MINERAL RESOURCES BULLETIN 19

GOVERNMENT OF WESTERN AUSTRALIA

KAOLIN IN WESTERN AUSTRALIA

by P. B. Abeysinghe and J. M. Fetherston

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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Cover photograph:
A sample of raw kaolin from the Gabbin deposit in the Murchison terranes of the Yilgarn Craton. The sample consists of fine white kaolin containing coarse quartz grains.

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Kaolin in Western Australia

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Abstract

Western Australia has produced 60 586 t of kaolin (valued at $2.5 million) during the period 1939–97. Greenbushes started production in 1984 and until December 1997 had produced 45 020 t or 74% of the State's total recorded production. Production in recent years has been limited to Greenbushes and Goomalling, with an annual average output during the last seven years (1991–97) of 3384 t, which is only about 2% of the total Australian production. In recent years, the kaolin produced in the State has been used mainly in the ceramics industry.

The State also produced 715 355 t of ball clay (valued at $4.8 million) from 1932 to 1997, and 5.7 Mt of variable grade fireclay (valued at $5.5 million) from 1922 to 1997. Both of these types of clay have been produced from localities in the Darling Range close to Perth, for use in the brick, tile, and pipe industries.

Most of the larger kaolin deposits in the State are residual in origin. The Greenbushes deposit was formed by the weathering of numerous steeply dipping pegmatites, whereas Jubuk, Ockley–Wickepin, Gabbin, and Kerrigan have formed as residual products of weathered granitic rocks in areas of mature drainage systems. Commercially viable transported deposits, developed from the deposition of kaolin in palaeochannels and in lacustrine environments, are less significant, except for the deposit at Mount Kokeby.

Although the historical production of kaolin in the State is low, there are large high-grade deposits that are yet to be developed. These include Jubuk, Ockley–Wickepin, Gabbin, Mount Gibson, and Kerrigan. The total known kaolin resource in the State is approximately 300 Mt (223 Mt inferred and 77 Mt indicated), of which about 50 Mt are suitable for high-grade applications such as paper coating and filler. Most of the kaolin resources are restricted to the Yilgarn Craton in the southwestern region of the State and are within a few hundred kilometres of port facilities. Although many residual kaolin deposits in the South-West terranes contain kaolin of acceptable brightness for paper grade applications, more detailed testing on rheology and particle-size distribution is required to fully evaluate many of these deposits.

KEYWORDS: Western Australia, industrial minerals, industrial mineral resources, mineral processing, Greenbushes, Jubuk, Ockley–Wickepin, Gabbin, Kerrigan, Mount Kokeby, kaolin, ball clay, refractory clays, palaeodrainage, rheology, size distribution, reflectivity.

Chapter 1

Introduction

Object and scope

The main objective of this Bulletin is to compile most of the available published and unpublished information on kaolin resources in the State into one publication, with an emphasis on high-grade material suitable for use as a paper filler and in coating applications. This Bulletin is not intended to be an exhaustive study of all the known occurrences, but is a comprehensive summary and highlights the development potential of a high-grade kaolin industry in Western Australia. In the industry, the term 'kaolin' is used for clays consisting of substantially pure kaolinite, and includes other important clay varieties such as ball clay, refractory clay, and flint clay.

This Bulletin includes information on deposits and occurrences of refractory clays and other industrial grade kaolinitic clays where the relevant information is available. However, it should be noted that the potential of clays in Western Australia for such uses has not been adequately addressed, due mostly to insufficient laboratory testing for such applications.

Sources of information

The sources of information are from both published and unpublished data, supplemented by field inspections. Unpublished information is derived from Geological Survey of Western Australia (GSWA) records, annual reports and technical files, and statutory exploration reports submitted to the Department of Minerals and Energy (DME) by various mining companies. Analytical data for many samples, submitted to DME by prospectors seeking geological advice, are also included in this Bulletin.

Some of the major deposits, and others thought to be significant, were visited and sampled by the authors. Approximately 115 samples were collected for laboratory testing. These were collected during field trips, mostly between March and July 1997. Although many tests are required to ascertain the suitability of kaolin for high-grade applications, the tests carried out for this publication were limited to mineral identification using X-ray powder diffractometry (XRD), mineral identification and crystallinity studies using scanning electron microscopy (SEM), particle-size fractionation studies, brightness measurements, and chemical analysis using X-ray fluorescence (XRF).

The primary reasons for limiting the tests to those above are the reconnaissance nature of the sampling and the excessive cost for other tests such as viscosity measurements. However, test results obtained do provide useful guidelines for interested parties to carry out more detailed exploration and evaluation in selected areas.

SEM and XRD tests were carried out at the Chemistry Centre of Western Australia, whereas all other analytical tests were carried out by Analabs, Perth. Localities of all samples collected by the authors are given in Appendix 1, and the localities of all the kaolin deposits, prospects, and occurrences discussed in this Bulletin are given in Appendix 2.

Bulletin layout

The economic viability of projects involving industrial minerals depends strongly on the location of the deposits in relation to infrastructure, the availability of other competitive minerals, and global production and usage trends. These trends, along with some mineralogical and geological aspects of kaolin, are discussed at length in Chapters 2 and 3.

Although local geological aspects (Chapter 5) are important in locating potential kaolin deposits, geomorphological factors also have a strong bearing on the development and discovery of such deposits. Therefore, a separate chapter (Chapter 4) has been assigned to discuss the geomorphological aspects of Western Australia that are relevant to the formation of kaolinitic clay deposits.

In accordance with the recent style of GSWA Mineral Resources Bulletins, the kaolin occurrences are grouped by tectonic units, with major deposits being discussed first. The tectonic units are primarily based on Memoir 3 (Geological Survey of Western Australia, 1990) although modifications of the boundaries, based on more recent work by Myers and Hocking (1998), have also been taken into account. However, for a more detailed description of the geology of these tectonic units the reader should refer to Memoir 3.

Abbreviations

ASTM	American Society for Testing and Materials
Aus $	Australian dollars
BSS	British Standard Sieve
E	Exploration Licence
GSWA	Geological Survey of Western Australia
ISO	International Standards Organisation
MC	Mineral Claim
M	Mining Lease
ML	Mineral Lease
P	Prospecting Licence
PCE	Pyrometric Cone Equivalent
PP	Private Property
PA	Prospecting Area
SEM	Scanning Electron Microscope
t	Tonnes
USA	United States of America
XRD	X-Ray Powder Diffractometry
TAPPI	Technical Association of the Pulp and Paper Industry

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Although the resource estimates indicated for the Ockley and Kerrigan deposits are based on information from company reports, Rio Tinto Exploration makes no representation in regard to the accuracy of the respective resources.

Chapter 2

Definitions, mode of occurrence and uses of kaolin

Kaolin

The name kaolin is derived from the Chinese term Kauling, the name for a hill near Jauchau Fu, Jiangxi Province in China, where clay was mined many centuries ago. The term kaolin is not uniquely defined in the scientific literature, but is used widely in a variety of ways as a clay-mineral group, a rock term, and as an industrial mineral, and is often used interchangeably with the term china clay.

As a clay-mineral group, kaolin has a theoretical chemical composition of 39.8% alumina, 46.3% silica and 13.9% water, and many kaolin deposits that are used industrially are remarkably close in composition to theoretical values (Murray and Keller, 1993). There is general agreement that kaolin as a rock term is composed of kaolinite (or halloysite) with smaller amounts of illite, montmorillonite, quartz–cristobalite, feldspar, alunite, and various forms of iron and titanium oxide (Harben and Bates, 1990).

Kaolin is typically a white, soft, plastic clay composed of kaolinite with a low iron content, and is made up of randomly oriented stacks of kaolinite flakes, smaller packets and sheaves, and individual flakes. The kaolin-forming clays are hydrous aluminium silicates with an approximate composition of $Al_2Si_2O_5(OH)_4$. Patterson and Murray (1983) defined kaolin as a clay consisting of substantially pure kaolinite (or related clay minerals) that is naturally or can be beneficiated to be white or nearly white, will fire white or nearly white, and is amenable to beneficiation to make it suitable for use in whiteware, paper, rubber, paint, and similar products. Other important varieties of this group are ball clay, refractory clay, and flint clay. Chemical compositions and specifications for some of the commercial kaolin clays are given in Tables 1 to 6.

Ball clay

Ball clay contains 55–80% kaolinite, along with minor quantities of illite, smectite, quartz, and organic matter. The organic matter may darken the clay colour to light grey, blue, brown, or black. The name has been in use in England since at least the 1700s to describe a fine-grained, highly plastic, black to light-grey or brown clay, which could be rolled into oval-shaped masses so that it could be rolled on and off wagons for transport to processing areas. The term is still used in the United Kingdom, United States, India, South Africa, and a few other countries. However, similar clay that is used in the same products as ball clay is commonly referred to as kaolin or china clay in most countries (Murray, 1996).

The American Society for Testing and Materials (ASTM) defines ball clay as a secondary clay (characterized by the presence of organic matter) with high plasticity, high dry strength, a long vitrification range, and a light colour when fired. Patterson and Murray (1983) considered ball clay a variety of kaolin because of the difficulty in distinguishing the minor differences between the light fired colour required by the ASTM definition and the white colour required for kaolin. Within this Bulletin, ball clay is treated as a separate type of clay because of its wide application in marketing and the widespread use of the term in the ceramic industry.

Major deposits of ball clay are the result of deposition of clay material in small swamp-like Tertiary basins, and occur in western Tennessee and Kentucky in the United States, in Devonshire and Dorsetshire in southwestern England, and in the Westwald area located north of Roblenz on the Rhine River in Germany.

Refractory clay (fireclay)

Refractory clay, also known as fireclay, is composed chiefly of kaolinite that does not burn white and can stand temperatures above 1500°C before fusing. The term 'fireclay' has different usages in different countries. The term is of Anglo-Saxon origin and refers to clays found in Carboniferous coal measures in Britain and the eastern USA. Kaolinite in fireclays is typically poorly ordered, in that it has a distinctive disordered b-axis. In Germany, any clay that is used for refractory purposes and contains a b-axis disordered kaolinite is referred to as fireclay. For this reason, fireclay is usually considered to be synonymous with refractory clay.

