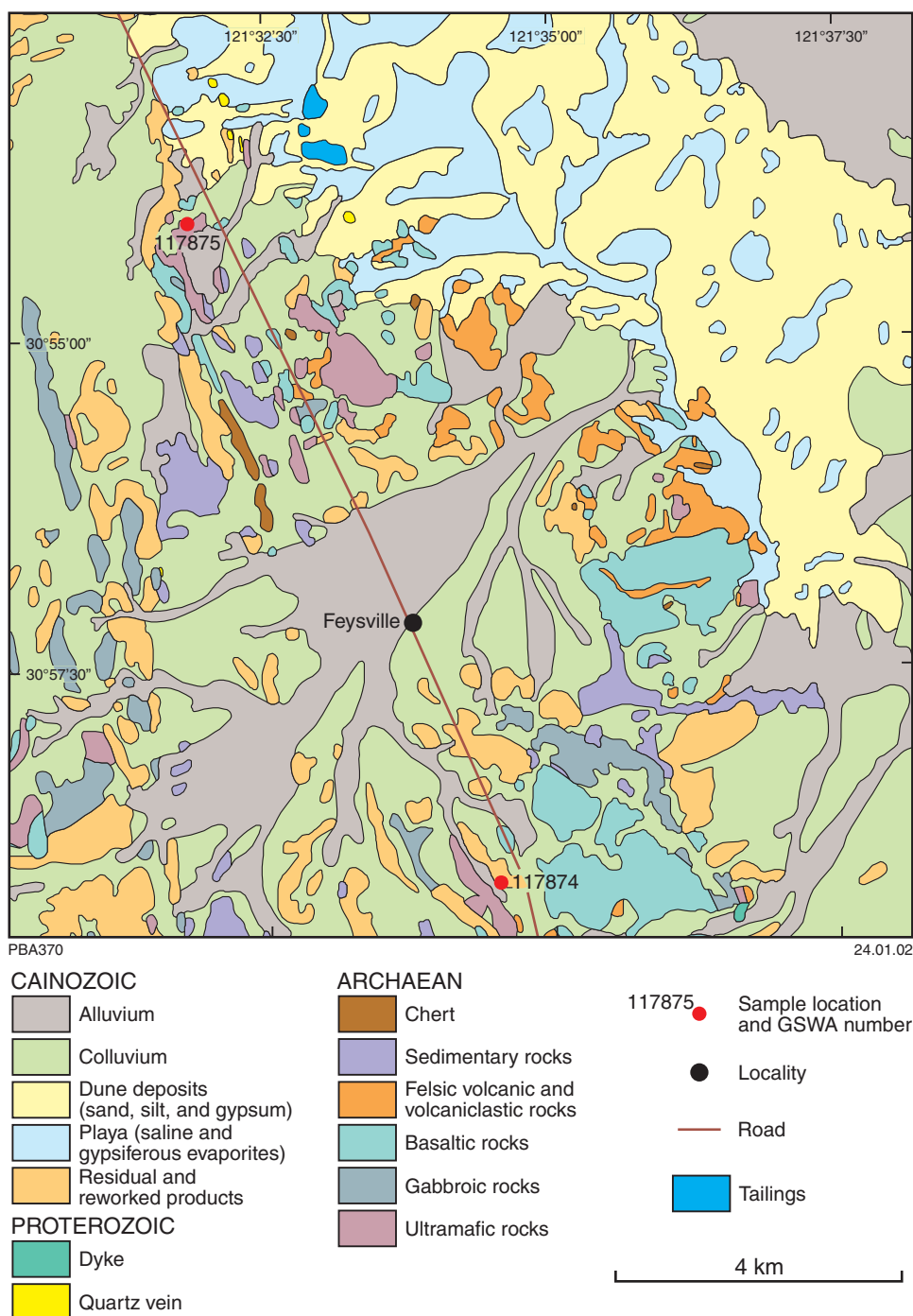


Figure 72. Geology of the area around Feysville (modified from Groenewald et al., 2000)

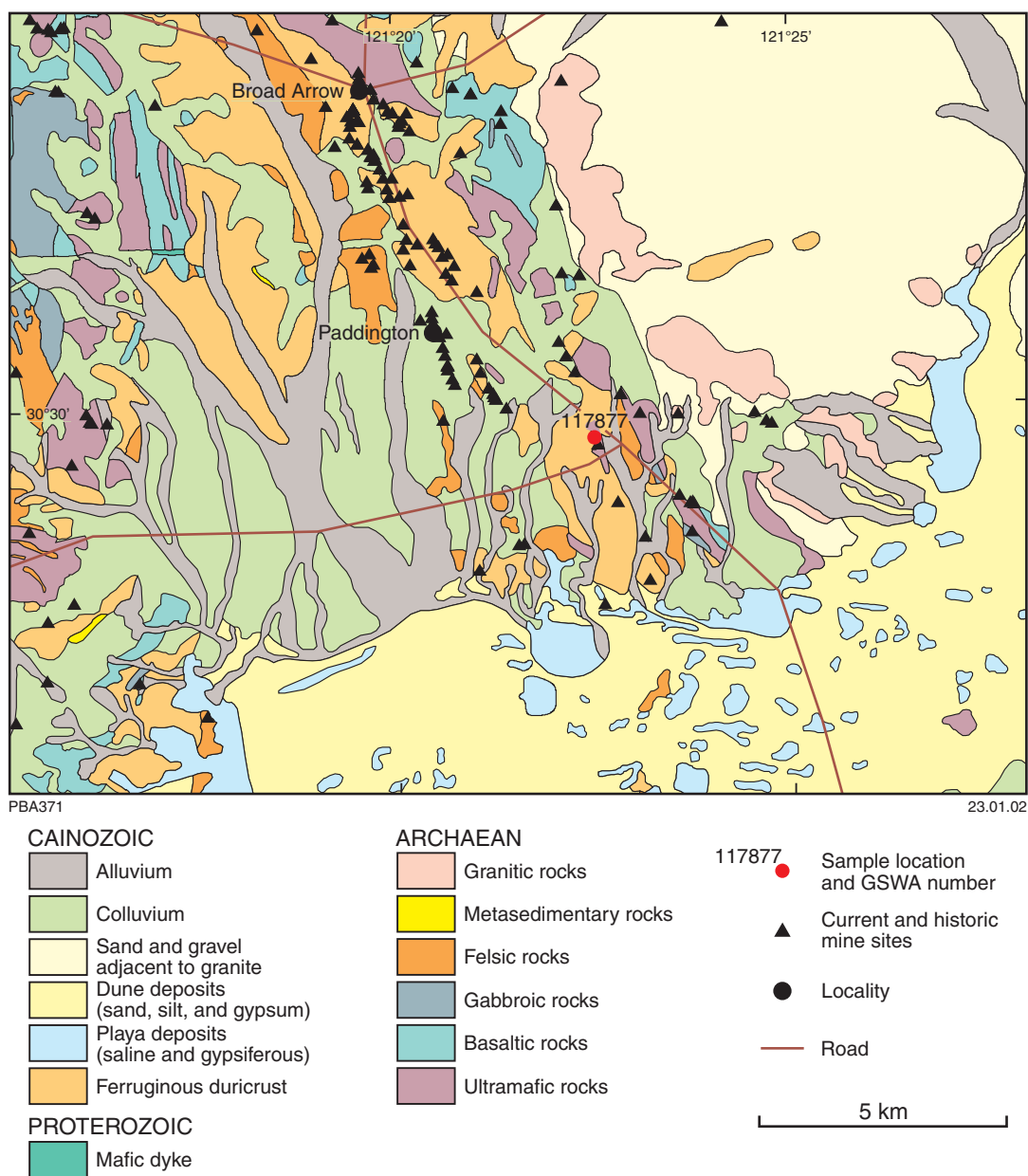


Figure 73. Geology of the area around Paddington (modified from Groenewald et al., 2000)

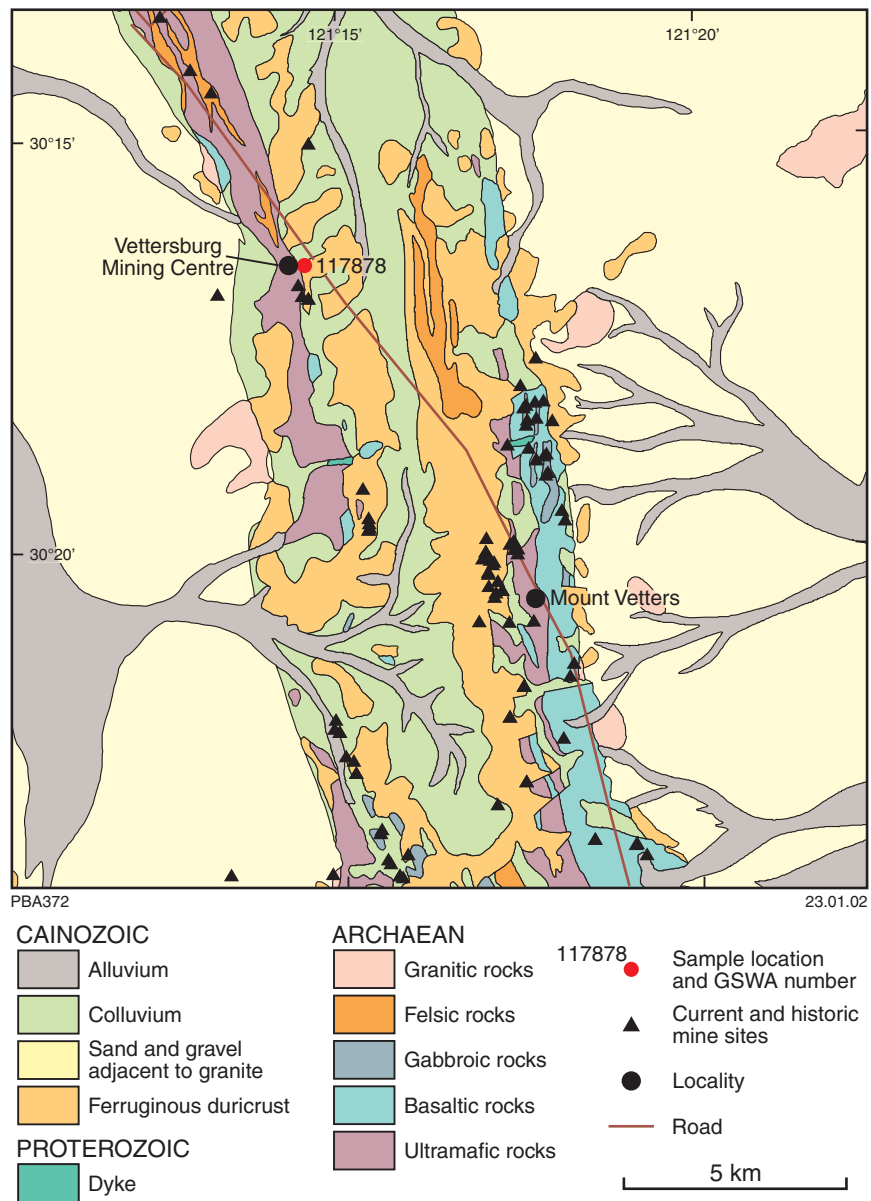


Figure 74. Geology of the area around Mount Vettors (modified from Groenewald et al., 2000)

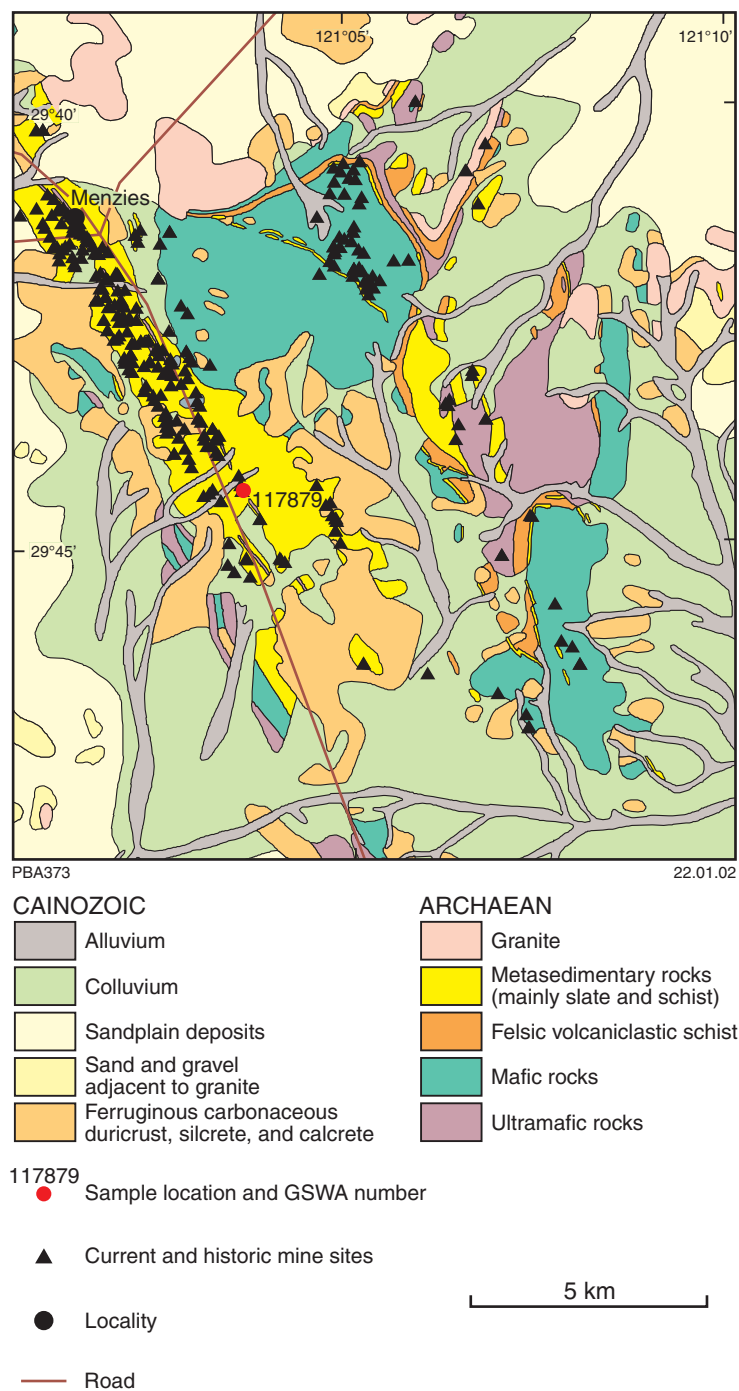


Figure 75. Geology of the area around Menzies (modified from Groenewald et al., 2000)

Cainozoic laterite, alluvium, colluvium, and sand (Fig. 74). A sample (GSWA 117878) of yellowish-brown to chocolate-brown clayey material, with red to brown pisolitic fragments, was collected from dump material of a shaft about 10 m deep. The sample contained more than 50% kaolinite and major quartz (Table 71). Firing tests indicated that the material is suitable as a filler for fast-drying clays at slightly higher firing temperatures (Table 73).