Refractory clay includes several varieties of kaolinitic clay that are used in the manufacture of products requiring resistance to high temperatures. The performance of refractory clays at high temperatures may be expressed in terms of their pyrometric cone equivalent

Table 1. Chemical composition and specifications for typical ball clays

Commercial grade *Producer/Country*	*Hywite Superb* *South Devon,* *ECCI (UK)*	*Hymod Blue* *Dorset,* *ECCI (UK)*	*1001* *S. Schmidt (Germany)*	*Bandy Black* *Spinks (USA)*	*Troup* *Texas,* *ECCI (USA)*
-2 micron	80	86	65	62	61
-1 micron	70	77	54	49	52
Modulus of rupture (Kgf/cm^2)	24	36	25	21.8	34.3
Casting concentration	65	60	65	60	60
Fired brightness	70	56	58.1	69.1	66.9
1180°C Absorption	6	3.0	6.4	12.7	11.1
Contraction	13	12.1	7.9	9.0	5.4
1240°C Fired brightness	68	51	55.5	[a]54.3	63.6
Absorption	2.6	1.8	2.6	3.2	8.9
1280°C Contraction	15	12.3	13.9	12.8	5.9
SiO_2	49	53	65	56.3	63
Al_2O_3	32	31	21	26.8	24
Fe_2O_3	1.1	1.4	0.95	1.17	1.5
TiO_2	0.9	0.9	1.4	1.54	1.3
CaO	0.2	0.3	0.2	0.08	0.13
MgO	0.4	0.5	0.75	0.35	0.58
K_2O	1.8	3.0	2.1	1.63	0.98
Na_2O	0.2	0.4	0.21	0.25	0.12
LOI	14.0	9.1	8.3	11.9	8.2
Kaolinite	68	57	58	60	66
Mica	20	33	17	21	9
Quartz	7	8	24	17	19
Carbonaceous material	4	1	–	–	–
Geological environment	Freshwater lake or floodplain in fault basin	Freshwater or estuarine wide shallow basin	Freshwater lake in or floodplain	Freshwater lake or floodplain	Freshwater lake or floodplain

NOTE: after Bristow (1987)
(a) at 1280°C
All units are percentage unless otherwise stated

Table 2. Chemical composition and specifications for typical fireclays, flint clays, and chamotte

Commercial grade *Source*	*Fireclay* *Midlands* *(UK)*	*Chamotte* *Charente* *(France)*	*Flint clay* *Oviedo* *(Spain)*	*Flint clay* *Olive Hill,* *Kentucky (USA)*	*Flint clay* *Missouri* *(USA)*
Fired/unfired	Fired	Fired	Fired	Unfired	Unfired
Typical refractories	–	–	–	33–34 PCE	33–34 PCE
SiO_2	51.1	55.2	54.5	45.5	44.42
Al_2O_3	43.6	40.5	41.1	36.0	38.63
Fe_2O_3	2.35	0.97	1.17	1.18	0.55
TiO_2	1.37	1.41	1.22	2.0	2.12
CaO	0.21	0.16	0.11	0.08	0.04
MgO	0.4	0.24	0.10	0.36	0.1
K_2O	0.2	1.04	0.51	1.0	0.3
Na_2O	0.08	0.39	0.11	0.1	0.12
LOI	0.70	0.14	0.2	13.0	13.90
Unfired					
Kaolinite	42	90	86	90	>85
Mica	25	6	6	0.25–0.5	–
Quartz	32	2	7	0.5–1.0	–
Feldspar	–	–	–	–	–
Anatase	1	1	1	tr	–
Fired					
Mullite	47	40	29	–	–
Cristobalite	24	25	–	–	–
Quartz	tr	2	4	–	–
Amorphous material	28	33	65	–	–
Geological environment	Carboniferous coal measure swamp	Eocene fresh-water flood-plain, lacustrine	Regionally metamorphosed Early Palaeozoic shale	Late Carboniferous swamp	Late Carboniferous swamp

NOTE: after Bristow (1987)
All units are percentage
PCE — pyrometric cone equivalent

Table 3. Chemical composition and specifications for typical china clays

Commercial grade Producer/Country	*Standard Porcelain ECCI (UK)*	*Remblend ECCI (UK)*	*Zettlitz 1A KSNP (Czech Republic)*	*Pleyber GX ECCI (France)*	*Burella 201 ECESA (Spain)*	*Cyprucast Cyprus IM (USA)*
+ 10 micron	2.2	17.6	7.3	6	–	17.4
-2 micron	70	39	67.5	61	39	57.6
Modulus of rupture (Kgf/cm^2)	14.0	5.0	14.3	10.0	11.4	4.0
Casting concentration	63	65	59.8	65	63.2	70 approx.
Casting rate	0.35	2.0	0.46	2.0	1.95	1.4
Fired brightness	91	86	89.4	91	91.3	90.4
1180°C Absorption	15	16	16.7	19	19.6	16.1
Contraction	9	7.5	7.9	8	5.5	6.3
Fired brightness	88	87	91.4	89	92.2	87.8
1280°C Absorption	6	9	12.5	10	15.0	13.7
Contraction	14	11	10.9	12	7.5	10.4
SiO_2	47.9	48.1	47	48	51	46
Al_2O_3	37.2	36.7	37	36.8	36	38
Fe_2O_3	0.68	0.93	0.88	0.72	0.72	0.47
TiO_2	0.03	0.05	0.17	0.36	0.02	1.6
CaO	0.07	0.05	0.48	0.18	0.05	0.05
MgO	0.27	0.3	0.43	0.06	0.23	0.09
K_2O	1.59	1.92	0.94	1.76	1.3	0.16
Na_2O	0.08	0.08	0.09	0.06	0.03	0.10
LOI	12.3	11.7	13.3	12.1	11.3	13.6
Kaolinite	88	87	89	89	74	95–97
Mica	9	12	10	9	20	2–3
Quartz	1	1	1	2	6	1
Feldspar	1	tr	–	–	–	–
Anatase	–	–	–	–	–	1
Geological environment	Hydrothermally kaolinized granite	Hydrothermally kaolinized granite	Weathered hydrothermally altered granite	Weathered hydrothermally altered granite	Hydrothermal /weathered felsite sill	Sedimentary kaolin

NOTE: after Bristow (1987)
All units are percentage unless otherwise stated

Table 4. Compositions of commercial ball and ceramic clays

Commercial grade Producer/ Country Usage	*SKD grade WBB (UK) Tableware*	*HTP grade K-T Clays Co (USA) Tableware*	*Sandblend 90 WBB (UK) Sanitary ware*	*Classic K-T Clays Co (USA) Sanitary ware*	*WBB (UK) Porcelain and bone china*	*Westerwald clay Stephen Schmid (Germany) Porcelain*	*Earthenware*
SiO_2	50.0	53.6	56.8	61.1	47.0	66.0	66.0
Al_2O_3	32.9	32.0	27.5	24.6	38	23.0	28.0
Fe_2O_3	1.2	1.1	1.0	11.0	0.39	1.2	1.2
TiO_2	1.0	1.4	1.3	1.4	0.03	1.6	1.6
CaO	0.2	0.3	0.2	0.3	0.1	0.2	0.2
MgO	0.3	0.3	0.3	0.5	0.22	0.5	0.5
K_2O	1.6	0.7	2.2	1.4	0.8	2.2	2.2
Na_2O	0.2	0.1	0.3	0.2	0.15	0.2	0.2
LOI	12.6	10.5	9.5	9.5	13.0	nd	nd
Carbon	1.6	–	1.8	–	–	–	–
pH	4.4	4.8	6.3	5.5	nd	nd	nd

NOTE: modified from Harben (1995)
WBB — Watts Blake Bearne & Co. PLC
nd — not determined
All units are percentage except for pH

Table 5. Typical specifications for commercial paper grade kaolin

	High brightness coating	*Standard coating*	*Fine coating*	*Air float filler*	*Fine filler*	*Fine high brightness filler*	*Middle Georgia coating clay KaoGloss*	
GE brightness (%)	89.5–92.0	85.5–87.5	86.5–88.0	80–81	81–83	84.5–85.5	86.5–87.6	
Particle size, -2 μm (%)	80–100	80–92	94–97	62.7	82–95	82–95	90–93	
Surface area, m^2/g	12–22	12–13	22	15	22	22	–	
325 mesh residue, max. (%)	0.01	0.01	0.01	0.4	0.3	0.3	0.005–0.15	(rotary dried, acid)
Moisture, max.(%)	1.0	1.0	1.0	2.0	slurry	slurry	2–4	(rotary dried, acid)
pH (28% solids)	6.0–7.7	6.0–7.9	6.0–7.10	5.0–7.5	6.0–8.0	6.0–8.0	3.5–4.5	(rotary dried, acid)
Brookfield viscosity, 20 rpm (centipoise)	350	350	350	n/a	n/a	n/a	300 (slurry)	
Viscosity at 70% solids (centipoise)	–	–	–	–	–	–	250 (solid)	

SOURCE: Harben (1995)

Table 6. Typical characteristics of commercial ceramic clays

	Kaolin clay	*Ball clay*
+ 10 µm (%)	2–20	–
-2 µm (%)	35–70	60–86
-1 µm (%)	–	45–80
Modulus of rupture (Kgf/cm^2)	4–15	20–40
Casting concentration (%)	55–70	60–65
Fired brightness	85–92	50–70
Absorption (%)	15–20	3–13
Contraction (%)	5–10	5–15
Fired brightness	87–93	50–70
Kaolinite content (%)	85–97	50–70

NOTE: modified from Harben (1995)

(PCE), which is a method of designating fusion points. The PCE of products made from refractory clays ranges from just above 19 (fusion point of 1541°C) to as high as 37 (fusion point around 1820°C). Refractory clays are classified as low, moderate, high, and super duty, according to their suitability for heat service (Table 7). Some refractory kaolins and fireclays containing diaspore, boehmite, or gibbsite have PCE values as high as 37 (Patterson and Murray, 1983).

Flint clay

Flint clays are hard, massive clay rocks that range in texture from ultra-fine grained to coarsely clastic, and characteristically, although not invariably, occur as basin margin facies in coal-bearing sequences. In New South Wales, Australia, flint clay is mined from coal measures in an area 200–300 km north of Sydney, at the north-western margin of the Sydney Basin. These strata are part of the Jurassic Ukebung Formation, which is composed mainly of flint clay with variable amounts of quartz-lithic sandstone, shale, ironstone, and coal. The source of kaolinite in flint clays is thought to be weathered volcanic rocks (Harben and Kuzvart, 1996).