Menzies

About 6 km south of Menzies along the Kalgoorlie road, there are a number of shafts on the western side of the road, with dump material containing creamy brownish to grey clay. On the eastern side of the road, there are shafts with dumps of yellowish-brown clay. A sample (GSWA 117879; Fig. 75) of greyish clay from the dumps of one of the shafts on the western side of the road had 40–50% kaolinite and major smectite (Table 71). The chemical analysis of the sample indicated 17.2% Al_2O_3 and 53.1% SiO_2 (Table 72). Firing tests yielded a very strong bar at 1160°C and the material would be suitable for use as a red filler (Table 73).

Other

In the past, bricks have been produced from clay deposits in the Kalgoorlie–Boulder and Coolgardie regions, but precise locations are not available. Samples from numerous other localities on the Yilgarn Craton (GSWA 117820–21, 117825, 117827–30, 117849–51, 117870–73, 117876, and 117880–85) have been tested for mineralogy and/or firing strengths, and their results are given in Tables 71 and 73. Bowley (1941) has given results of the testing of clay samples from numerous other localities on the Yilgarn Craton (Jimperding, Mokine, Capercup, Wilga, Burabadji, and Dwellingup), in addition to those already discussed, and these are summarized in Table 70.

Deposits in the Albany–Fraser Orogen and Bremer Basin

The Albany–Fraser Orogen is exposed along the southern and southeastern margin of the Yilgarn Craton. The Bremer Basin lies along the southern margin of Western Australia and overlies the Albany–Fraser Orogen (Figs 76 and 77). The rocks in the Albany–Fraser Orogen are characterized by gneiss and granitoid intrusions that can act as parental material for large deposits of clay, but the main clay deposits have been formed by the weathering of Eocene sedimentary rocks of the Bremer Basin.

The Albany–Fraser Orogen can be divided into two parts based on lithology (Myers, 1990c):

- A complex of high-grade quartzofeldspathic gneiss and layered intrusions called the Biranup Complex (1.2 – 1.1 Ga), and
- A complex of less intensely deformed high-grade orthogneiss and paragneiss intruded by sheets of

granite at about 1.1 Ga, and collectively called the Nornalup Complex.

The Biranup Complex forms a belt in the northern part of the orogen, and consists of quartzofeldspathic gneiss derived primarily from granitoid rocks, metagabbro, and metasedimentary rocks consisting mainly of quartzite. The Nornalup Complex forms the southern part of the orogen, and consists of quartzofeldspathic gneiss, granitic rocks, and pelitic and semi-pelitic metasedimentary rocks.

The northern foreland of the Albany–Fraser Orogen contains deformed psammitic and subordinate pelitic metasedimentary rocks, generally of greenschist facies. These rocks include the Stirling Range Formation, Mount Barren Group, and Woodline beds. A dense swarm of dolerite dykes subparallel to the orogen boundary intrudes the northern foreland.

The Bremer Basin, which extends offshore, lies along the southern margin of Western Australia between Point D'Entrecasteaux and Israelite Bay. The onshore sequence is composed of the Eocene Plantagenet Group, and the clay formed by weathering of the mudstone and siltstone of this group contains some quartz grit. Clay suitable for use in the brick industry is found as pockets of white kaolinitic clay of medium plasticity that commonly form in the weathered Plantagenet Group and also in bedded sandy clays with a red, brown, or yellow colour.

Albany region

The Albany area has a rugged to moderate rolling topography, with numerous areas of flat terrains surrounded by steep hills and gentle valleys. The areas west of Albany are covered with granitic and gneissic rocks, which are often weathered and lateritized (Figs 78 and 79). Some of the lateritic horizons contain lenses of kaolin. In the flat terrains west of Albany, especially the area around Bornholm, there are thick accumulations of colluvial and alluvial clay. The areas east of Albany contain large areas of the Pallinup Siltstone and associated laterite. There are also vast stretches of flat sandy plains in the areas east and west of Albany. A number of samples from these clay terrains, and kaolinitic and lateritic clay profiles, were collected for testing. Of these, a sample (GSWA 117841) from the Kalgan area was found to be very good for use as a structural clay, especially in the brick industry (Tables 74–76). All samples from the western side of Albany (GSWA 117831–35), including the Bornholm area, produced soft bars on firing, suggesting that the material is not very suitable for use in brick manufacturing (Table 76).

King River

About 5 km northeast of King River along Hassell Road, kaolinitic clay has been extracted from two small pits (approximately 50 × 25 × 3 m each), presumably for a local industry (Fig. 78). The clay is plastic, kaolinitic, and contains lenses of red lateritic material. Firing tests on sample GSWA 117839 from this pit indicated a good fast-drying material, although the bar produced at 1220°C was not very strong (Table 76). This sample contained

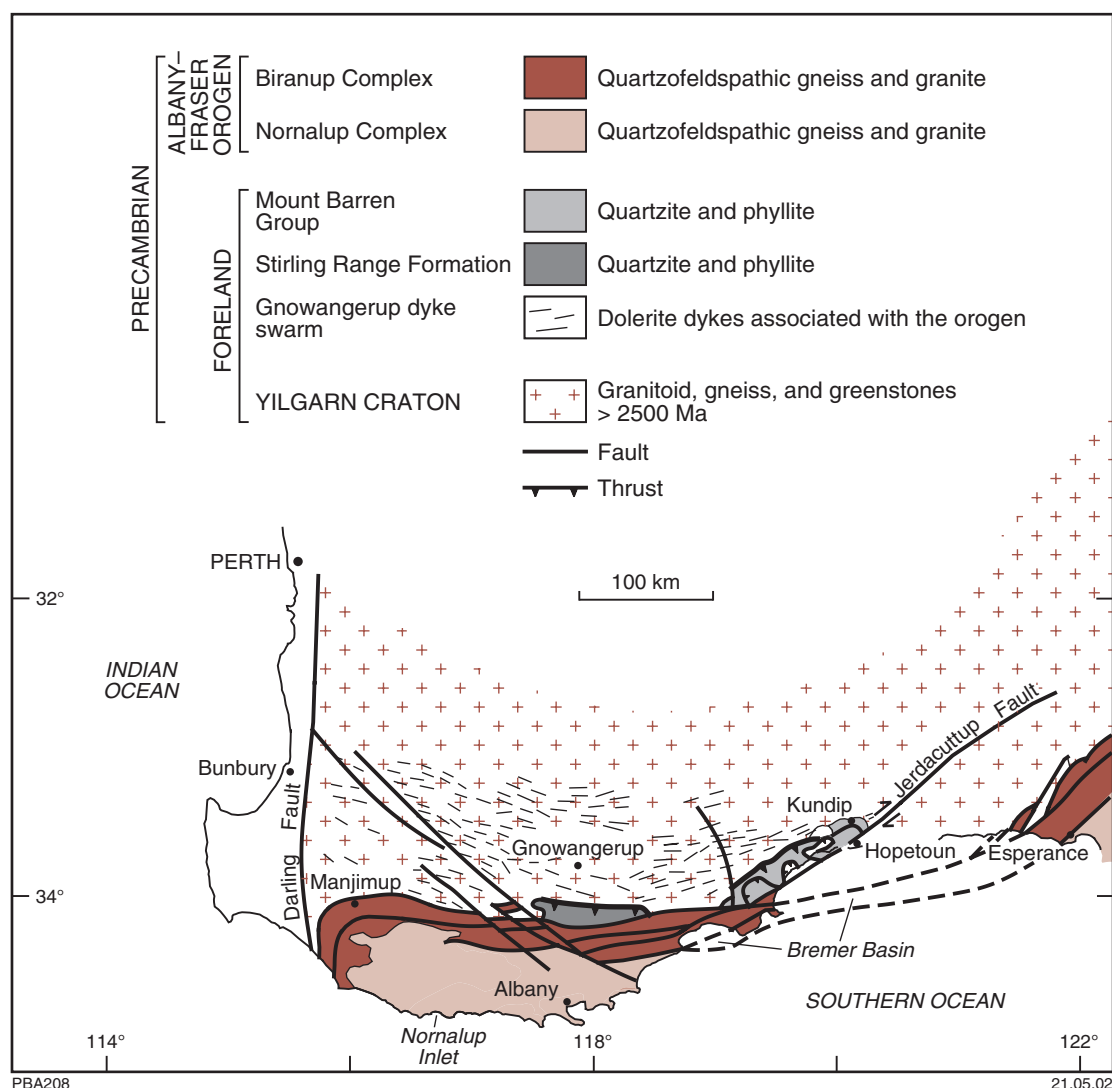


Figure 76. Simplified geological map of the western part of the Albany–Fraser Orogen (after Myers, 1990c)

40–50% kaolinite. The chemical analysis of the sample gave 15% Al_2O_3 , 76.50% SiO_2 , 1.32% Fe_2O_3 , and 6.59% LOI, indicating that it is of acceptable composition for use as structural clay (Tables 74 and 75). Another kaolinitic clay sample (GSWA 117840), from a farm dam about 2 km northeast of the previous sample, contained a major amount of kaolinite and produced a soft bar at 1220°C (Tables 75 and 76).

Firing tests on samples GSWA 117836–38, from localities near Oyster Harbour (Fig. 78), produced soft bars due to their relatively high sand content, and therefore they are considered to be not suitable for use in brick manufacture (Tables 75 and 76).

Kalgan

A sample (GSWA 117841; Fig. 78) of red-brown lateritic clay from a road cutting about 5 km northeast of Kalgan and 10 km northeast of GSWA 117839 (King River) produced a strong bar after 1220°C, with a light-red

terracotta colour (Table 76). The clay was found to be suitable for use in brick manufacture. The sample contained 40–50% kaolinite, and the chemical analysis of the sample gave 20.6% Al_2O_3 , 60.1% SiO_2 , 8.25% Fe_2O_3 , and 9.5% LOI, thus indicating that it is of acceptable composition for use as structural clay (Tables 74 and 75).

Esperance region

The main geological formations around Esperance (Fig. 42) are too sandy for use as structural clay. Nevertheless, seven samples (GSWA 117857 and 117859–64; Fig. 80) from more clay-rich material were collected from the area around Coramup Hill and from locations up to 40 km north of Esperance. Some samples contained up to 40% kaolinite, but none produced strong bars on firing (Tables 75 and 76). However, a known kaolin occurrence covers an area of 10 km² overlying the granite basement about 17 km west-northwest of Gibson (Abeyasinghe and Fetherston, 1999). The kaolin is mainly restricted to zones

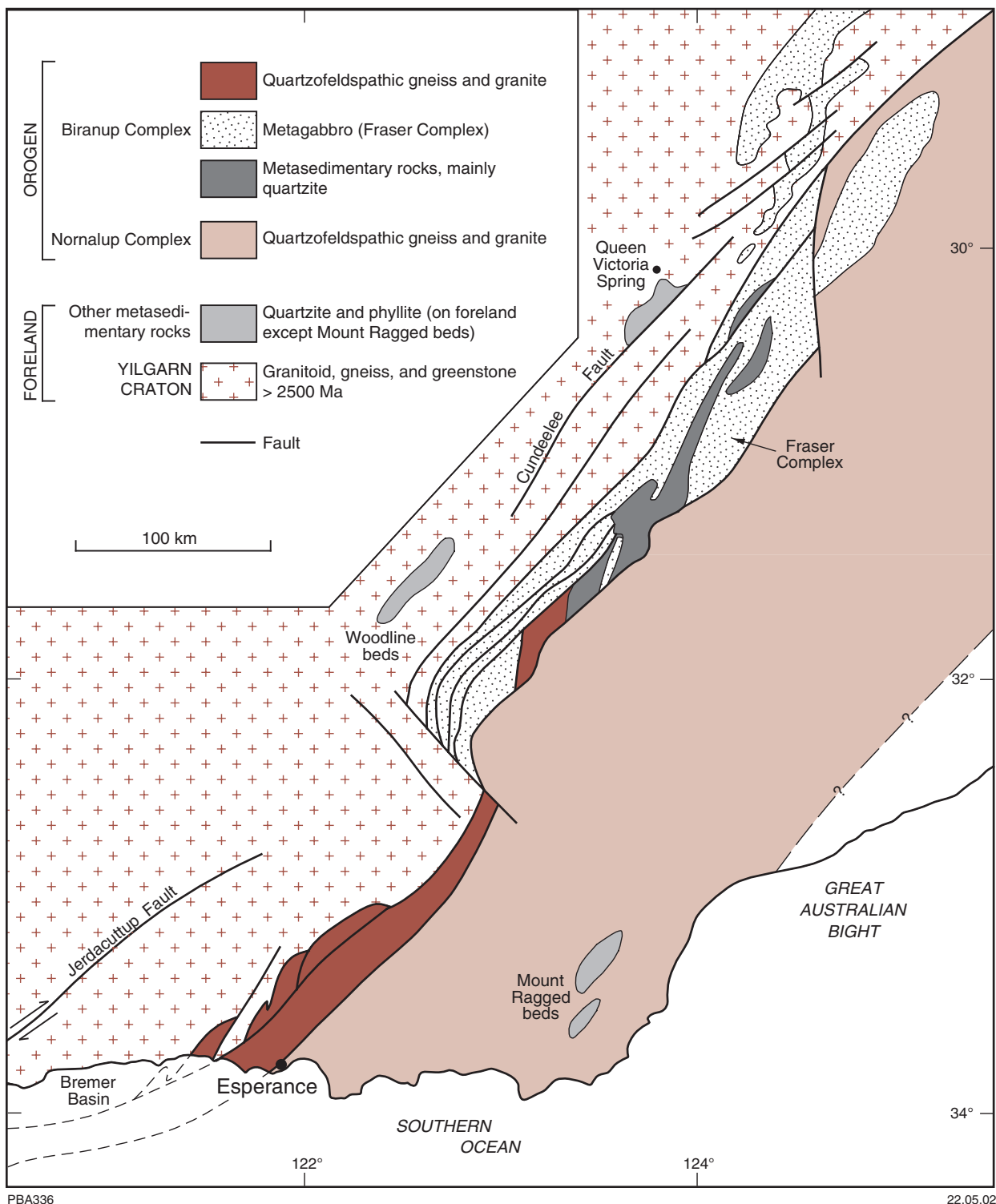


Figure 77. Simplified geological map of the eastern part of the Albany-Fraser Orogen (after Myers, 1990c)

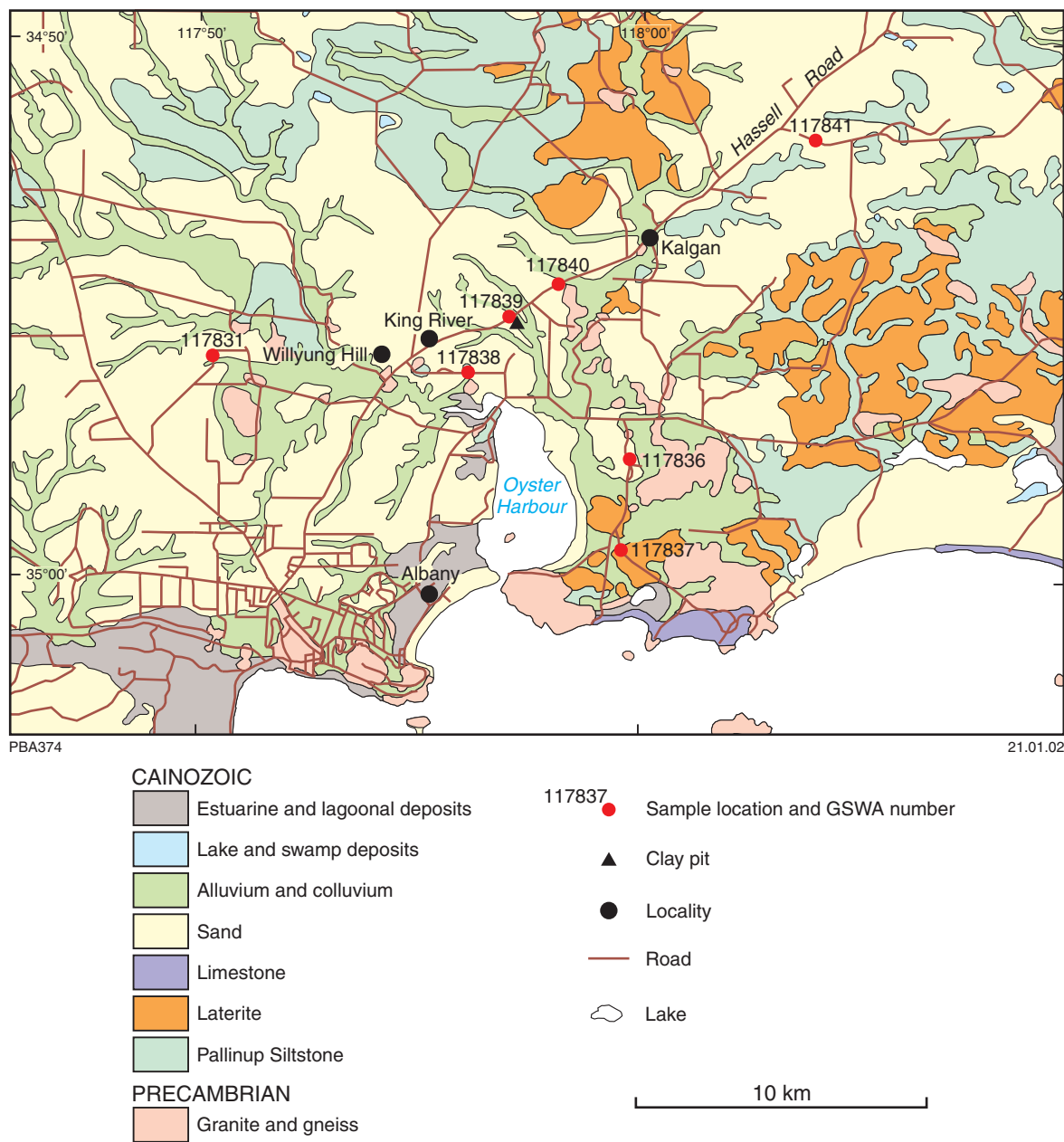


Figure 78. Geology of the area around Albany (modified from Muhling et al., 1984)

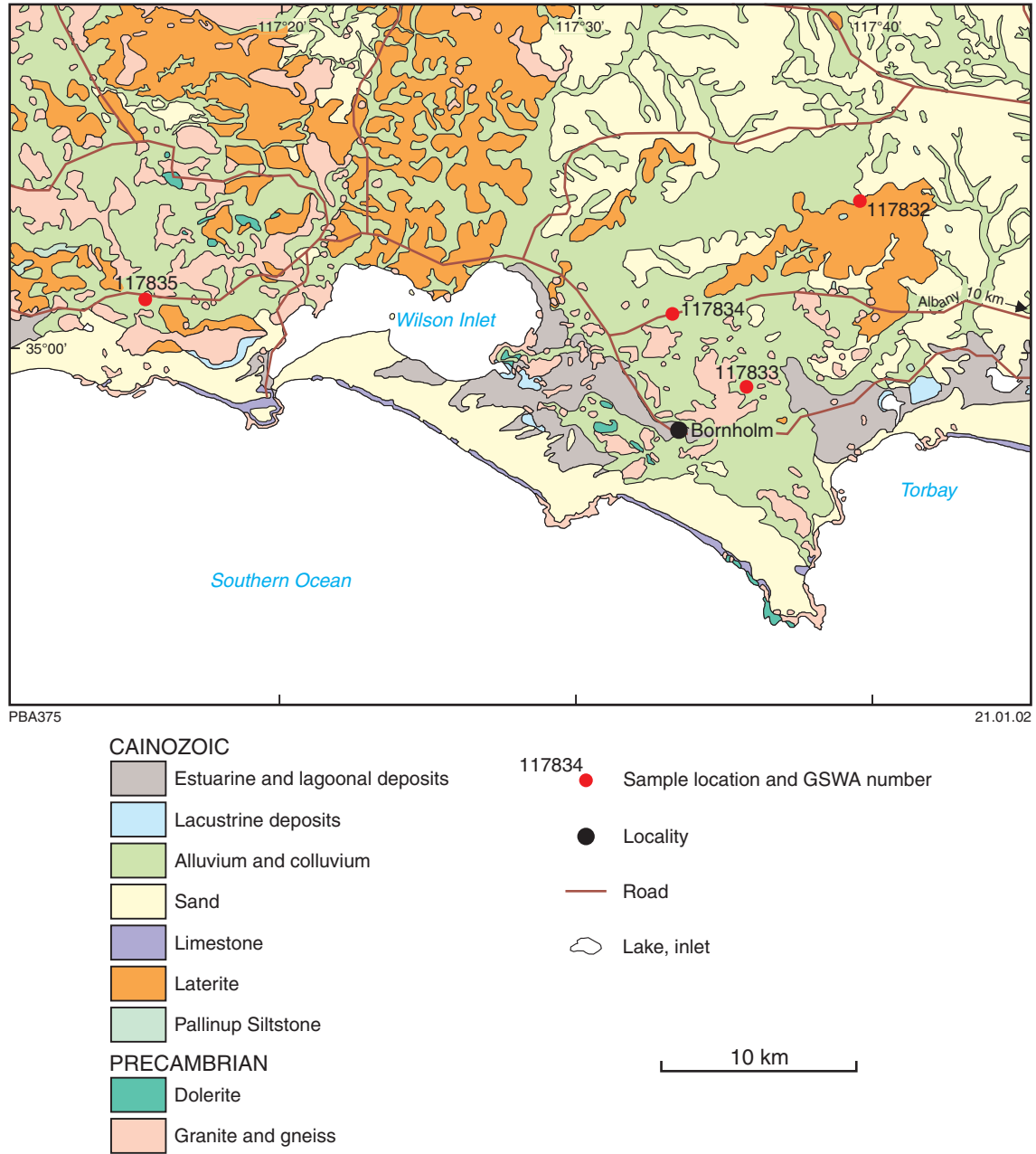


Figure 79. Geology of the area around Bornholm, west of Albany (modified from Muhling et al., 1984)

Table 74. Chemical analyses of structural clay samples from the Albany–Fraser Orogen and Bremer Basin

Locality GSWA no.	King River 117839	Kalgan 117841
	Percentage	
SiO ₂	76.50	60.10
Al ₂ O ₃	15.00	20.60
TiO ₂	0.62	1.20
Fe ₂ O ₃	1.32	8.25
MnO	<0.01	0.01
CaO	0.01	0.04
K ₂ O	0.06	0.21
MgO	0.08	0.14
P ₂ O ₅	0.01	0.01
SO ₃	0.06	0.05
BaO	<0.01	<0.01
Na ₂ O	0.03	0.04
LOI	6.59	9.50
Total	100.28	100.15
H ₂ O ⁻	0.62	0.99

of weathered granite and gneiss, and has formed as residual material in situ. Western Mining Corporation, on behalf of Simmons Holdings, conducted exploration for kaolin in the area during 1989–91 to determine whether the material could be used for high-grade applications such as in the paper industry. Although the outcome of this investigation was unsuccessful for paper filler and coating applications due to the unfavourable viscosity of the clay, the material is likely to be suitable for refractory applications in the ceramics industry, but it would require further testing.

Other localities

Samples from numerous other localities from the Albany–Fraser Orogen (GSWA 117842–48, 117854–56, and 117865–66), have been tested for their firing properties or mineralogy or both, and these results are given in Tables 75–76.

Deposits on the Pilbara Craton

The areas investigated for construction industry clay on the Pilbara Craton were close to Karratha, Roebourne, Whim Creek, and Port Hedland, or along the highway between these towns. The Cainozoic colluvial and alluvial horizons, as well as the floodplains associated with numerous rivers around Karratha, Roebourne, the Whim Creek region, and the northern margin of the Pilbara Craton, contain considerable areas of red to red-brown clay and sandy clay. Based on surface observations, the most favourable source area for clay for use as structural clay or in brick manufacturing appears to be the Pleistocene clay horizons derived from Archaean rocks around Roebourne. Such clayey horizons are common in the floodplains and alluvial material associated with the Harding, Jones, and Sherlock rivers. Most clays in this

region are deep red or reddish brown, whereas white or light-brown clays are rare. The clayey horizons along the Northern Highway west of Karratha, and those around Port Hedland, are generally rich in sandy or limy material and appear to be unsuitable for use as structural clay.

Thirteen clay samples (GSWA 145196–99, 117801–07, and 117814–15; Figs 42 and 81) between the Yannery and De Grey rivers were collected for mineralogical and firing tests. Of these, 11 samples contained significant smectite (Table 31) and were discussed in the chapter on **Bentonite**. However, on further testing, some of these samples indicated favourable properties for use as structural clay, and this is discussed below.

Karratha region

Firing tests indicated that all five samples collected from localities south and west of Karratha (GSWA 145196–99 and 117801) were too sandy and did not produce good strong bars on firing at temperatures above 1000°C. However, sample GSWA 117802, from about 1 km east of Lulu Creek (Fig. 82), on the way to Roebourne from Karratha, produced a strong dark-red bar at 1160°C, indicating that it is suitable for use in the manufacture of bricks (Table 77). Chemical analysis of the sample showed 10.5% Al₂O₃, 63.1% SiO₂, and 6.85% Fe₂O₃, indicating that the chemical composition of the sample is acceptable for use as structural clay (Table 78). However, the sample contained a high amount of smectite that could be undesirable for some uses. This sample was collected from the bank (1.5 m high) of a small creek on the northern side of the highway, and the clay bed appears to extend at least approximately 1.5 km south of the highway.

Roebourne region

Firing tests results for three samples (GSWA 117803–05) collected from localities around Roebourne indicated good material for use as filler material in the manufacture of bricks. Sample GSWA 117803 is from clayey material near Big Tree Well (near Cleaverville; Fig. 83) and samples GSWA 117804–05 are from alluvial clay horizons close to the Harding River (near Roebourne; Fig. 84). All three samples produced strong deep- to dark-red coloured bars at temperatures of around 1160°C, indicating that the material could be used in the manufacture of bricks (Table 77). Chemical analyses of these samples showed that Al₂O₃ ranged from 7.39 to 12%, SiO₂ from 56.4 to 77%, and Fe₂O₃ from 4.44 to 8.84%, and were within acceptable limits for use as structural clay (Table 78). However, the samples contain up to 40% of smectite (Table 31), which could be undesirable for some uses. The firing tests for two samples (GSWA 117806–07) from east of Roebourne (Fig. 81) produced soft bars due to their high sand and limy contents and are therefore considered unsuitable for use as structural clay (Table 77).

Whim Creek region

There are extensive areas of clay, sand, and gravel around Whim Creek, which extend for distances of over 50 km.

Table 75. Mineralogy of structural clay samples from the Albany–Fraser Orogen and Bremer Basin

Locality	Willyung Hill	West of Albany	Bornholm	Bornholm	Wilson Inlet	Close to Oyster Harbour	Close to Oyster Harbour
GSWA no.	117831	117832	117833	117834	117835	117836	117837
Kaolinite	major	minor	minor	subdominant	major	major	major
Halloysite	—	—	—	—	—	—	—
Smectite	—	—	—	—	—	—	—
Mica/illite	?minor	—	—	minor	—	minor	—
Vermiculite	?minor	—	—	?minor	?minor	—	—
Attapulgite	—	—	—	—	—	—	—
Talc	—	—	—	—	—	—	—
Quartz	dominant	dominant	dominant	subdominant	dominant	dominant	dominant
K-feldspar	—	?minor	major	—	minor	—	—
Na-feldspar	—	—	?minor	—	—	—	—
Amphibole	—	—	—	—	—	—	—
Calcite	—	—	—	—	?minor	—	—
Dolomite/ankerite	—	—	—	—	—	—	—
Hematite	minor	—	—	—	—	—	—
Anatase	—	?minor	—	—	—	—	—
Goethite	major	?minor	minor	minor	?minor	minor	minor
Gibbsite	minor	minor	minor	minor	minor	minor	minor
Halite	—	—	—	—	—	—	—
Ilmenite	—	—	—	—	—	—	—

Locality	Close to Oyster Harbour	King River	King River	Kalgan	Boxwood Hill	Boxwood Hill	Boxwood Hill
GSWA no.	117838	117839	117840	117841	117843	117846	117847
Kaolinite	major	subdominant	major	subdominant	major	major	subdominant
Halloysite	—	—	—	—	—	—	—
Smectite	—	—	—	—	?minor	—	—
Mica/illite	minor	minor	minor	minor	minor	minor	minor
Vermiculite	—	?minor	?minor	—	—	—	—
Attapulgite	—	—	—	—	—	—	—
Talc	—	—	—	—	—	—	—
Quartz	dominant	subdominant	dominant	subdominant	dominant	dominant	dominant
K-feldspar	—	—	—	—	minor	?minor	—
Na-feldspar	—	—	—	—	major	—	—
Amphibole	—	—	—	—	—	—	—
Calcite	—	—	—	—	—	—	—
Dolomite/ankerite	—	—	—	—	—	—	—
Hematite	—	—	—	?minor	?minor	—	—
Anatase	—	—	—	—	—	—	—
Goethite	minor	minor	—	minor	—	—	—
Gibbsite	minor	—	minor	minor	—	—	—
Halite	—	—	—	—	—	—	—
Ilmenite	—	—	—	—	—	—	—

Table 75. (continued)