Most flint clays are composed of comparatively well-ordered kaolinite with a low content of iron and other fluxing components, and are generally highly refractory. Commercial quality flint clay must have a PCE of 32 or higher and a bulk density above 2 g/cm^3. At high firing temperatures, flint clay is converted to a dense mat of interlocking tiny mullite needles and very viscous glass, and it shows high ceramic compatibility with plastic clays at both high and low temperatures. Flint clay refractories have a high resistance to thermal spalling while still retaining high density, a high resistance to slag and metal baths, good physical strength, and high-temperature load-bearing strengths (Bristow, 1987; Loughnan and Roberts, 1989).

Halloysite

Halloysite is a variety of kaolin, commonly formed by low-temperature hydrothermal alteration of acid volcanic rocks, and occurs in two forms. One is a hydrated form having the composition $Al_4Si_4O_{10}(OH)_8.4H_2O$, whereas the other is a dehydrated form with a composition of $Al_4Si_4O_{10}(OH)_8$. The hydrated form has a c-axis spacing greater than that of kaolinite, and is generally a dense porcelain-like, hard clay that dehydrates at surface temperatures or slightly above to a white or light-coloured porous, friable (almost 'cottony-textured') material. The dehydrated form is very similar to kaolinite in composition and mineral structure. The appearance of halloysite under the SEM is quite different to kaolinite, and it is usually in the form of tightly rolled scroll-like tubes (Patterson and Murray, 1983; Clarke, 1985).

Most of the leading ceramics manufacturers in the world consider halloysite from the northern part of New Zealand to be of superior quality. In northern New Zealand, three commercially significant deposits are known at Maturi Bay, Mahimahi, and Maungaparerua. Halloysite in these deposits has formed due to low-temperature hydrothermal alteration of rhyodacitic volcanic rocks. Halloysite in these deposits is extremely white, characterized by very low levels of titania and iron, and its tubular morphology results in enhanced green strength in the unfired body and enhanced translucency in the fired ware. Production from these deposits is by New Zealand China Clays Ltd (Harvey, 1996, 1997).

Mode of occurrence

Kaolin deposits can be broadly grouped into two categories of residual (or primary) and transported (or secondary) deposits.

Residual deposits

Residual deposits are formed in situ through the alteration, or kaolinization, of feldspar-rich rocks (such as granite,

Table 7. Pyrometric cone equivalents (PCE) and fusion points

Pyrometric cone equivalent (PCE)	*Fusion point temperature (°C)*	*Heat service*
19	1541	low duty
20	1564	low duty
23	1605	low duty
26	1621	low duty
27	1640	moderate duty
28	1646	moderate duty
28	1646	moderate duty
29	1659	moderate duty
30	1665	moderate duty
31	1683	moderate duty
31.5	1699	moderate duty
32	1717	high duty
33	1743	high duty
34	1763	super duty
37	1820	super duty

NOTE: modified from Pickering and Murray (1994) gneiss, or arkose) by weathering or hydrothermal processes. The mineralogical and chemical composition of the kaolin deposit depends on the nature of the parent rock and the type and degree of alteration.

Under humid climatic conditions, weathering of anhydrous silicates such as potash feldspar and illite can produce kaolinite. The process essentially involves the hydration of anhydrous silicates to produce kaolinite, silica, and potash. Typical kaolinization equations are:

$$2KAlSi_3O_8 + 3H_2O \Rightarrow Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2KOH$$

(potash feldspar) (kaolinite) (potash)

or

$$2KAl_2(AlSi_3)O_{10}(OH)_2 + 5H_2O \Rightarrow 3Al_2Si_2O_5(OH)_4 + 2KOH$$

(illite) (kaolinite) (potash)

The depth of weathering can vary from a few metres up to 100 metres in exceptional circumstances, and is controlled by local factors such as the susceptibility of the parent rock to weathering, topography, position of the watertable, and the balance between erosion and kaolinization. In residual or primary deposits, kaolin remains in situ or very close to the zone of origin.

In Western Australia, kaolin deposits have mostly formed as a result of weathering. Many deposits in granitic terranes, such as the Gabbin deposit, have formed as a result of the leaching and removal of silica, iron, potassium, sodium, calcium, and magnesium during weathering of granite. The extent of kaolinization partially depends on the nature of the parent rock. Granites with a high alumina to silica ratio are highly susceptible to kaolinization processes.

Unfavourable properties frequently encountered in residual kaolins include heterogeneity, high viscosity, high soluble-salt content, and staining by iron oxides. Sometimes, kaolin formed by weathering processes can be severely contaminated with iron oxides carried downwards by the movement of groundwater. A common source of these oxides may be from overlying, iron-rich hardpan.

Hydrothermal alteration involves the alteration of rocks by circulating hot water, and for this process the permeability of the parent rocks plays an important role. Permeability can be due to fracturing and/or granulation. The heat for generating the hot water may be from the cooling of an intrusive body or from a high concentration of radiogenic elements. For this type of deposit, granites are the most common host rocks, and those with a low abundance of biotite typically produce unstained white kaolin of high quality. An example of such kaolin, known as china clay in England, formed from the Variscan-aged granite batholiths of Devon and Cornwall in England.

Solfatara alteration is another process that may result in the formation of kaolin. This process typically occurs in the waning stages of acid volcanism, due to the interaction of the volcanic rocks with steam or hot water that is rich in sulfur. The crystal size of silica in these volcanic rocks is comparable to the kaolinite particles and is therefore extremely difficult to separate, thus resulting in an abrasive product. The main use of kaolin of solfatara origin is in the manufacture of white cement, where high silica and sulfate contents do not cause problems. Good examples of this type of deposit are found around Rome, and on the island of Milos in Greece (Bristow, 1987; Harben and Bates, 1990).

Transported deposits

Kaolinite produced by weathering can be transported by water and deposited in a quiescent environment, such as a lake, some distance away from the point of generation, forming a transported deposit. In Western Australia, transported deposits such as Mount Kokeby and Goomalling contain kaolin within a pallid zone, beneath laterite and mottled clays. Transported kaolin can undergo change, at times significantly, by diagenesis. A wide range of kaolin types can be found in these deposits, which can be broadly classified into three groups depending on their mode of origin, the physical characteristics of the kaolin in situ, and the grade of the kaolin product produced. These three groups of kaolin deposits are sedimentary kaolin; kaolinitic sand; and ball clay, fireclay, and flint clay.

Sedimentary kaolin

Sedimentary kaolin is reworked or transported material of high purity that yields over 60% of kaolin product that is white enough, after appropriate beneficiation, to be used for applications such as those in the paper industry. Some of the best known kaolin localities in the world are those in Georgia and South Carolina in the USA, and in the Amazon region of Brazil. Most of the kaolin worked in Georgia and South Carolina occurs in the form of lenses in a generally sandy succession. Late Cretaceous and early Tertiary kaolin deposits on the banks of the Capim River in the county of Ipixuna, Pará state in Brazil, are similar to those of Georgia in the USA (Bristow, 1987; Harben and Bates, 1990; Kendall, 1996a).

Kaolinitic sand

In many parts of the world, kaolin is extracted from sand that has a kaolin content of less than 20%, but the sand may be an important byproduct or even a coproduct. Kaolinitic sand can form either by the original deposition of a mixture of kaolin and sand, or by alteration in situ, by percolating groundwater, of feldspar in rocks such as arkose. Some examples of kaolinitic sand are the Triassic Hirschau–Schnaittenbach occurrences in Germany and the Cretaceous occurrences in the Cuenca and Guadalajara provinces in Spain.

Ball clay, fireclay, and flint clay

There is a progressive change from sedimentary kaolin towards ball clays in many areas. Ball clays are almost invariably laid down in freshwater lakes or river floodplains and are frequently associated with lignite. In many parts of the world, ball clays are often found in Eocene–Oligocene formations. Fireclays are widespread in association with the Carboniferous coal measures of Western Europe and the eastern part of the USA. Flint clays may be derived by sedimentary processes or by hydrothermal alteration in situ of sedimentary or igneous rocks, and often characteristically occur as basin margin facies in coal-bearing sequences. Flint clays are extraordinarily dense, massive clay rocks that range in texture from ultra-fine grained to coarsely clastic (Bristow, 1987; Loughnan and Roberts, 1989).

Exploration techniques

Exploration techniques should involve mapping, subsurface examination, sampling, and field tests. A thorough ground reconnaissance may supply information that will discourage additional expensive work such as drilling. The reconnaissance phase of exploration for kaolin deposits should involve the collection and testing of grab samples of kaolin from prospective clay outcrops, which may be found on the surface, on hillsides where recent landslides have occurred, along stream banks, in road cuttings, and in building excavations. In many areas of the wheatbelt of Western Australia, the excavations dug by farmers for building farm dams often expose underlying clay horizons, and hence are very useful in identifying prospective areas during reconnaissance surveys and also when using airphotos and Landsat data. The information from available borehole logs can also be useful in the discovery of kaolin mineralization, especially in areas where kaolin does not outcrop. Poor vegetation can sometimes reflect clay horizons because vegetation may not thrive on near-surface clay under certain circumstances, such as on waterlogged clay horizons. A number of springs found at the same level along the side of a hill indicates a somewhat impervious layer below that level, which may possibly contain clay. In hilly country, it is sometimes possible to locate clay horizons by examining the profile of a hill for the presence of flat benches caused by weathering.

Many geophysical methods of exploration for kaolin have been attempted, but with limited success. Perhaps the most useful tool in the exploration and field identification of kaolin is the Field Portable Infrared Mineral Analyser (PIMA) that is capable of identifying kaolinite from many other minerals such as sericite, pyrophyllite, chlorite, talc, and tremolite. Although persistent attempts have been made using seismic, electromagnetic, electric self-potential, and ground-penetrating radar techniques, the most hopeful results of these have been obtained from the ground-penetrating radar technique. However, with this technique the signals will only penetrate to depths of 5 to 7 m.

After outlining a broad area by preliminary surveys, the only effective method for delineating a kaolin deposit is by pattern drilling. The drilling can involve using a hand auger, powered auger drill, or diamond core-barrel drilling, depending on the terrain. Currently, the most successful method of drilling for clays appears to be aircore reverse-circulation (RC) drilling. Drillhole spacing is approximately 250 m for exploration and 50 m for evaluation and mine planning. Sometimes, hand-dug test pits can also be used when drilling facilities are not readily available. Such pits should be at least 1 m in diameter, and may be dug to depths of as much as 15 to 30 m. These can provide excellent representative samples. Initial sampling for chemical analysis and XRD studies is commonly carried out by the collection of composite samples from kaolin horizons in every drillhole. However, a more accurate but expensive method is to sample every metre of the kaolin horizon from each drillhole. Talbott (1985) has outlined further useful principles which may be applied when prospecting for clay deposits.

Chemical analysis, which usually involves the determination of the oxides of Al, Fe, Na, K, Si, Ca, Mg, and Ti, is generally carried out before any other tests for a first-pass assessment of the quality of the kaolin for various end-uses. For example, the alumina value gives a guide to the kaolinite content, and iron (total oxides) to the level of iron contamination. Sodium and potassium levels are very critical in refractory and ceramic manufacture. If these results indicate that the clay is substandard, then further testing of the material is not warranted. For applications such as pharmaceuticals, the clay has to be analysed for trace elements to see whether any undesirable elements such as arsenic and lead are present.

XRD studies on selected samples are necessary to assess the approximate mineralogy of the clay and to determine whether any minerals such as mica are present, since these are undesirable for some end-uses such as in the paper industry. SEM studies are helpful in understanding the morphology, crystallinity and also mineralogy, which are important criteria for assessing the material for many end-uses. SEM is also very useful for identifying the presence of halloysite in samples, since its presence is undesirable in paper grade kaolin.

Evaluation

Chemical analysis and XRD studies are used initially to establish the chemical purity and mineralogy of a clay deposit. The samples are then subjected to numerous tests, of which the most common are brightness, particle size, and viscosity. These tests are performed using dried and pulverized samples, and are useful for identifying any lens or section that may be off-colour, contain grit, have a high viscosity, or not meet the specifications in some other way. Costs often limit the number of tests actually performed.

Brightness

The brightness test consists of drying, pulverizing, and forming a plaque of the material to be tested. The brightness of the plaque is then compared with a standard of known brightness. There are two main systems for measuring brightness. These are the TAPPI (Technical Association of the Pulp and Paper Industry) or GE system used in the United States, and the ISO (International Standards Organisation) system used in Europe (Pickering and Murray, 1994). In the TAPPI system, brightness is measured at 457 mμ using a reflectance meter constructed, calibrated, and operated according to the requirements of TAPPI Standard T646-om-86. In the ISO system (TAPPI 534-om-86), different optical geometry is used (Pickering and Murray, 1994). GE (or TAPPI) brightness values of greater than 80% are required for filler clay and greater than 85% for coating clay (Table 5). ISO brightness values are about 1–2 units lower than the GE brightness (Bristow, 1987).

In this Bulletin, the brightness values given are indicated as either ISO or GE wherever possible. However, information obtained from other sources does not always specify the brightness as either ISO or GE, but the wavelength at which the brightness was measured is often given. It should be noted that the wavelength at which the brightness was measured is not necessarily indicative of either the ISO or GE method of determining brightness. Where the method is not known, this Bulletin indicates the wavelength at which the brightness was measured, rather than referring to either ISO or GE.

Particle size

Particle-size determinations can be achieved by the application of Stokes' principle, but the determinations are approximate because kaolin particles are shaped quite differently from the spheres assumed by Stokes' law. Coarse particles settle more rapidly than finer ones, and therefore the determination of a given particle size and distribution can be made by the use of the time and rate of settling in a given fluid. Typical particle-size analyses of filler and coating grades are shown in Figure 1.

Material retained on a 325-mesh screen (45 μm) is regarded as the grit or residue. A 100 g sample is thoroughly mixed and dispersed in water with a dispersing chemical. After carefully determining the weight and percent solids of the dispersed slip, the amount of residue retained on the screen is calculated as a percentage. Grit percentage is an important crude evaluation test. In the USA, a maximum 10–15% grit is set as the upper limit, but if the kaolin is of unusually high quality a higher grit content may be tolerated.

Viscosity

Flow properties of kaolin, as determined by viscosity measurements, are very important because they affect the functioning of the coating operation as well as the final quality of the paper. Two viscosity tests are used in the kaolin industry, one to measure the high-shear viscosity and the other to measure low-shear viscosity. The measurements are generally made on slurry suspensions of 71% solids. The low-shear viscosity is measured using a Brookfield four-speed viscometer, and the high-shear viscosity using a Hercules viscometer.

Uses

Paper

The paper industry is still the largest consumer of kaolin and uses approximately 47% of the world annual production of about 19 Mt. In the paper industry, kaolin is used as both a filler and as a coating pigment. Only a small number of deposits in the world are suitable for the production of high-quality paper coating grades of kaolin and thus the major producers and exporters in the USA,

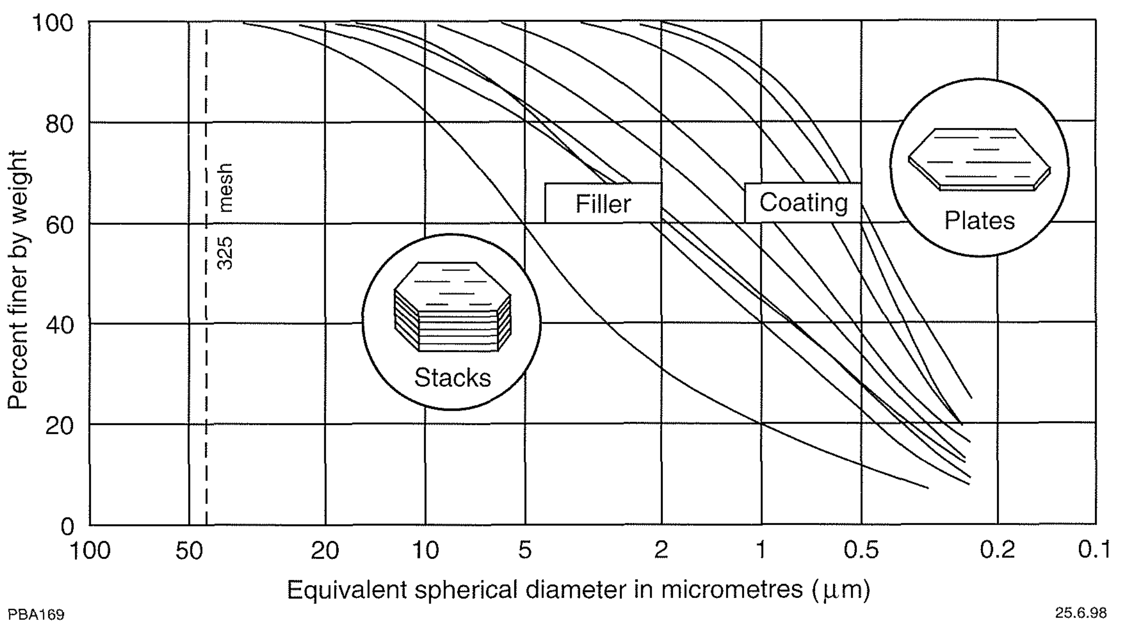

Figure 1. Typical particle sizes of paper filler and coating grades of kaolin (after Pickering and Murray, 1994)

UK, Brazil, and Australia can be considered as members of an elite club (Coope, 1996).

The function of kaolin as a filler is to reduce paper manufacturing costs, with kaolin occupying the interstices between the cellulose fibres and substituting for the more expensive pulp. The use of kaolin also enhances opacity and the overall finish and printing properties of the paper. The specifications for kaolin for use as a filler require that it should have greater than 90% kaolinite, less than 1% Fe_2O_3 +TiO_2, low abrasive quartz (1–2%), a GE brightness greater than 80%, and a particle size of 82–95% less than 2 µm. A variety of filler grades are produced with different brightness values. Some of the other relevant specifications for filler grade kaolin are shown in Table 5. Low-priced filler grade kaolin is produced by a dry process and has a minimum GE brightness of 80%. High-quality filler grade is produced by calcination, which yields a GE brightness of at least 93%.

The function of kaolin as a coating pigment is to endow the paper with a smooth, bright surface possessing good ink-receptive qualities and having good opacity. The plate-like morphology of kaolin is important in coating applications, with its high aspect ratio and surface area providing excellent coverage at low coating levels. The kaolin must have constant rheological and optical properties in order to be used in the high-speed coating process. The specifications for coating grade are that the kaolin should contain 90–100% kaolinite, and have low Fe_2O_3 (0.5–1.8%) and TiO_2 (0.4–1.6%), virtually no abrasive quartz, a GE brightness of greater than 85%, a particle size of 80–100% less than 2 µm, and a Brookfield viscosity (at 20 rpm) of 350 centipoise (Harben, 1995; Industrial Minerals, 1987). Other relevant specifications for coating grade kaolin are given in Table 5.

Kaolin represents 55–60% of all minerals consumed worldwide in paper filling and coating. However, this figure was much higher before the introduction of the alkaline paper-making process (Keegan, 1997). In this process, finely ground calcium carbonate (in the form of limestone, chalk, or marble) can provide a low-cost alternative to kaolin for use in the paper industry. However, calcium carbonates are poor glossers, hence a kaolin–carbonate blend is used by many paper makers, but the quantity of kaolin required for this purpose is small. Although alkaline paper-making processes in Europe have resulted in an increased use of carbonate, widespread paper production under acid conditions has prevented large-scale use of calcium carbonate. More recently, a move toward the alkaline paper-making process also appears to be taking place in some of the Asian countries.

Paint

Fillers play an important role in many paints and polymers, and the principal function of kaolin in this area is as a substitute filler for the more expensive TiO_2. Talc can also be used as a substitute filler and has an equal share of the market to that of kaolin. Kaolin and calcined kaolin are used as extenders mainly in some undercoats and in water-based paints. The scattering power of these extenders contributes to optical properties such as hiding power, opacity, and whiteness, which are required in decorative paints (Bristow, 1987).

Ceramics

The ceramics industry includes the production of many different items such as tableware, sanitary ware, wall tiles, floor tiles, and electrical and industrial porcelain. The majority of white-coloured ceramics contain a mixture of kaolin and ball clays, with the proportions varying depending on the product. Ceramic grade clays should contain 75–85% kaolinite since the other minerals in ball clay adversely affect colour, viscosity, and abrasiveness (Harben, 1995).

Typical properties of commercial ceramic clays are shown in Table 6. Deleterious elements, most notably iron, copper, and manganese, when present in either particulate form or adsorbed onto the kaolinite lattice, cause deterioration in product quality. On firing, such impurities are evident as specking and a loss in fired whiteness. Iron contents of 0.6–0.7% Fe_2O_3 are tolerable but will cause a loss of translucency in bone china. Potash levels should ideally be below 1.5% because alkali levels alter porosity and therefore vitrification.