Locality	Boxwood Hill	Munglinup	Munglinup	Coomabidgup	Monjigup (Lake Road)	Coramup Hill	Esperance (Dempster Road)
GSWA no.	117848	117854	117855	117856	117857	117859	117860
Kaolinite	major	dominant	dominant	major	minor	major	major
Halloysite	—	—	—	—	—	—	—
Smectite	—	—	—	—	—	—	—
Mica/illite	—	—	—	—	—	—	—
Vermiculite	?minor	—	—	—	—	—	—
Attapulgite	—	—	—	—	—	—	—
Talc	—	—	—	—	—	—	—
Quartz	dominant	major	major	dominant	dominant	dominant	dominant
K-feldspar	minor	—	—	—	minor	minor	minor
Na-feldspar	—	?minor	?minor	—	minor	—	—
Amphibole	—	—	—	—	—	—	—
Calcite	—	?minor	—	—	—	—	—
Dolomite/ankerite	—	—	—	—	—	—	—
Hematite	?minor	—	—	—	—	—	—
Anatase	—	—	—	—	—	—	—
Goethite	—	—	minor	?minor	—	?minor	?minor
Gibbsite	—	—	—	?minor	—	—	?minor
Halite	—	—	—	—	—	—	—
Ilmenite	—	—	—	—	—	—	—

Locality	White Lake	Gibson	Gibson	Gibson	Scadden	Scadden
GSWA no.	117861	117862	117863	117864	117865	117866
Kaolinite	major	major	major	?major	major	minor
Halloysite	—	—	—	?major	—	?minor
Smectite	—	—	—	—	—	—
Mica/illite	—	minor	—	—	—	?minor
Vermiculite	—	—	—	—	—	—
Attapulgite	—	—	—	—	—	—
Talc	—	—	—	—	—	—
Quartz	dominant	major	dominant	major	dominant	dominant
K-feldspar	?minor	major	minor	minor	?minor	?minor
Na-feldspar	—	—	—	—	—	?minor
Amphibole	—	—	—	—	—	—
Calcite	—	—	—	—	—	minor
Dolomite/ankerite	—	—	—	—	—	?minor
Hematite	—	—	—	—	—	—
Anatase	—	—	—	—	—	—
Goethite	?minor	?minor	?minor	?minor	?minor	—
Gibbsite	—	—	minor	—	—	—
Halite	—	—	—	minor	—	—
Ilmenite	—	—	—	—	—	—

NOTE: Dominant: >50%; subdominant: 40–50%; major: 10–40%; minor: 2–0%

Table 76. Test results for structural clay samples from the Albany–Fraser Orogen and Bremer Basin

Locality GSA no.	Willyung Hill 117831	West of Albany 117832	Bornholm 117833	Bornholm 117834	Wilson Inlet 117835	Close to Oyster Harbour 117836
Salt (ppm)	140	243	655	334	262	212
pH	6.4	5.5	6.7	5.2	6.9	5.3
>90 mm (%)	39.8	53.6	63.4	61.6	53	61.4
Shrinkage (%)						
Drying (110°C)	0.5	0	2.5	2.5	3.5	0.5
Firing	0	0	0	1	2	<0.5
Total	0.5	0	2.5	3.5	5.5	0
Friability index	8	10	10	10	10	10
Fired temperature (°C)	1160	1160	1160	1220	1160	1160
Fired colour	Red	Cream	Red to dark red	Off white	Light red	Light red
C (%)	0.164	0.799	1.03	0.131	0.187	0.338
S (%)	0.0193	0.0043	0.0306	0.0529	0.0387	0.0117
Comments	Material is very silty and contains some gravel. Yields a soft bar at 1160°C and is unsuitable for brickmaking (Appendix 3)	Sandy material with some creamy shale. Contaminated with organic material (Appendix 3)	Material is too sandy and silty and is unsuitable for brickmaking (Appendix 3)	Yields a soft bar. Contains quartz and some ironstone. Not suitable for brickmaking (Appendix 3)	Material is very sandy. Yields a soft bar and is unsuitable for brick-making (Appendix 3)	Very silty material. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)
Locality GSA no.	Close to Oyster Harbour 117837	Close to Oyster Harbour 117838	King River 117839	King River 117840	Kalgan 117841	Manypeaks 117842
Salt (ppm)	148	121	328	187	173	2 814
pH	6.6	6.8	5.1	5.2	6.4	7.8
>90 mm (%)	78	71	18.2	65.4	12.2	66.8
Shrinkage (%)						
Drying (110°C)	0	0.5	3.5	0	6	5
Firing	0	<0.5	2	0.5	5	0.5
Total	0	0	5.5	0.5	11	5.5
Friability index	10	10	5–6	10	1–2	10
Fired temperature (°C)	1160	1160	1220	1220	1220	1160
Fired colour	Red	Red	Off white	Off white to white	Light red to terracotta	Dark red
C (%)	0.283	0.114	0.0729	0.126	0.0989	0.108
S (%)	0.0153	0.0036	0.0175	0.0063	0.0128	0.0137
Comments	Yields a soft bar and is unsuitable for brick-making	Too sandy. Unsuitable for brickmaking	Fine silty material with some ironstone. Good fast-drying material, but does not yield a very strong bar at 1220°C (Appendix 3)	Contains fine white sand and a trace of mica. Yields a soft bar at >1220°C. Unsuitable for brick-making (Appendix 3)	Contains fine silty material with ironstone that acts as a pigment during firing. Yields a strong bar at 1220°C. Suitable clay for brick-making (Appendix 3)	Yields a very soft bar at >1160°C and is unsuitable for brickmaking (Appendix 3)

Table 76. (continued)

Locality	Boxwood Hill	Qualinup Swamp	Qualinup Swamp	Boxwood Hill	Boxwood Hill	Boxwood Hill
GSWA no.	117843	117844	117845	117846	117847	117848
Salt (ppm)	1 847	2 083	1 681	962	1 882	3 669
pH	9.1	9.1	9.1	8.1	8.2	7.5
>90 mm (%)	48.6	19.2	59.4	42	67.6	51.2
Shrinkage (%)						
Drying (110°C)	6.5	8	4	2.5	0	6
Firing	1.5	1.5	0	0	0	1.5
Total	8	9.5	4	6	0	7.5
Friability index	10	5–6	10	6	10	10
Fired temperature (°C)	1160	1160	1160	1220	1220	1160
Fired colour	Red to dark red	Red	Red	Dark to off white	Light yellow	Red
C (%)	0.0607	0.133	0.343	0.022	0.0261	0.0644
S (%)	0.0103	0.048	0.008	0.0055	0.0058	0.025
Comments	Contains sand, silt, and some ironstone. Unsuitable for brick-making (Appendix 3)	Yields a soft bar and is unsuitable for brick-making (Appendix 3)	Too sandy and silty. Unsuitable for brick-making (Appendix 3)	Too sandy and silty. Unsuitable for brick-making (Appendix 3)	Very sandy. Yields a soft bar and is unsuitable for brick-making (Appendix 3)	Very sandy. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)
Locality	Munglinup	Munglinup	Coomabidgup	Monjigup (Lake Road)	Coramup Hill	Esperance (Dempster Road)
GSWA no.	117854	117855	117856	117857	117859	117860
Salt (ppm)	12 567	761	532	97	773	393
pH	7.8	7.7	6.4	7.2	6.9	8.4
>90 mm (%)	49.8	48.2	82.6	96	69.2	60.2
Shrinkage (%)						
Drying (110°C)	4.5	3	Does not yield a bar	Does not yield a bar	4	3.5
Firing	3	1.5	Too sandy	Too sandy	0.5	2.5
Total	7.5	4.5			4.5	6
Friability index	10	10			10	10
Fired temperature (°C)	1160	1160	1160	1160	1160	1160
Fired colour	Orange and cream	Red	–	–	Red	Light red
C (%)	0.247	0.0628	0.301	0.0801	0.0908	0.21
S (%)	0.0501	0.015	0.0137	0.0028	0.0088	0.011
Comments	Yields a soft bar and is unsuitable for brick-making (Appendix 3)	Yields a soft bar at >1160°C and is unsuitable for brick-making (Appendix 3)	–	–	Very sandy material. Yields a soft bar and is unsuitable for brick-making (Appendix 3)	Very sandy material. Yields a soft bar and is unsuitable for brickmaking (Appendix 3)

Table 76. (continued)

Locality GSWA no.	White Lake 117861	Gibson 117862	Gibson 117863	Gibson 117864	Scadden 117865	Scadden 117866
Salt (ppm)	1 770	3 687	560	16 874	1 888	2 206
pH	7.7	7.6	8	–	5.2	9.3
>90 mm (%)	62.6	66	60.6	44.4	57.2	47.6
Shrinkage (%)						
Drying (110°C)	5	2.5	6.5	2	3	4.5
Firing	1	0.5	4	3	0.5	1
Total	6	3	10.5	5	3.5	5.5
Friability index	10	10	10	10	10	10
Fired temperature (°C)	1160	1160	1160	1160	1160	1160
Fired colour	Orange	Orange	Red	Orange	Red	Red
C (%)	0.112	0.121	0.14	0.22	0.0654	0.591
S (%)	0.0304	0.0575	0.0102	0.0444	0.0186	0.0123
Comments	Too sandy and silty. Unsuitable for brick- making (Appendix 3)	Yields a soft bar and is unsuitable for brick- making (Appendix 3)	Yields a soft bar and is unsuitable for brick- making (Appendix 3)	Yields a soft bar and is unsuitable for brick- making (Appendix 3)	Too sandy and silty. Unsuitable for brick- making (Appendix 3)	Yields a soft bar. Unsuitable for brick- making (Appendix 3)

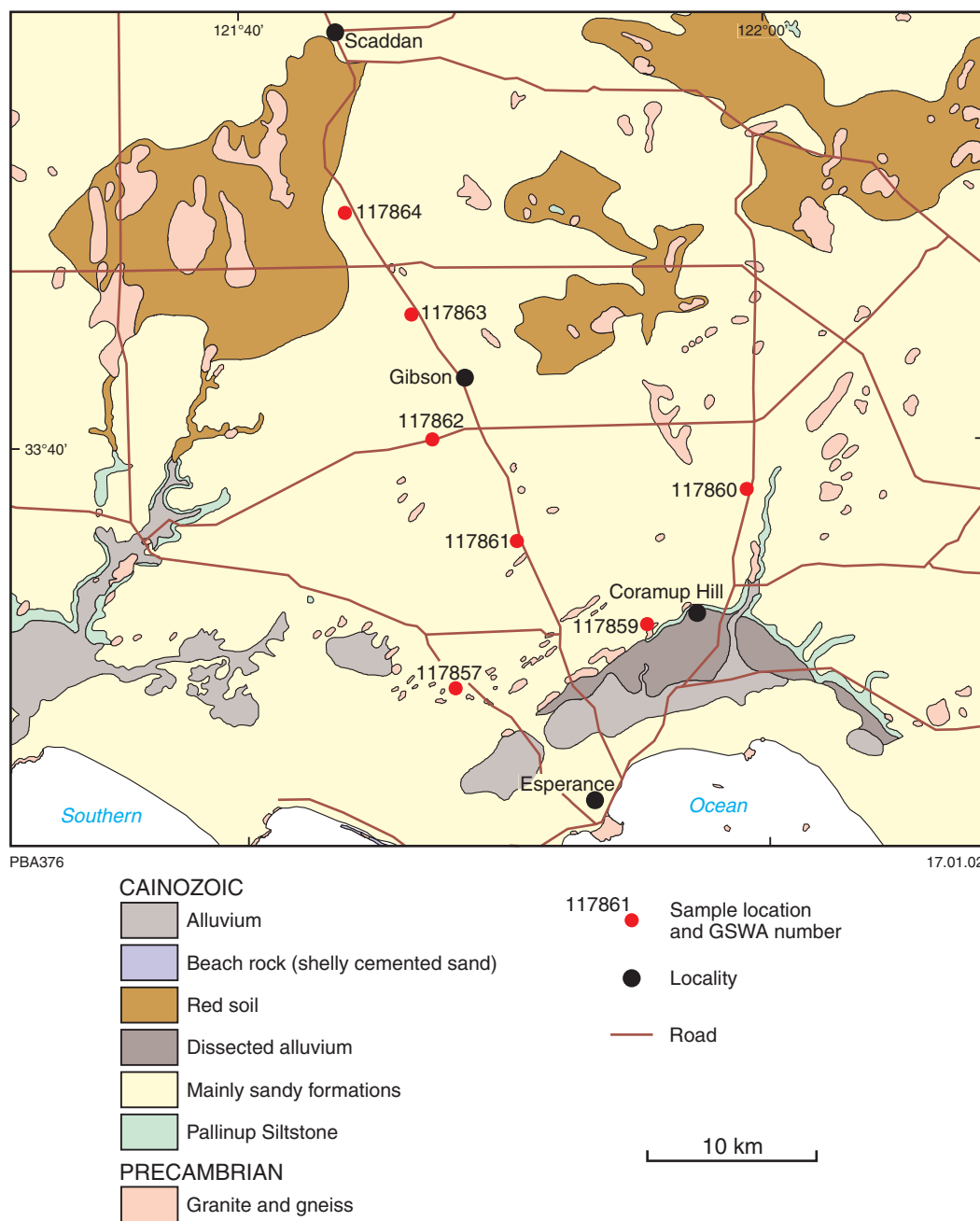


Figure 80. Regional geology of the area around Esperance (modified from Morgan, 1972)

Table 77. Test results for structural clay samples from the Karratha, Roebourne, and Port Hedland regions

Locality GSA no.	Karratha 145196	Karratha 145197	Karratha 145198	Maitland River 145199	Yannery River 117801
Salt (ppm)	38 940	873	790	30 798	4 932
pH	8.3	8.2	8.8	7.2	7.9
>90 µm (%)	40.2	60.6	38.2	46.6	62
Shrinkage (%)					
Drying (110°C)	4	1.5	7	4	2
Firing	1.5	0.5	—	2	0
Total	5.5	2	—	6	2
Friability index	2	6	10	0	3
Fired temperature (°C)	1160	1160	1160	1160	1160
Fired colour	Dark red with cream spots	Light green	Dark red	Deep red with cream spots	Dark red with grey spots
C (%)	0.683	1.95	1.68	0.644	0.921
S (%)	0.0482	0.0126	0.0095	0.0264	0.0406
Comments	High salt content and unsuitable for brickmaking(Appendix 3)	Material consists of excessive coarse red sand and is unsuitable for brickmaking (Appendix 3)	High limestone contamination and the bar exfoliated. Unsuitable for brickmaking	Material is sandy and contains a high proportion of limestone and excessive salt. Unsuitable for brickmaking (Appendix 3)	Contains a high proportion of silica and appreciable limestone. Unsuitable for brickmaking (Appendix 3)

Locality GSA no.	Lulu Creek 117802	Cleaverville 117803	Roebourne 117804	Roebourne 117805	Harding River 117806
Salt (ppm)	6 643	445	24 426	17 995	390
pH	7.8	8.3	8	7.6	8
>90 µm (%)	27.6	5.6	27.2	71.8	25.2
Shrinkage (%)					
Drying (110°C)	8	9	3.5	0.5	4
Firing	1.5	1.5	4	0	4.5
Total	9.5	10.5	7.5	0.5	8.5
Friability index	1	1	0	2	0–1
Fired temperature (°C)	1160	1160	1160	1160	1160
Fired colour	Dark red	Dark red to very dark red	Deep red	Deep red	Dark red
C (%)	0.71	1.5	0.358	0.157	0.855
S (%)	0.266	0.0074	0.2	0.0165	0.0087
Comments	Contains red sand, some gravel, and limestone. Suitable for red filler (Appendix 3)	Fine clay. Strong bar at >1160°C. Good red-firing clay (Appendix 3)	Fine and silty material. Good strong bar, possible good red filler (Appendix 3)	Red sand and silt. Low fusing temperature. Possibly suitable for red filler (Appendix 3)	Contains red sand, silt, and some gravel. Unsuitable for brickmaking (Appendix 3)

Table 77. (continued)

Locality GSWA no.	Jones River 117807	Whim Creek 117808	Whim Creek 117809	Strelley River 117814	De Grey River 117815
Salt (ppm)	35 931	22 656	25 960	613	193
pH	7.6	7.3	9.8	7.5	7.8
>90 µm (%)	24.8	40.8	62.6	31.8	31.4
Shrinkage (%)					
Drying (110°C)	7	5	3	1.5	4.5
Firing	4.5	4	2.5	3.5	2
Total	11.5	9	5.5	5	6.5
Friability index	0	0	2	0	0–1
Fired temperature (°C)	1160	1160	1160	1160	1160
Fired colour	Deep red with cream spots	Deep red	Deep red and some glaze	Deep red	Deep red
C (%)	0.236	0.132	0.0208	0.6	0.207
S (%)	0.681	0.0838	0.19	0.0068	0.0049
Comments	Contains red sand and some gravel. Unsuitable for brick-making due to high salt content (Appendix 3)	Contains red sand and shale. Very strong bar and good colour. Could be used as good red filler (Appendix 3)	Contains red sand and silt. Low fusing temperature. Bar exfoliated when drying. Possible use as red filler (Appendix 3)	Low fusing temperature and yields a strong bar at >1160°C. Dries fast and is good for use as red filler (Appendix 3)	Low fusing temperature and yields a strong bar at >1160°C. Dries fast and is good for use as red filler (Appendix 3)

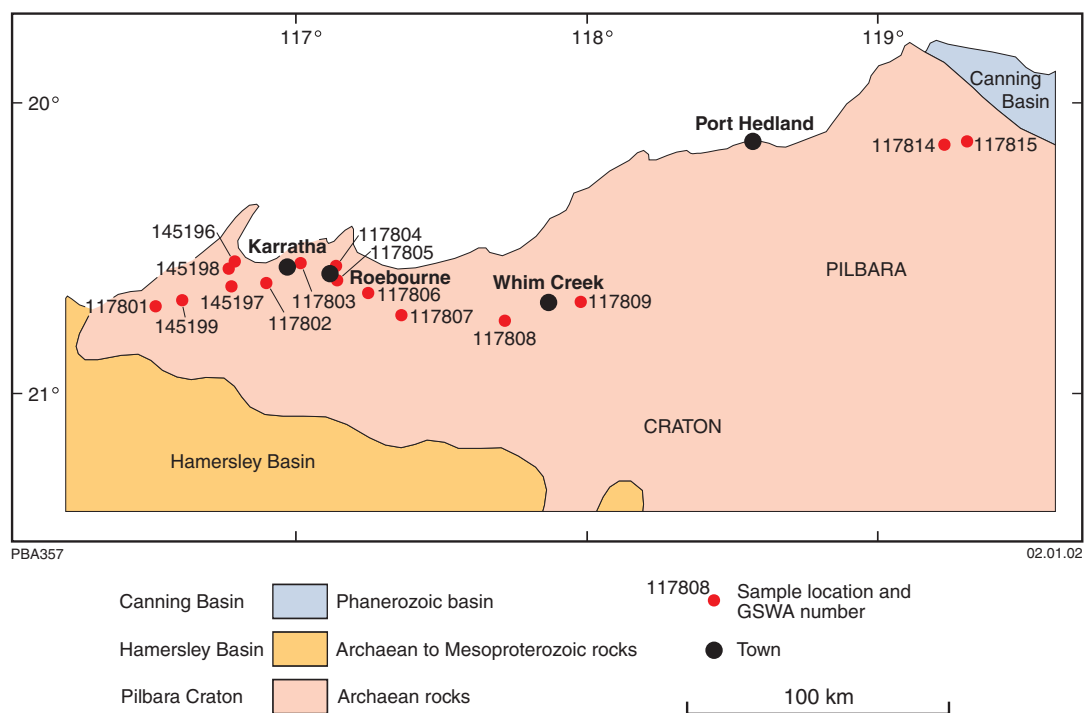


Figure 81. Clay sample localities in the Karratha, Roebourne, Whim Creek, and Port Hedland regions

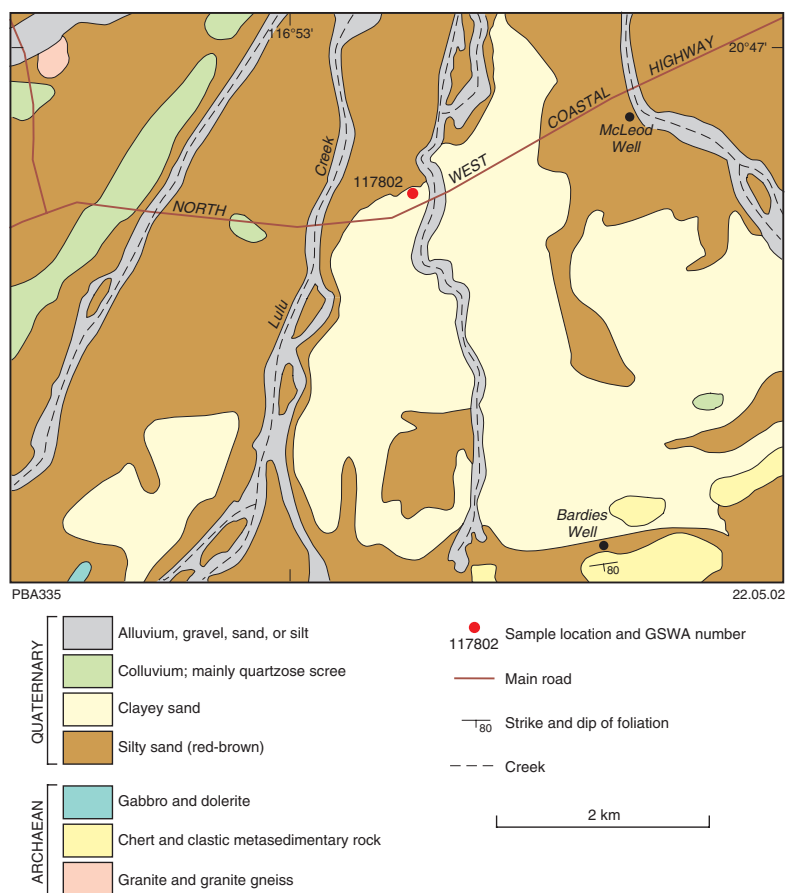


Figure 82. Geology of the area around Lulu Creek (modified from Biggs, 1979)

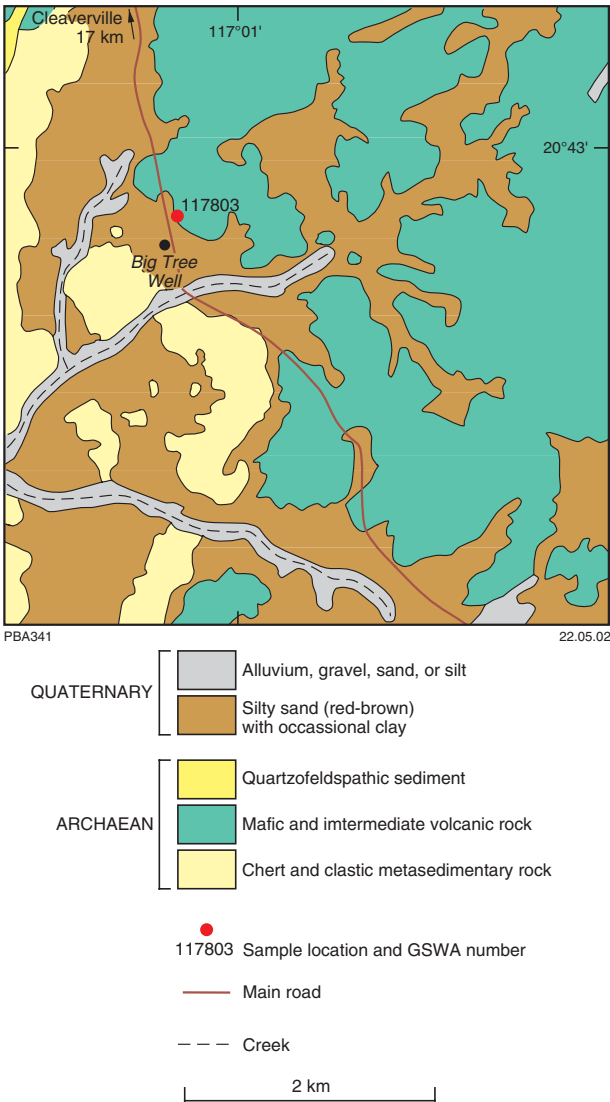


Figure 83. Geology of the area around Big Tree Well (modified from Archer, 1979a)

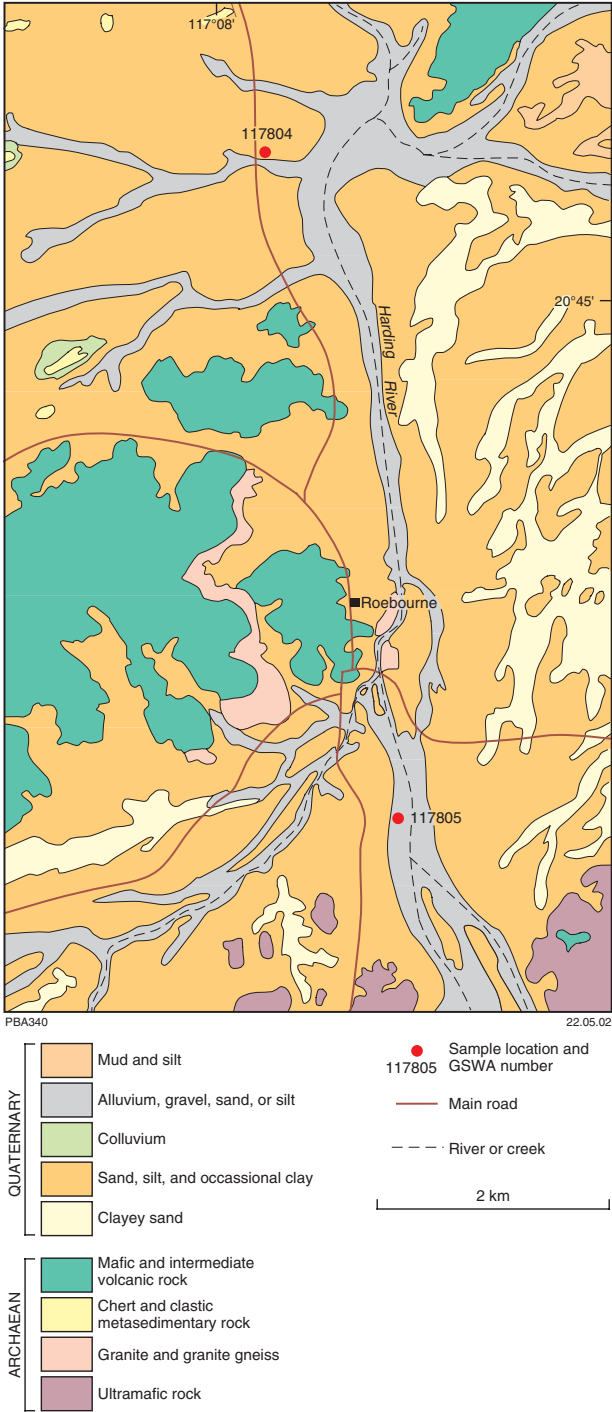


Figure 84. Geology of the area around Roebourne (modified from Archer, 1979a,b)

Table 78. Chemical analyses of structural clay samples from the Karratha, Roebourne, Whim Creek, and Port Hedland regions

Locality	Lulu Creek	Cleaverville	Roebourne	Roebourne	Whim Creek	Whim Creek	Strelley River	De Grey River
GSWA no.	117802	117803	117804	117805	117808	117809	117814	117815
Percentage								
SiO ₂	63.10	56.40	64.90	77.00	68.10	74.30	70.40	70.50
Al ₂ O ₃	10.50	12.00	10.50	7.39	11.80	9.75	11.40	11.60
TiO ₂	0.65	0.86	0.64	0.81	0.65	0.33	0.65	0.71
Fe ₂ O ₃	6.85	8.50	8.84	4.44	6.67	4.78	5.77	5.99
MnO	0.12	0.11	0.08	0.09	0.07	0.04	0.08	0.10
CaO	4.37	5.97	1.40	1.45	0.63	0.19	0.89	0.63
K ₂ O	1.11	1.08	1.55	1.80	2.05	1.95	2.17	1.82
MgO	2.20	2.19	1.99	1.40	1.78	0.93	1.24	1.22
P ₂ O ₅	0.05	0.05	0.03	0.03	0.03	0.03	0.06	0.04
SO ₃	0.55	0.05	0.25	0.05	0.27	0.39	0.02	0.01
BaO	0.05	0.04	0.05	0.04	0.07	0.05	0.06	0.05
Na ₂ O	0.66	0.41	0.94	0.95	1.63	1.98	1.34	1.19
LOI	10.00	12.40	8.04	4.13	5.93	4.84	5.18	5.03
Total	100.21	100.06	99.21	99.58	99.68	99.56	99.26	98.89
H ₂ O ⁻	2.62	2.72	2.22	1.26	1.24	1.28	1.21	1.29

Most of these Pleistocene horizons are distributed within the drainage systems associated with the Balla Balla River, Peawah River, and Poverty Creek. Two samples (GSWA 117808–09; Fig. 85), collected from localities within 15 km of Whim Creek, produced good strong deep-red bars on firing at temperatures of around 1160°C, indicating that the material could be used in the manufacture of bricks (Table 77). The Al₂O₃ of these samples ranged from 9.75 to 11.8%, SiO₂ from 68.1 to 74.3%, and Fe₂O₃ from 4.78 to 6.67%, and these values are within acceptable limits for use as structural clay

(Table 78). XRD studies indicated that the samples contained more than 50% quartz and major feldspar, with possible minor smectite (Table 79).