Viscosity and rheology are very important factors in the manufacture of sanitary ware, which is produced by casting a ceramic slip containing deflocculants. Quick-casting properties are a prerequisite, and the casting rate, which is a measure of the dewatering capacity of a clay, is determined by the particle size. The coarser the grain size, the quicker the dewatering. The presence of delaminated kaolin can also significantly alter the casting properties of a clay. Delaminated kaolin is hydrous kaolin in which the stacks of crystal platelets have been separated by wet attrition. In ceramic applications, the kaolin used must be homogeneous to prevent uneven shrinkage (Industrial Minerals, 1987; Kendall, 1996b).

Refractories

The use of clay-based refractories declined substantially with the switch from open-hearth steelmaking to basic-oxygen steelmaking, especially in Japan and Western Europe. However, refractory clays are used in a variety of applications such as firebricks and blocks, insulating bricks, refractory mortars and mixes, monolithic and castable materials, ramming and airgun mixes, and other products. Because of such diverse applications the specifications for refractory clays are varied (Bristow, 1987; Skillen, 1996a).

The most essential property of a refractory clay is its resistance to heat. Refractory grade clays are required to withstand temperatures of at least 1500°C (PCE 19) and are classed according to suitability for heat service as low duty (PCE 19–26), moderate duty (PCE 27–31.5), high duty (PCE 32–33), and super duty (PCE 34–37) (Table 7). Higher duty refractories, such as those based on high-purity magnesia, have tended to take the place of clay-based refractories. However, clay-based refractories with an enhanced alumina content have maintained their position in the refractories market, and the special qualities of flint clays have also ensured that they have maintained their market position. Large tonnages of flint clay are used in North America, but its place in Europe is taken by calcined ball clays (chamotte) and to a lesser extent by calcined fireclays (Patterson and Murray, 1983; Bristow, 1987).

Plastics

Kaolin helps to provide plastics with a smooth surface finish, reduces cracking and shrinkage during curing, and obscures fibre reinforcement patterns. The dominant use of kaolin in plastics is as a filler for PVC coatings on cables. Calcined kaolin has good electrical resistance, and even a small amount can improve the resistance of the plastic sheath. In this capacity, kaolin acts as a functional extender, rather than just a filler. In other applications in the plastics industry, kaolin imparts properties such as impact resistance, gloss, stiffness, and brittleness. Calcined kaolin is also used as a functional filler in polythene film used in the agricultural industry. In these polythene films, when the quantity of calcined kaolin present is 7–8% by weight, it can enhance the infra-red absorption characteristics, thereby helping to retain heat in greenhouses. Kaolin also has an application in audio and video cassette tapes, where it functions as an anti-blocking agent (Industrial Minerals, 1987, 1991).

Fibreglass

Kaolin is used in the fibreglass industry as a source of Al_2O_3 and SiO_2, and helps to obscure the pattern of reinforcing fibres. The clay should typically contain at least 37% Al_2O_3, 44% SiO_2, 0.6% CaO, and a maximum of 2% Na_2O, 1% Fe_2O_3, and 1% H_2O (Loughbrough, 1993). A low moisture content is critical, hence most kaolin used in the fibreglass industry is from producers using the air-flotation process (Gallagher, 1996).

Chemicals and pharmaceuticals

Kaolin is used in the manufacture of chemicals, including catalysts. Kaolin is an ingredient in the manufacture of zeolite catalysts, and a very special grade of kaolin is used in the manufacture of cordierite catalyst supports used in car exhaust systems. Kaolin with a low iron and sulfate content is used extensively in the production of catalysts and molecular sieves.

Kaolin is also used in the pharmaceutical industry for the manufacture of medicines used to alleviate intestinal disorders, and many white pills are composed mainly of a filler such as calcium carbonate or kaolin. Cosmetic grade kaolin should contain less than 2 ppm arsenic, 20 ppm heavy metals, 350 ppm chlorides, and the pH should be 7.5 ± 0.5 (Bristow, 1987).

Other uses

Rubber

Fine-grained kaolin is used in the rubber industry for reinforcing and stiffening, especially for non-black rubber (Industrial Minerals, 1991).

Printing inks

Kaolin is widely used in printing inks as an extender pigment. However, it is often necessary to coat the kaolin particles with a hydrophobic material because of the hydrophilic nature of kaolin (Industrial Minerals, 1991).

Environmental

The absorbent properties of kaolin make it useful as a feedstock for artificially produced zeolites, which have numerous environmental applications. Such usage is likely to provide new market opportunities for kaolin (Cooper et al., 1996). Anutech and Australian Kaolin NL are jointly developing a kaolin-based derivative, known as XAM, to be used in the treatment of industrial waste water.

Mining

All major kaolin mines in the world use openpit mining. A variety of stripping methods are used to remove overburden, depending on the availability of heavy equipment in the area, the depth of overburden, the overburden-to-clay ratio, the watertable, and climate. The commonly used method to remove overburden involves bulldozers, hydraulic hoes, and shovels, which load large all-wheel drive offroad trucks. Pan-type self-loading scrapers have often been used, but are less efficient in soft or wet overburden. Bucket-wheel excavators are used to load conveyor belts in many European kaolin mines. In some developing countries, hand removal of earth is still utilized with the use of pick and shovels, wheelbarrows, and even hand removal of the overburden from the openpit where it is carried out in baskets on the heads of bearers.

The exposed kaolin can then be mined by the same methods as those used for removal of the overburden, but kaolin must be handled with much more care to assure quality control and to recover all possible ore-grade material. A single mine may contain as many as four or five separate grades of crude kaolin. In kaolin deposits where clay is stratified horizontally, the quality differences are generally layered, and in such deposits mining may sometimes be done vertically to achieve effective blending and to produce crude ore with more consistent properties. A hydraulic hoe or shovel can be used for mining such deposits.

Pickering and Murray (1994) stated that, in areas of high artesian pressure, it might be possible in future to mine or strip kaolin using large cutterhead dredges. This could open up kaolin deposits that currently cannot be economically stripped.

Beneficiation

Commercial deposits of kaolin have a variable kaolinite content, from as little as 10% to as much as 95% kaolinite. The quality and grade can be increased by beneficiation. Over the past 20 years, processing techniques have evolved very rapidly and Keeling (1997) has identified the following trends:

- Increased use of blunging and preliminary degritting at the mine site, with pipeline transport of the slurry to the processing plant;
- Use of continuous centrifuges for particle-size separation;
- Development of high-intensity magnets to remove iron-bearing phases;
- Ultraflotation to remove very fine grained iron and titanium oxides;
- Replacement of frame filter presses with large continuous rotary-drum vacuum filters;
- Use of high-capacity spray driers.

Saleable kaolin is produced by two basically different processes: dry and wet. The dry process yields a product of lower cost and quality than the wet process, and the properties of the finished kaolin generally reflect that of the crude kaolin. Therefore, the kaolin in the original deposit should have the required brightness, low grit content, and particle-size distribution. The dry process involves primary crushing of the kaolin to about 5 cm-sized lumps, drying in rotary dryers, grade sizing and sand removal, pulverizing, and air-flotation. A flow sheet for dry-method processing is given in Figure 2.

In the wet process, crude kaolin of variable quality is processed to produce a uniform high-quality product. The first step in the process is to fractionate the kaolin slurry into coarse and fine fractions by using continuous centrifuges, hydrocyclones, or hydroseparators. Magnetic minerals are removed by high-powered magnets, and then the kaolin is delaminated into individual plates. The kaolin is then leached to remove ferruginous colouring compounds. This is achieved by acidifying the kaolin with sulfuric acid to a pH of about 2.5 to dissolve the iron, and then adding a strong reducing agent such as a hydrosulfite to form a soluble sulfate that can be removed during the dewatering step. The dewatering of the flocculated kaolin slip is accomplished by using evaporators, rotary vacuum filters, or filter presses. After filtration, the kaolin filter cake can be extruded in a noodle form and dried in apron or rotary dryers, or it can be calcined or redispersed to the fluid state and spray dried, drum dried or shipped in slurry form as 70% solids. A flow sheet for wet-method processing is given in Figure 3.

In the wet process, a standard method for improving brightness and whiteness is to use a high-intensity magnetic separator, which removes substantial quantities

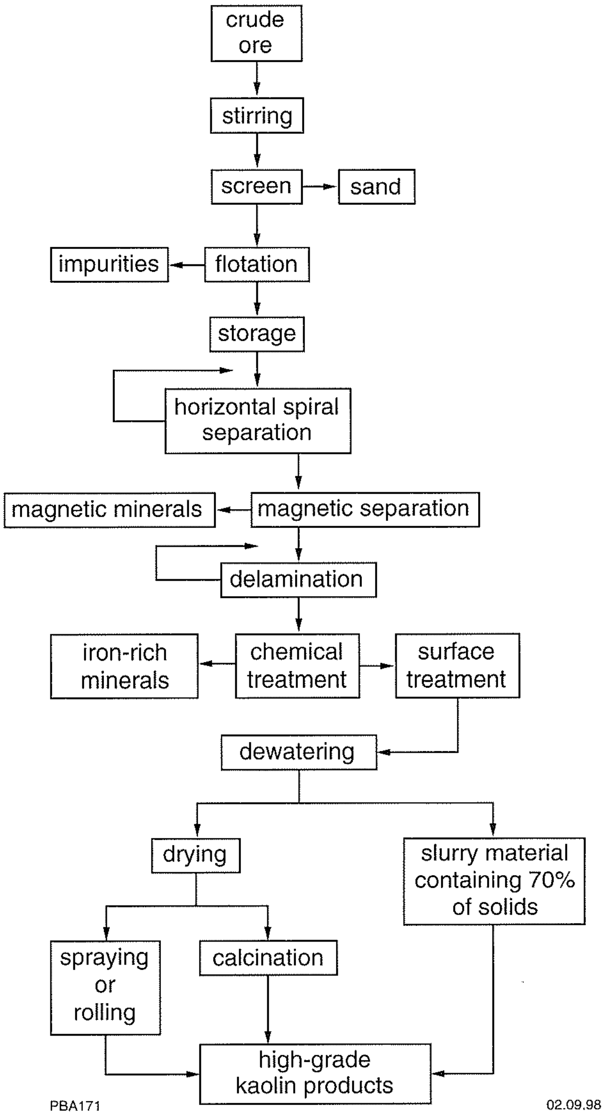

Figure 3. Flow sheet for processing of kaolin by the wet method

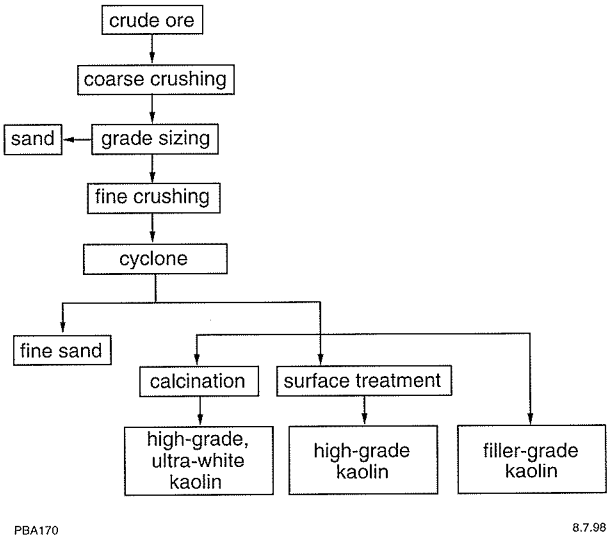

Figure 2. Flow sheet for processing of kaolin by the dry method

of iron and titanium mineral impurities. The intensity of these magnets ranges from 1.8–5.0 Tesla. The magnet is demagnetized periodically, and a high volume of water under pressure is backflushed through the matrix to flush out the impurities (Pickering and Murray, 1994). Delaminated kaolin is produced by splitting apart the larger books or stacks of kaolin using a process known as wet-attrition grinding.

Another widely used method for producing special kaolin products is calcination. When kaolin is calcined to temperatures of approximately 1050°C, it is converted to mullite, silica–alumina spinel, and cristobalite. This product is whiter, brighter, and has better hiding properties (opacity) when used in thin-film applications, but is more viscous and abrasive.

Special chemical processes may be used to modify the surface of kaolin in order to improve its function in many applications such as ink, rubber, paint, and plastics. Such surface-modified kaolin can be hydrophilic, hydrophobic, or organophilic (Patterson and Murray, 1983).

Chapter 3

Production and market trends

World production

Kaolin is mined and processed in many countries, and it is one of the few industrial minerals of sufficient value, in its highly refined state, to be widely exported into international markets. The global kaolin production in 1996 was approximately 19 Mt. The main countries producing refined kaolin are USA, UK, Ukraine, China, Brazil, Germany, and the Czech Republic (Table 8). Thailand, France, Spain, Malaysia, and Mexico also produce significant quantities. Australia, up until the closure of the Weipa deposit in Queensland in 1997, was among the major exporting nations for kaolin (Coope, 1997).

With respect to kaolin production data from different countries, there is a lack of reliability of true production levels due to the inclusion of other clays. This is due to the fact that there are no internationally accepted guidelines for reporting production data for many industrial minerals, including kaolin.

USA

The USA is the world's largest producer of kaolin and produced 9.5 Mt in 1996, a marginal increase over 1995, with 60% of domestic production and 85% of exports being used in the paper industry. The state of

Table 8. World kaolin production (thousand tonnes)

Year	*1987*	*1988*	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*
USA	8 008	8 973	8 974	9 761	9 143	8 735	8 830	8 770	9 480	9 530
UK	3 059	3 277	3 140	3 037	2 911	2 502	2 461	2 530	2 650	2 600
Ukraine	–	–	–	–	–	1 000	1 000	1 015	950	1 000
China	500	500	500	500	500	700	800	850	900	950
Brazil	700	850	900	800	900	900	750	760	760	900
Germany	703	777	823	601	598	630	650	600	570	550
Czech Republic (Czechoslovakia prior to 1992)	551	579	557	533	500	505	550	550	500	500
Thailand	207	223	177	208	256	304	397	417	461	450
France	309	337	281	370	344	334	350	327	346	350
Spain	380	438	440	375	370	350	148	290	300	300
Malaysia	97	117	108	153	187	244	250	253	211	220
Mexico	200	159	142	156	167	144	216	193	189	195
Romania	400	400	400	400	400	200	200	200	150	150
Australia	184	163	260	363	200	241	180	200	210	190
Turkey	125	204	257	251	187	186	139	150	155	155
Egypt	125	124	122	149	140	96	157	150	150	180
India	94	107	111	100	100	110	129	134	150	150
South Africa	152	175	140	132	135	132	147	132	147	150
Japan	112	120	133	177	119	123	110	138	166	170
Bulgaria	263	220	280	186	180	110	110	115	115	115
Portugal	67	101	101	71	70	120	110	120	90	100
Austria	92	89	85	81	72	65	64	87	75	75
Korea	547	774	1 311	1 345	1 760	1 856	80	80	80	80
Indonesia	114	147	157	160	140	231	42	53	50	50
New Zealand	26	30	26	25	21	28	28	28	30	32
Former USSR	3 000	1 300	2 000	1 800	1 800	–	–	–	–	–
Total	**21 200**	**21 750**	**23 000**	**23 300**	**22 000**	**19 605**	**17 898**	**18 142**	**18 885**	**19 142**

NOTE: Countries sorted by 1996 production
1987–1991 totals include a number of other countries not specifically indicated
SOURCE: Metals and Minerals Annual Review (1990, 1991); Highley (1993); Coope (1996, 1997)

Georgia produces over 80% of the total kaolin production in the USA, and each of the five largest producers (Engelhard Corp., ECC America, J. M. Huber Corp., Thiele Kaolin Co., and Dry Branch Kaolin, a subsidiary of Imetal S.A.) has an output of over 1 Mt per year. Other major producers in the USA include Nord Kaolin Co. and Kentucky-Tennessee Clay Co. (K-T Clay) (Coope, 1996, 1997; Keegan, 1997).

Georgia–South Carolina district

The upper coastal plain of Georgia and South Carolina is the most important kaolin production locality in the world. The kaolin deposits occur as lens-shaped beds in upper Cretaceous and lower Tertiary sediments. The average thickness of these kaolin bodies is about 3 m, although in places it can be as high as 12 m. The commercial kaolin bodies in these stratigraphic units are extremely pure and consist essentially of kaolinite, with less than 5% grit material coarser than 45 µm.

There are two kaolin-bearing stratigraphic units of commercial interest in these sediments: the upper Cretaceous Buffalo Creek Formation and the middle Eocene Jeffersonville Member of the Huber Formation, both forming part of the Oconee Group. The kaolin of the Buffalo Creek Formation is rather soft, relatively coarse in particle size (averaging 65% finer than 2 µm), with a smooth conchoidal fracture and abundant stack-like crystals packed face-to-edge. Dombrowski (1993) suggested that the soft kaolin is due to the development of large vermicular crystals of kaolinite as a result of a series of sedimentary processes such as erosion, weathering, and groundwater action on the igneous rocks of the Piedmont Plateau and associated arkosic sands. The kaolin of the Jeffersonville Member is harder and tougher, considerably finer in particle size (averaging 85% finer than 2 µm), and is dominantly fine platy crystals that are packed face-to-face. However, this kaolin contains more hematite and anatase. The hard kaolin deposits have developed due to the deposition of kaolin-rich sediments in saline water causing face-to-face flocculation that resulted in a tightly packed sediment (Dombrowski, 1993). The blending combinations possible from utilizing these two sources of crude clay have enabled the production of many diverse kaolin products required by various industries.

More than 75% of the approximately 9 Mt of kaolin produced annually in Georgia and South Carolina is used in the paper industry. Many varieties of paper grade kaolin are produced. These include No. 1, 2, and 3 coating grades, ultrafine glossing clay, delaminated clays, light-scattering opaque grades, coarse and fine calcined clays, and filler clays. The GE brightness of paper coating kaolins produced in this area ranges from 86 to 90%, while calcined kaolin ranges from 89 to 94%, and filler kaolin ranges from 78 to 90%. Other users of Georgia kaolin include the plastics and ceramics industries (Pickering and Murray, 1994).

Other localities in the USA

These areas include California, Florida, Texas, and Minnesota. In California, kaolin is mined and processed as a byproduct from a sand operation near Ione in the Central Valley of California. Host rocks belong to the Ione Formation of Eocene age. Clay recovery is 20 to 25% and products are made which range in GE brightness from 76 to 83%. The kaolin from the area is marketed to the ceramics, paper filling, and fibreglass industries.

In Florida, kaolin is recovered as a coproduct from a sand mine near Edgar. Kaolinitic sand in the Fort Preston Formation of middle Eocene age is mined to a depth of 6 to 17 m. An average of 15% plastic clay is recovered from the sand. The product is marketed to the ceramics industry for the manufacture of whiteware, tiles, glazes, and refractories.

In Minnesota, kaolin is produced from several small mines, and is used as an additive in Portland cement manufacture to increase the alumina content, and as a filler in soybean meal for animal feeds.

UK

The production of kaolin in the UK in 1996 was approximately 2.6 Mt. The UK is the largest exporter of kaolin in the world, with much going to the USA which is the largest importer despite its own abundant supply. The largest producer in the UK is English China Clays (ECC) with a production of approximately 2.5 Mt of kaolin per year (on a dry basis) from its operations around St Austell in Cornwall. EEC is also the largest kaolin producer in the world. Other UK producers are Watts Blake Bearne & Co PLC (WBB), and Goonvean & Rostowrack China Clay Co. WBB is primarily a supplier of kaolin to the ceramics industry, although 17% of its total output of 35 000 tpa ends up in paper filling applications. During 1995, Goonvean & Rostowrack China Clay Co. consolidated its position as the UK's second largest producer by acquiring the Bodelva and Greensplatt kaolin operations from Redland Minerals. Goonvean & Rostowrack China Clay Co. now operates five mines or processing plants with a combined capacity of 230 000 tpa and supplies 65% of its production to the paper industry, mostly for filling purposes, with only a small amount going into coating applications (Coope, 1996, 1997; Keegan, 1997).

The Cornwall–Devon area of southwestern England is the main area of kaolin production in the UK, and is the second most important kaolin-producing area in the world. Production is from a number of residual deposits related to the Cornubian granite batholith of Variscan age, especially those related to the low-iron lithium-mica granite plutons at St Austell and Tregonning.

The kaolinite from these deposits is coarse, averaging around 25–35% finer than 2 µm. Most of the kaolin crystals are stack-like in habit. Small amounts of smectite are fairly common, but distribution is patchy. Minor accessory minerals that are easily removed in the degritting process include tourmaline, topaz, apatite, fluorite, zircon, cassiterite, wolframite, rutile, hematite, and turquoise. The largest kaolinized bodies are found at the intersection of several fracture zones. The shape of these kaolinized bodies is generally similar to a funnel, with the narrowed end extending downward as much as several hundred metres in some cases. However, the kaolinized bodies may have different and irregular shapes depending on the orientation of rock fractures.