Port Hedland region

Large areas around the Strelley and De Grey rivers, about 65–70 km east of Port Hedland, are covered with Quaternary alluvial clay horizons. Two clay samples (GSWA 117814–15; Fig. 81) from the alluvial deposits near the Strelley and De Grey rivers produced strong bars with a deep-red colour at 1160°C (Table 77). The Al₂O₃ of these samples ranged from 11.4 to 11.6%, SiO₂ from 70.4 to 70.5%, and Fe₂O₃ from 5.77 to 5.99%, and these values are within acceptable limits for use as structural clay (Table 78). However, the samples contained

Table 79. Mineralogy of structural clay samples from the Whim Creek area

Locality	Whim Creek	Whim Creek
GSWA no.	117808	117809
Kaolinite	minor	minor
Halloysite	—	—
Smectite	?minor	?minor
Mica/illite	minor	minor
Vermiculite	?minor	?minor
Attapulgite	—	—
Talc	minor	—
Quartz	dominant	dominant
K-feldspar	major	major
Na-feldspar	—	—
Amphibole	minor	—
Calcite	?minor	—
Dolomite/ankerite	—	—
Hematite	?minor	—
Anatase	—	—
Goethite	—	—
Gibbsite	—	—
Halite	—	minor
Analcime	—	minor

NOTE: Dominant: >50%; subdominant: 40–50%; major: 10–40%; minor: 2–0%

Table 80. Test results for structural clay from the Minderoo area

GSWA no.	145195
Salt (ppm)	536
pH	8.2
>90 µm (%)	10
Shrinkage (%)	
Drying (110°C)	7.5
Firing	7
Total	14.5
Friability index	0
Fired temperature (°C)	1160
Fired colour	Dark red
C (%)	0.253
S (%)	0.0176
Comments	Material contains some fine biotite and has a good strong red-firing colour suitable for brickmaking (Appendix 3)

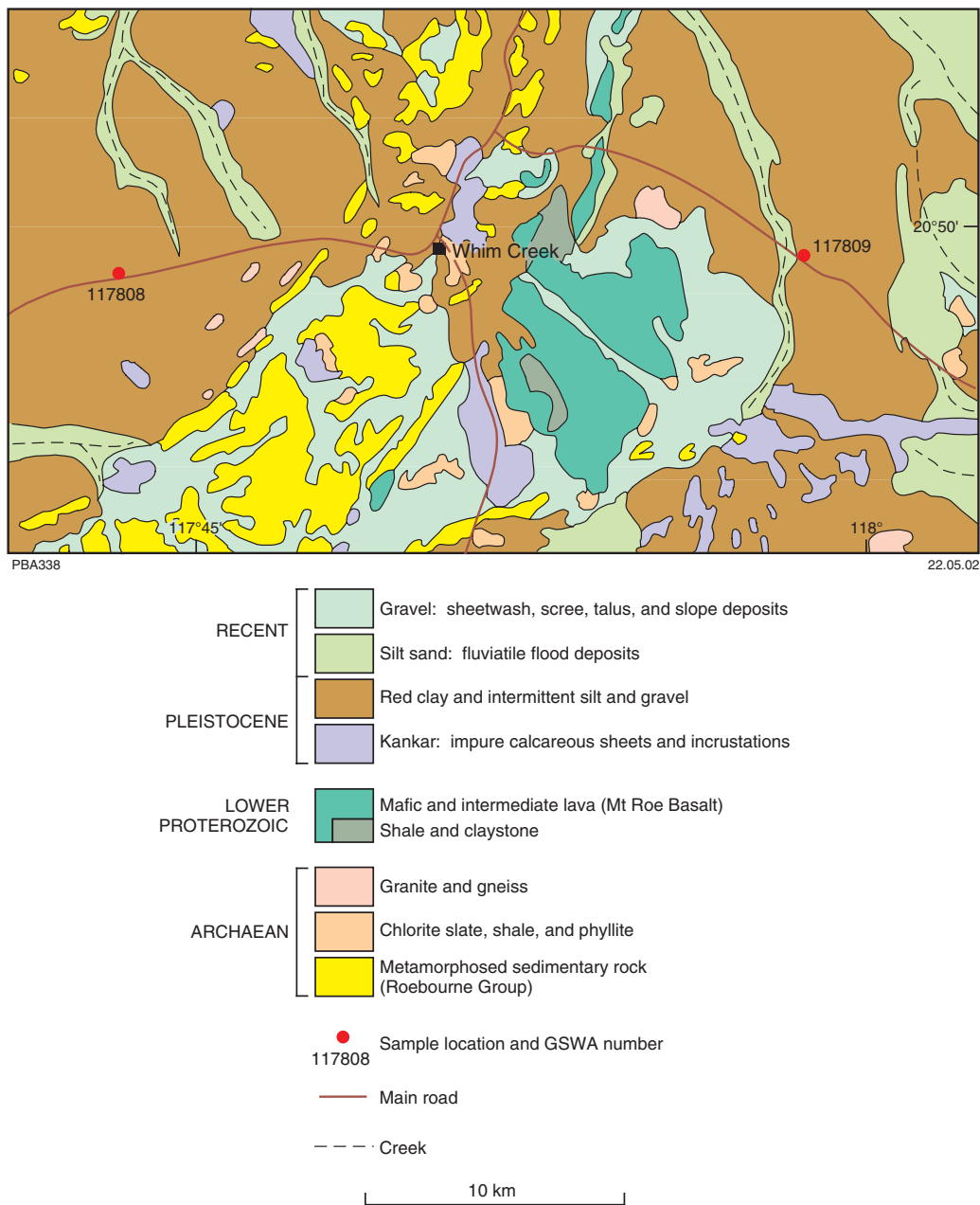


Figure 85. Regional geology of the area around Whim Creek (modified from Ryan et al., 1965)

high amounts of smectite (Table 31), which could be undesirable for some uses.

Deposits in the Carnarvon Basin

Minderoo

Between Minderoo and Onslow, there are numerous claypans, as well as bare, red-brown sandy clays (Fig. 42). Sample GSWA 145195 was collected from a clay horizon close to a claypan. The clay horizon, as seen in some of the vertical erosional cliff faces, appeared to be more than

2 m thick. The clay was red, somewhat plastic, and contained fine biotite. The dry clay on the surface at this location was cracked and formed rounded thin flakes approximately 10–20 mm across. The sample had a high smectite content, with the firing tests producing a strong red-coloured bar that indicated good material for use as a filler (Table 80).

Chapter 5

Summary

Bentonite

The widely used definition of bentonite is that it is a clay-rich rock consisting essentially of montmorillonite from the smectite group of minerals, regardless of its origin or occurrence. Depending upon whether sodium or calcium is the dominant exchangeable ion, the variety of montmorillonite may be either sodium or calcium montmorillonite. Bentonite is commonly classified on its swelling capacities when wet or added to water. Sodium-rich bentonite has very high swelling capacities and forms gel-like masses when added to water. Calcium-rich bentonite has much lower swelling capacities than the sodium-rich varieties. Saponite, hectorite, nontronite, and saunonite are different varieties of smectite minerals having respectively magnesium, lithium, iron, and zinc as the cation substitution in the clay structure. The name 'fuller's earth' is used for clay or other fine-grained, earthy material suitable for bleaching, absorbent, and certain other uses, although it has no compositional or mineralogical meaning.

The important uses of bentonite are in drilling mud, iron ore pelletizing, foundry sand, pet litter, impermeable layers and liners in civil engineering applications, animal feeds, bleaching oils, and detergents.

The annual global production of bentonite is about 8–9 Mt. The largest producer of bentonite is the USA, with a production of about 4 Mt of bentonite in 1997. In Australia, current production of bentonite is limited to Queensland (60 000 tpa) and New South Wales (10 700 tpa), with minor production from Western Australia (358 t reported during 1999–2000). Prior to 2000 (during the period 1942–77), Western Australia produced 15 483 t of bentonite valued at \$A117 283.

The price of bentonite products varies depending on the grade. For example, the price of Wyoming foundry-grade bentonite (with 85% <200 mesh) is much higher (about \$A350 per tonne) than for Wyoming crude bentonite (approximately \$A65 per tonne). Prices have shown an upward trend since 1996. The resurgence in the oil-well drilling sector has boosted demand for bentonite and this is expected to continue.

In Western Australia, bentonite deposits of economic significance are known in the Marchagee, Watheroo, Cardabia, and Calwynyardah regions. The smectite variety

in most of the bentonite deposits in Western Australia is the magnesium-rich variety, saponite, although the Cardabia deposits contain nontronite (iron-rich smectite). High-grade sodium bentonite, similar to that at Wyoming in the USA, has not yet been found in Western Australia.

Bentonite in the Marchagee and Watheroo areas is dominantly a saponitic bentonite and is restricted to the Quaternary alluvial deposits in a number of claypans. The deposits in the Watheroo area (Lakes A, B, and E) contain a resource of about 435 000 t. The current owner of the Watheroo deposits is looking at promoting the material for use as a geotechnical clay sealant, mainly for uses in landfill sites, water run-offs, compensating basins–settling ponds, and tailings dams.

The dominant smectite mineral in the bentonite from Cardabia is nontronite, an iron-rich smectite. The tests on the Cardabia bentonite carried out for various applications have not been conclusive, but preliminary tests suggest that the chemically treated material can be used as a binding agent in iron-ore pellet production, but more research would be required.

Bentonite, consisting of mainly saponite clay, is associated with the tuffaceous crater-lake sediments overlying the Calwynyardah lamproite field. The resource of bentonite in the deposit is estimated at about 4.4 Mt. Since the exploration target in this area is diamonds, the bentonite has not been rigorously tested for its quality and possible uses.

Other known smectite occurrences in the State are restricted to occurrences in the Karratha area on the Pilbara Craton, at Wokalup and Bengier in the Perth Basin, at Qualinup Swamp and Manypeaks in the Albany–Fraser Orogen, and a number of localities on the Yilgarn Craton.

Attapulgitite

Attapulgitite, also known as palygorskite, is a cream to grey hydrated magnesium silicate with a fibrous or chain-type structure. The name 'fuller's earth' (as well as palygorskite) is also used in the USA for attapulgitite.

The important uses of attapulgitite are as a suspending agent (in adhesives, cosmetics, sealants, liquid detergents, shampoos, flexographic inks, etc), and in drilling mud,

NCR paper, animal feed, pet litter, pharmaceuticals, and a number of other uses utilizing its absorbent properties.

Global production of attapulgite is approximately 2.8 Mtpa and of this more than 90% is produced from the USA. Australian attapulgite production is about 20 000 tpa, and all of this is from the Lake Nerramayne deposit in Western Australia.

The prices of various grades of attapulgite have remained stable during 1994–97, and have shown an increasing trend from 1997–99. The price of speciality gel grades in 1999 was approximately \$A805, whereas that of granular grades was about \$A250–530. The most significant growth in attapulgite applications is expected to be in its use as a thickener, gellant, suspension agent, and stabilizer in a wide range of industries.

The only known locality for commercially significant attapulgite deposits in Western Australia is Lake Nerramayne. The deposits are found in playa lakes at the western margin of the Yilgarn Craton. The playa lakes are elongate and parallel to the Darling Fault. The high-grade horizons generally contain in excess of 65% attapulgite, smectite clay, and kaolinite, and the low-grade horizons contain 45–65% of this material. The Lake Nerramayne deposit is currently owned and operated by Hudson Resources. The main product from the plant is pet litter, which is sold in Australia, New Zealand, Japan, and Asia. Other uses are as a pesticide carrier, stockfeed and fertilizer binder, and soil conditioner.

The Lake Nerramayne attapulgite deposit is yet to be developed to its true potential. With a measured reserve of 10 Mt and an inferred resource of another 100 Mt, Hudson Resources is well placed to diversify its products and increase its markets and production. At the current production levels, the deposit has a mine life in excess of 100 years. The deposit is strategically located near the port of Geraldton, comparatively close to many rapidly developing markets in South East Asia.

The only other known attapulgite occurrence in the State is at Boodanoo Hill, near Mount Magnet. However, the claypan–playa lakes north of the Murchison River, in the Byro Pool area, and the extensive lake system further north on Muggen Station (approximately 130 km north of Lake Nerramayne), could be considered as potential areas for attapulgite.

Construction industry clay

Construction industry clay includes a wide variety of clay and weathered fine-grained rocks, such as shale, that are used to make products such as structural and fire bricks, drain tiles, vitrified pipes, and roofing tiles. Clay is also one of the raw materials used in cement manufacture. The surface weathering of almost any hard rock, with the exception of pure sandstone and limestone, can form clay.

The common uses of structural clays are in the manufacture of a wide variety of bricks, pipes, and tiles. Other uses include the manufacture of terracotta, art

pottery, modelling clays, and aggregates. Most of the construction industry clay produced in Western Australia is used in the manufacture of bricks, pipes, and tiles. Significant exceptions are the use of clay by Alcoa for residue liners, and the use of clay by cement manufacturers.

In 1999, the production of construction industry clay in Western Australia, as reported to DMPR, was 72 059 t, but the true figure is considered to be in excess of 2.3 Mt. More than 99% of the construction industry clay produced in the State is from the Perth Metropolitan Area, with the remainder produced from Geraldton. The brick industry in Western Australia is well established and is dominated by two major companies, Midland Brick Company Pty Ltd and Metro Brick (owned by Bristle Ltd), in the Perth region. There is also significant production of bricks in regional towns such as Geraldton. The Perth-based companies, as well as factories in regional centres, export significant quantities of bricks to overseas destinations. The high-quality products from West Australian companies appear to be capturing more markets in the Asian region, as well as in other States of Australia.

Construction industry clay is widely distributed in Western Australia, but the known resources of high-quality material are restricted to Perth. Potential sources of structural clay in the Perth Basin are associated with many geological units, and some of the more important units are the Guildford Formation, Leederville Formation, Osborne Formation, Cardup Group, and Yarragadee Formation. The localities producing structural clay in the Perth region include Muchea – Bullsbrook East, the Swan Valley, Armadale–Cardup–Byford–Mundijong, Toodyay, and Gidgegannup. The identified resources in the Perth region (on the basis of areas approved by the Government and Local Government organizations) are estimated to total 37.1 Mt, with 31.1 Mt estimated in not approved areas.

Prospective areas of clay for use as structural clay in the northern areas of the Perth Basin include Camac, Bootenall, and alluvial and colluvial formations around Geraldton. In the southern region of the Perth Basin, prospective areas for construction industry clay include Wokalup, Bengier, Roelands, and Waterloo.

On the Yilgarn Craton, construction industry clays suitable for structural clay applications are known in a number of regions, and some of the more notable areas include Mount Kokeby, Brookton, Bolgart, Goomalling, Corrigin, Katanning, Collie, Piawanning, Manjimup, and Narrogin. A number of clay samples collected from localities around Albany, Ravensthorpe, and Kalgoorlie produced hard solid bars on firing at temperatures above 1160°C, indicating the suitability of the material for use as structural clay.

Numerous clay samples tested from the Roebourne region on the Pilbara Craton were also found to contain suitable material and produced solid bars when fired to temperatures above 1160°C, thus indicating the suitability of the material for use as structural clay.