The kaolin products from these deposits (Pickering and Murray, 1994) include:

- Paper coating clay with 80% -2 µm and an ISO brightness of 85.5–87.5%;
- Paper filling clay with 45% -2 µm and an ISO brightness of 79.5–82.5%; and
- Ceramic kaolin with 57–70% -2 µm, which fires relatively white.

China

China has a long history in both the development and utilization of kaolin resources. It has been determined from historical ruins of the Yangshao and Longshan Cultures that the white pottery fired 4000 years ago in the early Neolithic Age contains kaolin, whilst the engraved pottery from the Shang Dynasty 3000 years ago is completely made of kaolin.

China, with an annual production of 0.95 Mt (1996), is the fourth largest producer of kaolin in the world, behind the USA, UK, and Ukraine (Table 8). China hosts large resources of kaolin with more than 700 deposits being known, and with overall resources totalling about 5500 Mt. The deposits are spread over 19 provinces, cities, and autonomous regions (Shaode, 1995). The distribution of China's ceramic industry is basically the same as that of its kaolin deposits. The most well-known ceramic production centre is Jingdezhen (known as the ceramic capital) in Jiangxi province, while other well-known ceramic production centres are Liling in Hunan province, Foshan in Guangdong province, Yixin in Jiangsu province, Zibo in Shandong province, and Tangshan and Handan in Hebei province. A summary of the main Chinese kaolin deposits is given in Table 9. Although China has large resources of kaolin, the country still depends on imports to meet its needs for paper coating kaolin. However, English China Clays International (in joint venture with Fujian Jiuzhou Longyan Kaolin Clay Co. of China) has plans to open a 100 000 tpa ceramic processing plant in Longyan Province, China, by July 1998 (Cameron, 1998).

Brazil

Brazil produced 0.9 Mt of kaolin in 1996 and is emerging as a rising force in the global kaolin industry. The major kaolin deposits in Brazil are located in the Amazon region, and formed as transported deposits. Two new operations by Pará Pigmentos SA (PPSA) and Rio Capim Caulim (RCC), producing high-grade coating kaolin, started in 1996. These have boosted the current total capacity of refined kaolin to the order of 1.5 Mtpa, with a projected total capacity of around 3 Mtpa by the year 2000. Other kaolin-producing companies in Brazil include Caulim da Amazonia SA (CADAM) and Cia de Pesquisa de Recursos Minerais (CPRM). CADAM completed a major expansion at the end of 1995 (Coope, 1997; Marcos de Franca, 1996; Kendall, 1996a). CPRM hopes to privatize its operation as part of the government's privatization program, which it is hoped will help stimulate growth and investment in Brazil (Industrial Minerals, 1997a,b).

PPSA is a joint venture company between CADAM, Cia Vale do Rio Doce (CVRD), and Mitsubishi Corporation of Japan, with financial and capital participation by the International Finance Corporation (IFC) and the Brazilian National Development Bank (BNDES). PPSA operates kaolin deposits located on the banks of the Capim River in the county of Ipixuna, Pará state. These upper Cretaceous–lower Tertiary age deposits are situated approximately 150 km southwest of Belém, and are hosted by sediments of the Barreiras Group. The kaolin resources are estimated at about 150 Mt, with a measured resource of 66 Mt of high-quality, high-brightness ore that will be used in the paper industry worldwide. Kaolin from these deposits is soft, rather coarse in crude particle size (about 60% finer than 2 µm), with a conchoidal fracture, a low iron and titania content, a high percentage of stack-like crystals packed face-to-edge, and a high Hinckley crystallinity index (Hinckley, 1963). In almost all respects, these kaolins closely resemble the upper Cretaceous Buffalo Creek Formation kaolins of central Georgia in the USA. Hurst and Bosio (1975) reported a leached GE brightness as high as 89% for this Brazilian kaolin, with low Brookfield and Hercules viscosities, indicating the potential for upgrading by the wet process to paper grade kaolin. PPSA uses three quality-control parameters to determine its mining plan: particle size, in situ brightness, and grit content. The GE brightness in situ is exceptional and averages 85–86%, but can reach 89% before centrifuging. The grit cut-off is set at 40%, but the average is 25–30%.

RCC is now 58% owned by Dry Branch Kaolin of the USA, 34% by Amberger Kaolinwerke GmbH (AKW) of Germany, and 8% by Mendes Junior of Brazil. The RCC kaolin resource is estimated to contain approximately 100 Mt and is situated close to the PPSA operation, along the Capim River. Cia de Pesquisa de Recursos Minerais (CPRM), a federal government company established in 1969, has discovered another deposit in the Capim River area.

The well-known Amazon Brand paper and board coating kaolins sold by Caulim da Amazonia SA (CADAM) are produced from huge resources located on a plateau close to the Jari River in Amapá state. CADAM is one of the lowest cost kaolin producers in the country and produced 633 000 t in 1995, mainly for paper coating. The deposits are situated about 350 km west of Belém, the large city near the mouth of the Amazon River. They are apparently Pliocene in age, and occur in the Belterra Formation of the Barreiras Group. The kaolin of commercial quality is 25 to 32 m thick, very fine in particle size (at least 75% finer than 2 µm), and extends

Table 9. Main kaolin deposits of China

Mining area	*Nature of mineralization*	*Minerals and partial chemical composition*	*Comments*
Guanshan area of Xushuguan, Suzhou city	Stratiform interbeds in Permian–Triassic systems and Jurassic igneous rocks	Halloysite, kaolinite, pyrite, alunite, organic matter; Al_2O_3>30%, SiO_2<65%, Fe_2O_3<4%, SO_3<4.5%	Paper-making, electronic, and rubber industry grades produced by China Kaolin Co.
Yangxi area of Wuxian county, Suzhou city	Stratiform and gigantic vein deposits in faulted areas of Permian and Devonian sandstones	Kaolinite, halloysite, rutile, pyrite, alunite; Al_2O_3>24%, SiO_2 50–70%, Fe_2O_3 ±3%	Paper-making, electronic, refractory, and filler grades produced by China Kaolin Co.
Yangdong area of Xushuguan, Suzhou city	Caves in Permian limestone	Halloysite, kaolinite, pyrite; Al_2O_3>33%, SiO_2<46%, Fe_2O_3<3%, SO_3 2–3%	Produces grades suitable for catalysts, paper-making, and rubber industries
Jiepai deposit, Hunan province	Stratiform bodies in weathered zones of migmatite	Halloysite, kaolinite, quartz, albite, limonite; Al_2O_3 16.5–23.5%, SiO_2>65–72%, Fe_2O_3 0.22–1.5%	Production of 150 000–200 000 tpa by Jiepai Porcelain clay mine
Liling deposit, Hunan province	Zones of weathered quartz porphyry	Kaolinite, quartz, mica; Al_2O_3 14–15%, SiO_2>70%, Fe_2O_3<0.93%, K_2O>4%	Production of 10 000 tpa by Liling Porcelain clay mine
Maomin deposit, Guangdong province	Resulted from Tertiary weathering of feldspar	Kaolinite, halloysite, quartz, mica, feldspar; Al_2O_3>11%, SiO_2<83%, Fe_2O_3 0.93%, TiO_2<0.32%	Produces paper grade kaolin
Shandai deposit of Zhanjiang city, Guangdong province	As flat beds in weathered zones of granite	Kaolinite, halloysite, quartz, mica, feldspar; Al_2O_3 27–38%, Fe_2O_3 0.25–2.35%, TiO_2 0.02–0.93%	Capacity to produce 10 000 tpa; development of mine by Zhanjiang Kaolin
Donggongxia kaolin of Longyan city, Fujian province	Weathered zones of adamellite	Halloysite, kaolinite, quartz, illite; Al_2O_3 15–18%, SiO_2 65–73%, Fe_2O_3 1.5–2.0%	Mined by Minxi Kaolin Co.; capacity 30 000–50 000 tpa
Daquito kaolin deposit of Yongchun, Fujian province	Weathered product of granite porphyry and volcaniclastic rocks	Kaolinite, illite, quartz, feldspar, goethite; Al_2O_3 15–18%, SiO_2 72–76%, Fe_2O_3 1.09–1.55%, TiO_2<0.6%	Produces 20 000 tpa of ceramic grade kaolin
Xingzi kaolin deposit of Jingdezhen, Jiangxi province	Weathered granite and pegmatite	Kaolinite, halloysite; Al_2O_3 26–32%, SiO_2 51–58%, Fe_2O_3 1.3–2.3%	Main mine of Jiangxi province; produces 10 000 tpa of ceramic grade kaolin
Beishan kaolin of Qingtian county, Zhejiang province	Product of hydrothermal alteration of tuff	Kaolinite, dickite, quartz, pyrophyllite; Al_2O_3 19–24%, SiO_2 67–74%, Fe_2O_3 0.07–0.82%, TiO_2 0.3–0.6%	Small-scale production for ceramic industry
Xuyong kaolin of Sichuan province	Product of leaching; occurs in Permian limestone as pyrite-bearing 'kaolinite clay-rocks'	Halloysite, kaolinite, gibbsite, organic matter; Al_2O_3 34–38%, SiO_2 36–48%, Fe_2O_3 0.12–2.47%	Long history of small-scale mining
Datong kaolin deposit, Shaanxi province	Coal-bearing Carboniferous and Permian beds	Kaolinite, hydromica, gibbsite; composition is very close to theoretical kaolinite and has Fe_2O_3<1%	Long history of mining of 50 000–100 000 tpa of ceramic and refractory grade kaolin
Changbai kaolin deposit, Jilin province	Hydrothermal alteration of Jurassic tuff	White, soft, compact blocks of dickite, alunite, and pyrophyllite; Al_2O_3 39.00–40.77%, SiO_2 43.59–45.96%, Fe_2O_3 0.17–0.20%	Production of 5000–10 000 tpa

SOURCE: Shaode (1995)

over an area of several tens of square kilometres. The kaolin occurs beneath the flat tops of an extensive series of steep-sided plateaus covered with thick tropical rainforest. The part of the plateau area explored so far is known to contain more than 250 Mt of commercial grade kaolin, but most of the plateaus are largely unexplored (Marcos de Franca, 1996; Kendall, 1996a; Pickering and Murray, 1994).

Other regions in Brazil that contain commercial kaolin deposits include the Amazon region and Mogi das Cruzes in Sao Paulo state. The kaolin from the Amazon region is considered to be derived from reworked, weathered granitic rocks of the Guyana Shield, which were deposited in a large lacustrine basin. Deposition is interpreted to have occurred in a generally deltaic environment at the head of the lake. The kaolin from Mogi das Cruzes is used in the domestic paper industry.