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Appendix 1

Locations of samples collected by the author

<i>GSWA no.</i>	<i>Locality</i>	<i>1:250 000 map sheet</i>	<i>Latitude</i>	<i>Longitude</i>
117801	Yannery River	DAMPIER	20°52'28"	116°30'54"
117802	Lulu Creek	DAMPIER	20°47'38"	116°53'46"
117803	Cleaverville	ROEBOURNE	20°43'32"	117°00'54"
117804	Roebourne	ROEBOURNE	20°44'10"	117°08'12"
117805	Roebourne	ROEBOURNE	20°47'07"	117°08'24"
117806	Harding River	ROEBOURNE	20°49'40"	117°14'44"
117807	Jones River	ROEBOURNE	20°54'18"	117°21'39"
117808	Whim Creek	ROEBOURNE	20°55'24"	117°42'44"
117809	Whim Creek	ROEBOURNE	20°51'33"	117°58'36"
117814	Strelley River	PORT HEDLAND	20°19'05"	119°13'41"
117815	De Grey River	PORT HEDLAND	20°18'21"	119°18'20"
117816	Wokalup	COLLIE	33°06'14"	115°52'42"
117817	Benger	COLLIE	33°13'24"	115°50'35"
117818	Roelands	COLLIE	33°17'29"	115°47'07"
117819	Waterloo	COLLIE	33°19'24"	115°45'57"
117820	Newlands	COLLIE	33°41'26"	115°53'07"
117821	Greenbushes	COLLIE	33°53'25"	116°06'23"
117822	Manjimup	PEMBERTON	34°17'24"	116°08'39"
117823	Boyup Brook	COLLIE	33°48'54"	116°23'33"
117824	Dinninup	COLLIE	33°48'10"	116°32'24"
117825	Highbury	DUMBLEYUNG	33°04'25"	117°14'47"
117826	Boundain	CORRIGIN	32°56'55"	117°17'37"
117827	Highbury	DUMBLEYUNG	33°01'49"	117°13'49"
117828	Woodanilling	DUMBLEYUNG	33°33'11"	117°25'12"
117829	Tenterden	MOUNT BARKER – ALBANY	34°22'44"	117°32'57"
117830	Kendenup	MOUNT BARKER – ALBANY	34°29'27"	117°35'43"
117831	Willyung Hill	MOUNT BARKER – ALBANY	34°55'54"	117°50'19"
117832	Albany	MOUNT BARKER – ALBANY	34°56'21"	117°39'27"
117833	Albany	MOUNT BARKER – ALBANY	35°01'33"	117°35'41"
117834	Albany	MOUNT BARKER – ALBANY	34°59'30"	117°33'10"
117835	Denmark	MOUNT BARKER – ALBANY	34°59'10"	117°15'26"
117836	Kalgan–Albany	MOUNT BARKER – ALBANY	34°57'45"	117°59'45"
117837	Kalgan–Albany	MOUNT BARKER – ALBANY	34°59'27"	117°59'34"
117838	Kalgan–Albany	MOUNT BARKER – ALBANY	34°56'10"	117°56'05"
117839	King River	MOUNT BARKER – ALBANY	34°55'08"	117°57'00"
117840	Kalgan–Albany	MOUNT BARKER – ALBANY	34°54'31"	117°58'06"
117841	Kalgan	MOUNT BARKER – ALBANY	34°51'48"	118°03'52"
117842	Manypeaks	MOUNT BARKER – ALBANY	34°41'56"	118°12'24"
117843	Boxwood Hill	BREMER BAY	34°22'19"	118°46'12"
117844	Qualinup Swamp	BREMER BAY	34°24'11"	119°02'51"
117845	Qualinup Swamp	BREMER BAY	34°24'25"	119°00'28"
117846	Boxwood Hill	BREMER BAY	34°22'58"	118°50'08"
117847	Boxwood Hill	BREMER BAY	34°19'46"	118°46'30"
117848	Boxwood Hill	BREMER BAY	34°15'36"	118°49'58"
117849	Jerramungup	NEWDEGATE	33°54'28"	119°02'25"
117850	Fitzgerald River	NEWDEGATE	33°44'59"	119°20'51"
117851	West River	NEWDEGATE	33°39'32"	190°45'06"
117852	Ravensthorpe	RAVENSTHORPE	33°35'00"	120°08'47"
117853	Ravensthorpe	RAVENSTHORPE	33°36'08"	120°12'27"
117854	Munglinup	RAVENSTHORPE	33°42'52"	120°52'38"
117855	Munglinup	RAVENSTHORPE	33°44'50"	121°03'57"
117856	Coomabidgup	RAVENSTHORPE	33°42'34"	121°25'05"
117857	Monjigup Lake Road	ESPERANCE	33°47'57"	121°47'58"
117859	Coramup Hill	ESPERANCE	33°45'57"	121°55'26"
117860	Dempster Road	ESPERANCE	33°41'36"	121°59'21"
117861	White Lake	ESPERANCE	33°43'12"	121°50'25"
117862	Gibson	ESPERANCE	33°39'53"	121°47'11"
117863	Gibson	ESPERANCE	33°35'49"	121°46'25"
117864	Gibson	ESPERANCE	33°32'30"	121°43'54"
117865	Scadden	ESPERANCE	33°23'11"	121°41'34"
117866	Scadden	ESPERANCE	33°10'04"	121°42'42"
117867	Salmon Gums	NORSEMAN	32°55'41"	121°37'03"
117868	Lake Gilmore	NORSEMAN	32°46'24"	121°32'45"
117869	Lake Cowan	NORSEMAN	32°04'14"	121°40'47"

Appendix 1 (continued)

<i>GSWA no.</i>	<i>Locality</i>	<i>1:250 000 map sheet</i>	<i>Latitude</i>	<i>Longitude</i>
117870	Higginsville	WIDGIEMOOLTHA	31°46'36"	121°41'33"
117871	Widgiemooltha	WIDGIEMOOLTHA	31°39'34"	121°38'48"
117872	Mandilla	WIDGIEMOOLTHA	31°17'39"	121°29'44"
117873	Kambalda	WIDGIEMOOLTHA	31°04'19"	121°37'02"
117874	Feysville	KURNALPI	30°59'08"	121°34'31"
117875	Feysville	KURNALPI	30°54'07"	121°31'50"
117876	Kalgoorlie	KALGOORLIE	30°38'08"	121°26'59"
117877	Paddington	KALGOORLIE	30°30'21"	121°22'30"
117878	Mount Vettors	KALGOORLIE	30°16'33"	121°14'32"
117879	Menzies	MENZIES	29°44'21"	121°03'05"
117880	Bullabulling	BOORABBIN	31°01'57"	120°50'24"
117881	Bullfinch	SOUTHERN CROSS	30°59'12"	118°58'59"
117882	Warralakin	SOUTHERN CROSS	31°01'33"	118°32'30"
117883	Mukinbudin	BENCUBBIN	30°53'05"	118°06'58"
117884	Kununoppin	KELLERBERRIN	31°03'17"	117°56'34"
117885	Yelbeni	KELLERBERRIN	31°01'42"	117°40'43"
117886	Watheroo Lake E	MOORA	30°09'26"	115°57'19"
117887	Watheroo Lake E	MOORA	30°09'26"	115°57'19"
117888	Watheroo Lake B	MOORA	30°13'12"	116°08'23"
117889	Watheroo Lake A	MOORA	30°07'25"	115°58'36"
145171	Bibby Road	DONGARA – HILL RIVER	30°28'23"	115°21'57"
145172	Bibby Road	DONGARA – HILL RIVER	30°27'18"	115°18'48"
145173	Gairdner Range	DONGARA – HILL RIVER	30°15'36"	115°10'41"
145174	Camac	DONGARA – HILL RIVER	30°02'53"	115°22'01"
145175	Pinjarrega Lake	MOORA	30°02'21"	115°43'46"
145176	Three Springs	PERENJORI	29°37'39"	115°49'45"
145177	Marchagee	MOORA	30°03'25"	116°00'14"
145178	Marchagee	MOORA	30°03'25"	116°00'14"
145179	Yandanooka	PERENJORI	29°24'00"	115°36'41"
145180	Mount Horner	DONGARA – HILL RIVER	29°05'35"	115°10'50"
145181	Mount Hill	DONGARA – HILL RIVER	29°03'23"	115°08'34"
145182	Ellendale Bluffs	GERALDTON	28°52'14"	114°56'28"
145183	Lake Nerramyne	AJANA	27°47'00"	115°26'08"
145184	Lake Nerramyne	AJANA	27°46'59"	115°26'04"
145185	Lake Nerramyne	AJANA	27°46'58"	115°25'57"
145186	Lake Nerramyne	AJANA	27°47'00"	115°25'56"
145187	Lake Nerramyne	AJANA	27°46'53"	115°26'00"
145188	Lake Nerramyne	AJANA	27°46'47"	115°26'02"
145189	Lake Nerramyne	AJANA	27°46'47"	115°26'02"
145190	Mount Sommer	GERALDTON	28°41'41"	114°43'28"
145191	Nanson	GERALDTON	28°35'33"	114°43'31"
145192	Nabawa	GERALDTON	28°26'37"	114°45'12"
145194	Minderoo	ONSLOW	21°52'57"	115°02'42"
145195	Minderoo	ONSLOW	21°51'03"	115°03'08"
145196	Karratha	DAMPIER	20°43'13"	116°47'17"
145197	Karratha travel stop	DAMPIER	20°48'19"	116°46'33"
145198	Karratha rubbish tip road	DAMPIER	20°44'37"	116°46'00"
145199	Maitland River	DAMPIER	20°51'14"	116°36'24"

NOTE: Locations are from GPS observation (GDA94)

Appendix 2

Other localities discussed in the Bulletin

<i>Locality</i>	<i>1:250 000 map sheet</i>	<i>Latitude</i>	<i>Longitude</i>
Balkuling	KELLERBERRIN	31°57'02"	117°06'03"
Bardoc	KALGOORLIE	30°21'00"	121°18'00"
Beverley	PINJARRA	32°07'00"	116°55'00"
Bolgart	PERTH	31°16'00"	116°30'00"
Boodanoo Hill	KIRKALOCKA	28°34'34"	118°18'47"
Bootenall	GERALDTON – HOUTMAN ABROLHOS	28°52'00"	114°38'00"
Brookton	PINJARRA	32°19'23"	116°54'38"
Busseton	BUSSETON–AUGUSTA	33°47'00"	115°30'00"
Calwynyardah	NOONKANBAH – LENNARD RIVER	17°59'55"	124°46'59"
Cane River	ONSLow	21°46'30"	115°20'31"
Capercup	COLLIE	33°33'51"	116°41'41"
Cardabia	WINNING POOL – MINILYA	23°33'00"	114°04'59"
Cardup	PINJARRA	32°15'00"	115°59'46"
Chandler	KELLERBERRIN	31°06'00"	118°25'00"
Clackline	PERTH	31°43'00"	116°31'00"
Collie	COLLIE	33°23'00"	116°16'00"
Corrigin	CORRIGIN	32°20'00"	117°52'00"
Cunderdin	KELLERBERRIN	31°44'00"	117°18'00"
Dale River	PINJARRA	32°14'35"	116°49'10"
Duranillin	COLLIE	33°31'00"	116°48'00"
Dwellingup	PINJARRA	32°44'35"	116°05'14"
Ferguson	BUSSETON–AUGUSTA	33°37'18"	115°29'39"
Gidgegannup	PERTH	31°48'00"	116°11'00"
Glen Forrest	PERTH	31°55'00"	116°06'00"
Goomalling	PERTH	31°18'00"	116°50'00"
Gutha	KIRKALOCKA	28°58'47"	117°06'03"
Jennacubbine	PERTH	31°26'00"	116°43'01"
Kanowna (approximate)	KALGOORLIE	30°36'00"	121°36'00"
Katanning	DUMBLEYUNG	33°41'00"	117°33'00"
Koordarrie	YANREY–NINGALOO	22°11'00"	115°02'00"
Lower Chittering	PERTH	31°34'50"	116°01'10"
Meckering	KELLERBERRIN	31°33'00"	117°07'59"
Middle Swan	PERTH	31°51'22"	116°01'01"
Mount Kokeby	PINJARRA	32°16'52"	116°51'27"
Muchea	PERTH	31°35'00"	115°58'00"
Narrogin	CORRIGIN	32°56'00"	117°10'00"
Piawanning	MOORA	30°50'00"	116°23'00"
Quairading	CORRIGIN	32°01'00"	117°24'00"
Rocky Pool	KENNEDY RANGE	24°05'00"	114°07'59"
Toodyay	PERTH	31°33'00"	116°28'00"
Upper Swan	PERTH	31°46'00"	116°01'00"
Wagin	DUMBLEYUNG	33°16'30"	117°18'30"
Wellard	PINJARRA	32°18'38"	115°51'00"

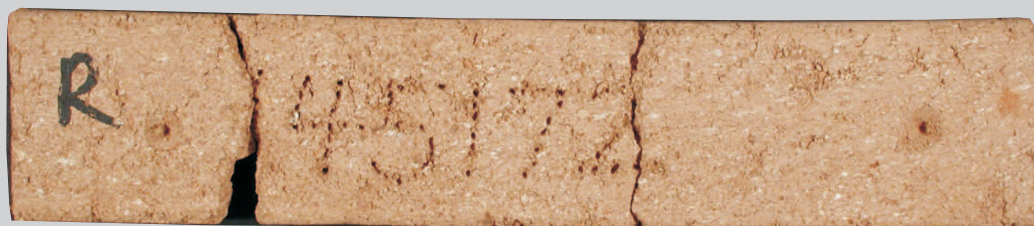
NOTE: Locations are based on published reports and/or GSWA geological series maps at 1:50 000 and 1:250 000 scale

Appendix 3

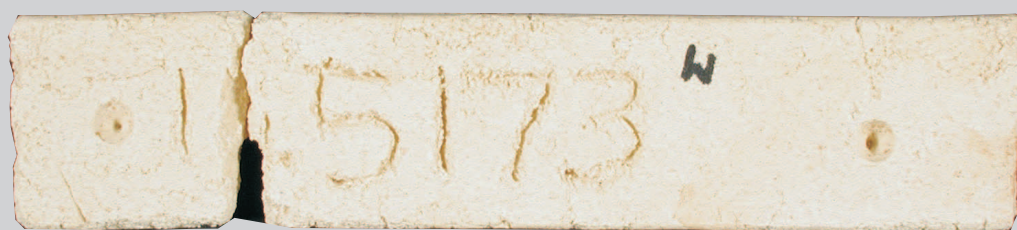
**Photographs of fired structural clay samples
collected from various localities
during the current project**



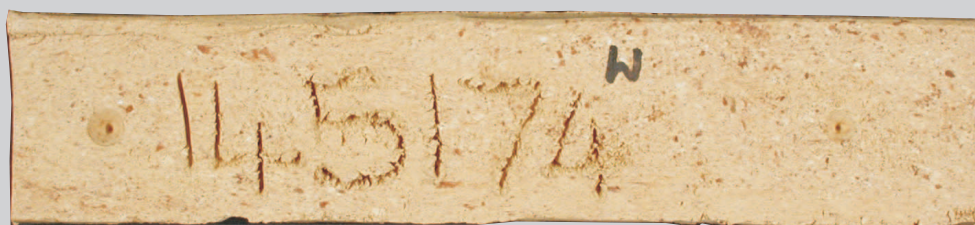
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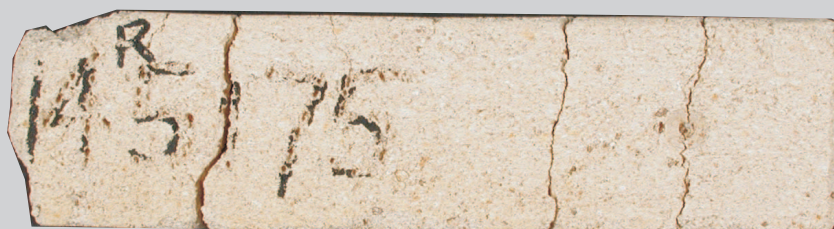
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145173



145174



145175

5 cm



145176



145179



145180



145181



145182

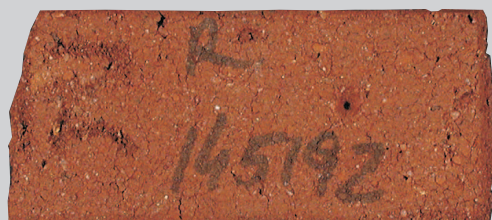
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145191



145192



145195



145196

5 cm



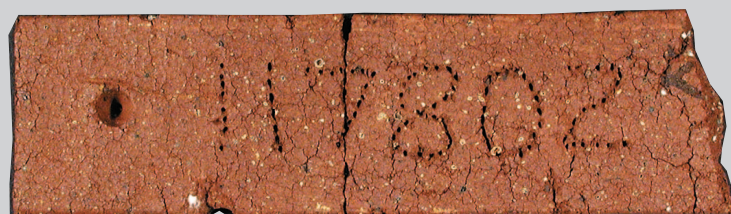
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145199



117801



117802



117803

5 cm



117804



117805



117806



117807

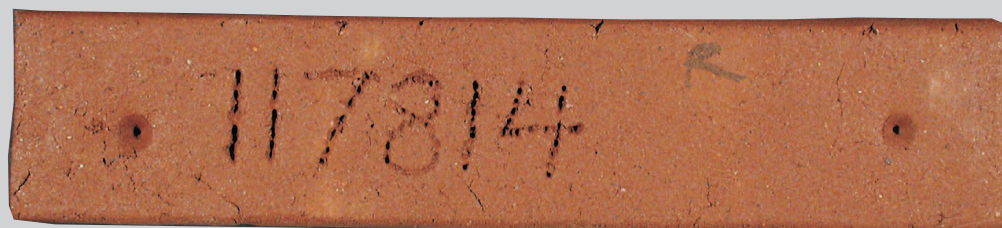


117808

5 cm



117809



117814



117815



117816



117817

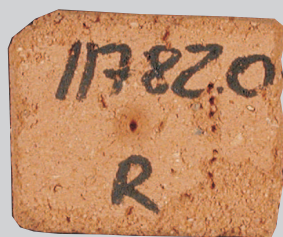
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117819



117820



117822

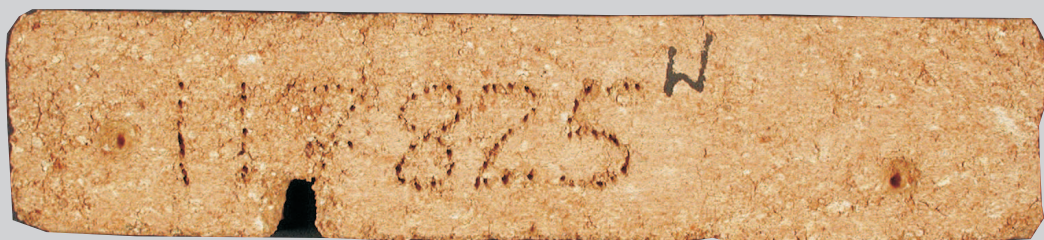


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5 cm



117824



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117828

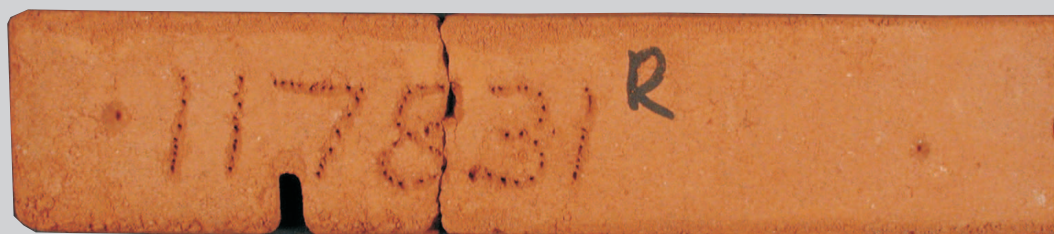
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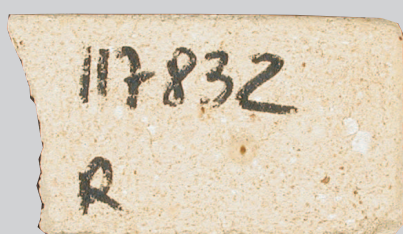
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117831



117832



117833

5 cm



117834



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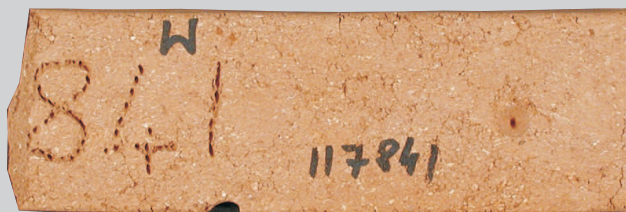


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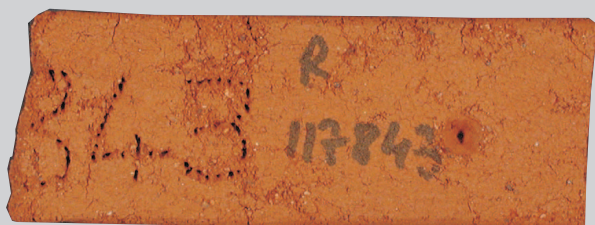
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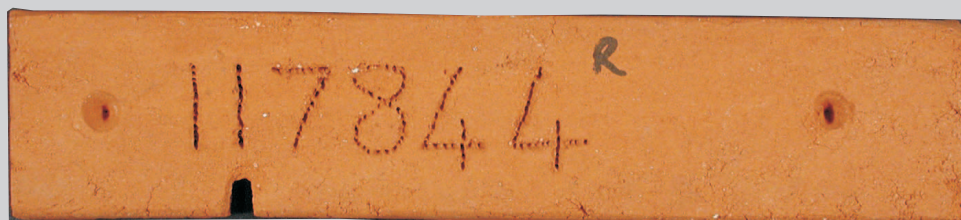
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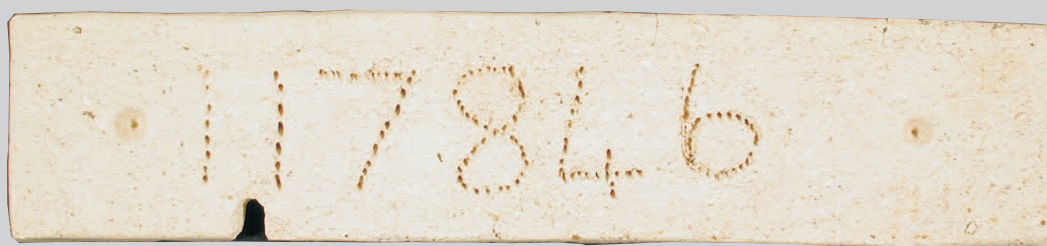


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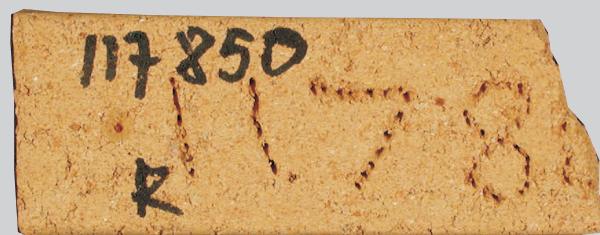
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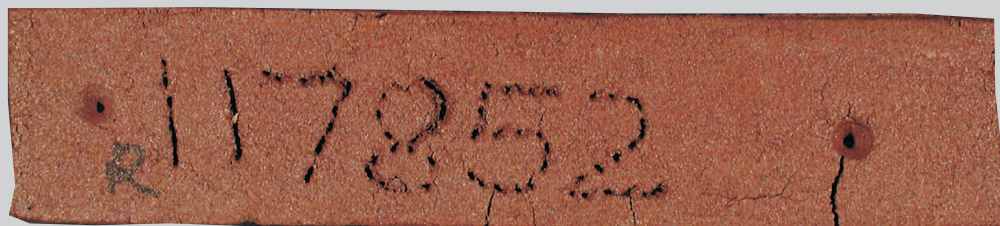


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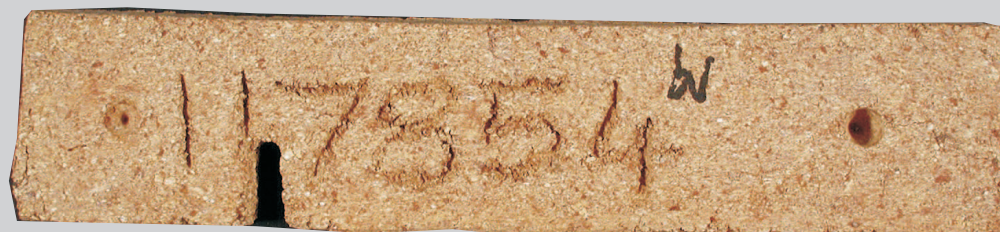
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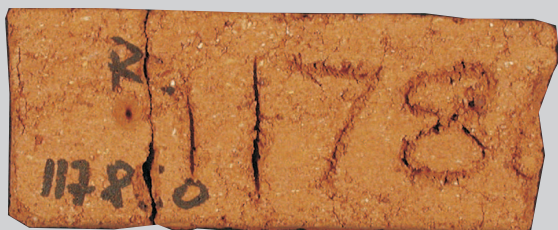


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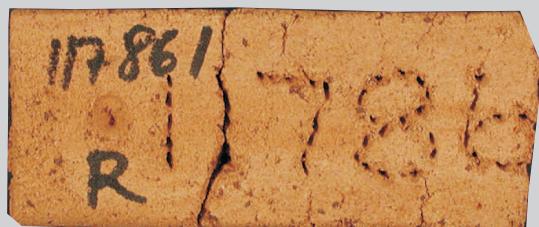
5 cm



117859



117860



117861



117862



117863

5 cm



117864



117865



117866



117867



117868

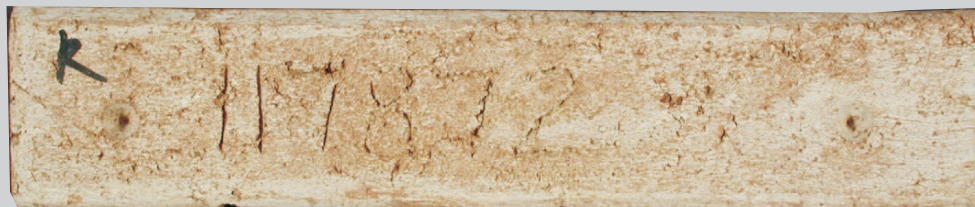


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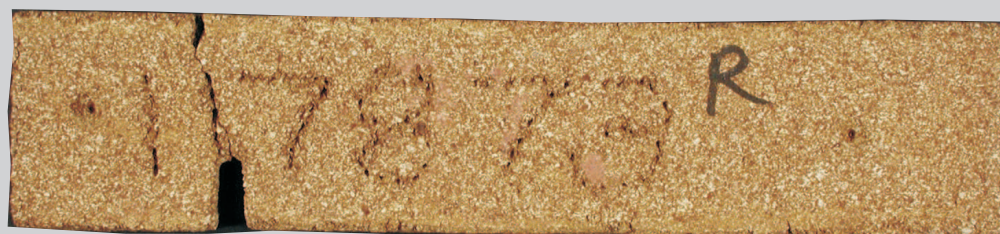
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117871



117872



117873

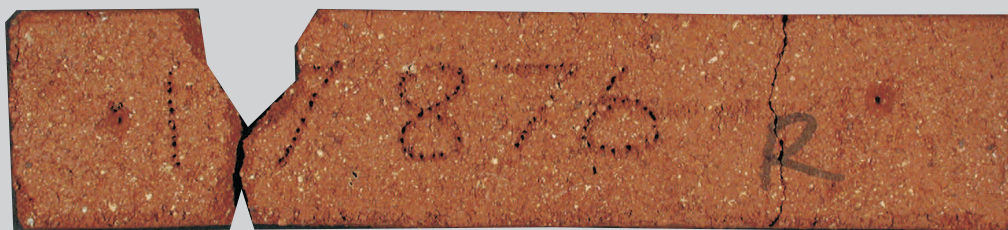


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117875

5 cm



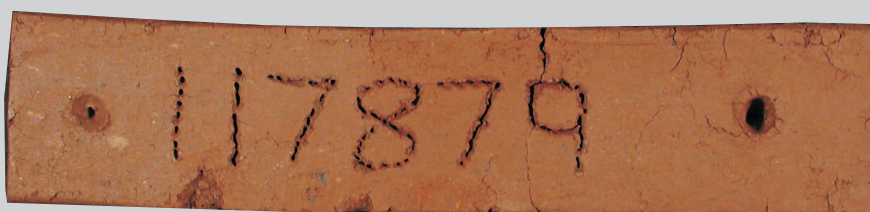
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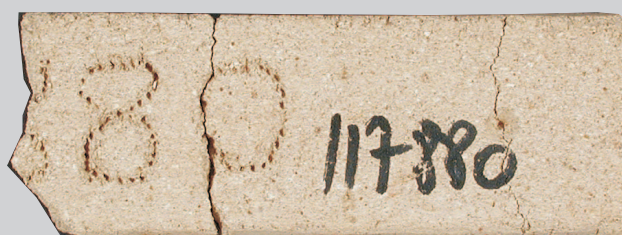
117877



117878



117879



117880

5 cm



117881



117882



117883



117884



117885

5 cm

Appendix 4

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This Bulletin on bentonite, attapulgite, and common clays in Western Australia compiles much of the available published and unpublished information on these clay resources in the State, and highlights their development potential. Bentonite is currently only mined at Watheroo, but there are a number of other sites with significant potential. Attapulgite is currently mined at Lake Nerramyne and this deposit has great scope for expansion of its activities. The production of construction industry or common clays is primarily centred around Perth and other large population centres, and this Bulletin documents the testing of such clays throughout the State.



Further details of geological publications and maps produced by the Geological Survey of Western Australia can be obtained by contacting:

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Department of Mineral and Petroleum Resources
100 Plain Street
East Perth WA 6004
Phone: (08) 9222 3459 Fax: (08) 9222 3444
www.mpr.wa.gov.au**