Germany

Germany produced approximately 550 000 t of kaolin in 1996. Most of this was supplied by Amberger Kaolinwerke GmbH (AKW), Eduard Kick Kaolin und Quartzsandwerke GmbH & Co., Gebruder Dorfner GmbH Kaolin und Kristallquartzsandwerke, and Hutschenreuther AG. However, AKW now has a total capacity of around 600 000 tpa as a result of a series of acquisitions involving Eduard Kick Kaolin and the two former East German operations of Camminauer Kaolinwerke and Kemmlitzer Kaolinwerke in Saxony.

AKW mines transported kaolin deposits in the Hirschau and Schnaittenbach areas of Bavaria, in southwest Germany. These deposits occur within east–west trending half-graben structures, and have formed within slightly clayey feldspathic sand of Triassic age, derived from granitic source rocks in the mountains of the Naab basin. Deposits average about 76% quartz, 12% feldspar, and 12% kaolin. The quartz has an average grain size of 1 mm, the feldspar about 0.1 mm, and the kaolin about 2 μm.

Gebruder Dorfner GmbH Kaolin und Kristallquartzsandwerke continues to produce around 100 000 tpa from deposits at Hirschau, and markets three grades of kaolin with ISO brightnesses of 75–85%, and particle sizes of 43–46% less than 2 μm. In addition, a range of calcined and ceramic clays is sold, together with a surface-treated calcined clay for use in polymers.

Residual kaolin, derived from the alteration of ignimbrites and porphyritic andesites of the Bohemian Massif, is extensively mined in northwest Saxony in southeastern Germany, between Dresden and Leipzig. This kaolin is used as a pigment in paper, paint, and plastic; as a filler in rubber; and as a raw material in fine-art ceramics and porcelains. In Tirschenreuth, a kaolinized pegmatite is mined for ceramic and pigment grade clay products.

Kaolin mining in the former East Germany has a long history, especially around Seilitz in the Meissen region. These deposits are derived from altered pitchstone, felsite, and quartz porphyry (Industrial Minerals, 1991; Pickering and Murray, 1994).

Czech Republic

The Czech Republic is one of the main kaolin producers in eastern Europe, with a production of 500 000 t in 1996. The principal producer of kaolin is Zapadoceska Kaolinove. This company has operations at Kaznejov and Horni Briz in the Plzen area, with a combined capacity of around 300 000 tpa of refined kaolin. Another producer, Selecky Kaolin, is developing a new mining area at Stara Rolen in the Karlovy Vary region, with initial production planned for 1998. In the Karlovy Vary region, kaolin is mined from altered granites for use as a paper and rubber filler, and in the production of fine porcelain and refractories (Coope, 1997; Pickering and Murray, 1994).

Other main producers of refractory clay within the Republic are Ceske Lupkove Zavody AS (CLZ), Moravske Samotove a Lupkove Zavody (MSLZ), Rako Lupky Sro (RLS), and Severoceske Keramicke Zavody (SKZ). The mining and processing operations of CLZ are located at Nove Straseci, near Rakvonik, and have a capacity of 200 000 tpa. In 1994, the company produced 100 000 t of refractory clays, with a grading of 35 to 45% Al_2O_3. MSLZ produces both raw and calcined refractory clays containing 35–41% Al_2O_3, some of which is consumed in the production of chamotte bricks. RLS produces around 30 000 tpa of calcined refractory clays containing 35–39% Al_2O_3. SKZ is also a significant producer of refractory clays and produces clays containing 42% Al_2O_3 (Skillen, 1996a).

France

In 1996, France produced 350 000 t of kaolin. Most production has been by six companies based in Brittany. The deposits in Brittany are residual and the material is used for ceramics, fillers, and pigments. Both residual and transported deposits are mined around the Massif Central (Loughbrough, 1993; Pickering and Murray, 1994). The major producing groups in France are La Source Compagnie, Groupe Minéral Harwanne (GMH), and Société Kaolinière Armoricaine (SOKA) (Loughbrough, 1993; Coope, 1997; Groupe Minéral Harwanne, 1997).

La Source Compagnie is a member of the Australian-owned Normandy Poseidon group, and its main kaolin-operating subsidiaries are Kaolins d'Arvor and Kaolins de Beauvoir. Kaolins d'Arvor operates several quarries at Plomeur, 10 km from Lorient in Brittany, and has an output of around 60 000 tpa. Kaolins de Beauvoir extracts kaolin from Echassières in Allier, 60 km from Clermont Ferrand. The company produces two main grades totalling 30 000 tpa: Kaolin BIP for use in tableware, enamel, and polished tiles, and Kaolin BIO for use in sanitary ware.

GMH owns two kaolin-producing companies in France: Sociètè Minière des Kaolins du Morbihan and Sociètè des Kaolins du Finistère. The former company operates two openpit mines at Lanvrian (near Plomeur) and Kerbrient. The operations process 500 000 tpa of untreated raw material, which involves washing, cyclone separating, refining, pressing, drying, and the production of powder and granules. The production of kaolin totals about 80 000 tpa, with 10 000 tpa of mica and 100 000 tpa of sand produced as byproducts. These products are used in ceramics, fibreglass, and other miscellaneous uses such as rubber and paints (Groupe Minéral Harwanne, 1997). Sociètè des Kaolins du Finistère operates the Berrien deposit and is developing a new pit at Loqueffret, which will enable the company to expand its range of products towards high-quality kaolin for tableware. The production of kaolin totals about 50 000 tpa, with 50 000 tpa of sand as a coproduct. The kaolin products are used in the manufacture of ceramics, in the paper industry, and for glass fibre (Groupe Minéral Harwanne, 1997).

SOKA extracts approximately 250 000 tpa of crude kaolin from a deposit at Quessoy, 16 km southeast of Saint-Brieuc in Brittany. This kaolin is processed into five different grades, producing 120 000 tpa of processed kaolin, of which over 60% is exported. Approximately 60% of production is consumed by the sanitary ware industry, with 25–30% used for tiles and the remainder for applications such as fertilizer, animal feed, and adhesives.

Spain

Spain produced 300 000 t of kaolin in 1996. The main companies involved in the kaolin industry are Caolines de Vimianzo SA (Cavisa) and Explotaciones Ceramicas Españolas SA (Ecesa).

Cavisa is owned by Rio Tinto Minera SA (RTM). At the beginning of 1993, 65% of the equity in RTM was purchased by Freeport McMoran Inc. Cavisa mines a residual kaolin deposit at Vimianzo, Cap Finisterre, in Galicia, and produces close to 100 000 tpa of paper grade kaolin and is increasing its output of ceramic grade kaolins.

In mid-1990, Ecesa bought two other Spanish kaolin producers, now known as Explotaciones Caoliniferas Españolas SA and Caosil SA, and has become one of the largest producers of kaolin in Spain. The company has increased production capacity from 70 000 tpa to 90 000 tpa at its main extractive operations at Burela de Cabo in Lugo Province (Loughbrough, 1993).

In central Spain, in the region from Guadalajara to Valencia, there are numerous occurrences of a slightly kaolinitic sand. The sand is used in glass manufacture, and the kaolin is washed and concentrated for use in pigment and ceramic applications (Pickering and Murray, 1994).

Malaysia

In 1996, Malaysia produced approximately 220 000 t of kaolin. Although there are about 20 mines in the country, there are only three major producers: Associated Kaolin Industries Bhd, Kaolin Malaysia Sdn Bhd, and Tinex Kaolin Corp. Sdn Bhd. Kaolinitic clay deposits are found in many states of Malaysia (Table 10), but apparently none of the resources contain kaolin of coating grade.

Table 10. Kaolinitic clay deposits in Malaysia

State	*Location*	*Resources (Mt)*	*Application*
Kedah	Kuala Muda	n/a	n/a
Perak	Tapah-Bidor	50	ceramic/filler grade
Selangor	S.G. Long	0.5	filler grade
	Rawang	n/a	n/a
Johor	Kota Tinggi	4	ceramic/filler grade
Sarawak	Kuching	1.3	ceramic grade
	Muara Tuang	0.8	ceramic grade
	Telagus	19	filler grade
Sabah	Papar	0.07	ceramic grade
	Kawang	5	ceramic grade

NOTE: after Skillen (1994)
n/a — not available

Associated Kaolin Industries Bhd produces about 70 000 tpa for use in paper filler, paint, ceramics, palm-oil refining, and fertilizers. About 50% of this material is exported to Japan, South Korea, Taiwan, Hong Kong, the Philippines, Singapore, the Middle East, and Sri Lanka. Growth sectors in kaolin usage are considered by the company to be in the domestic market, particularly in tiles and sanitary ware.

Approximately 60% of Kaolin Malaysia Sdn Bhd's total production of 2000 tpa is consumed domestically, while the remainder is exported to Japan, Taiwan, China, Thailand, and the Middle East.

Tinex Kaolin Corp. Sdn Bhd is the newest of the mainstream kaolin producers and manufactures high-grade filler for the paper market. Production capacity is around 4000 t per month, 3000 t of which is filler grade for the Japanese (70%) and domestic (30%) paper markets. The other 1000 t are divided 50:50 into ceramics and paint, for local use and export to Taiwan and elsewhere in the ASEAN (Association of South East Asian Nations) region (Skillen, 1994).

India

India produced 150 000 t of kaolin in 1996. Indian kaolin resources are estimated to total 870 Mt, of which 20 Mt are proven reserves. Kaolin is found in many areas of India, and much is simply washed before being sold. The highest quality deposits in India are found in the Bhagalpur and Singhbhum districts of Bihar, the Quilon, Trivandrum, and Cannanmore districts of Kerala, the Mayurbhanj district in Orissa, the Birbhum district of West Bengal, and Sabarkantha in Gujarat (Loughbrough, 1993). The kaolin deposits on the narrow southwestern coastal plain from Cochin to Quilon to Trivandrum are transported in origin, and are derived from the alteration and erosion of nearby charnockite, gneiss, and granite. Kaolin from these deposits is used domestically for refractories, rubber filler, and miscellaneous pigments. A production plant at Veli, Trivandrum, refines kaolin from Thonnakkal, 30 km to the north, by using fractionation, reduction leaching, filtering, and drying. In the Jaipur district of Rajasthan, kaolin is produced from a residual deposit derived from a pegmatitic granite. In this area, much of the clay is mined underground (Pickering and Murray, 1994).

Kaolin mining in India is mostly carried out by 25–30 small companies. Some of the larger companies are Ashapura Minechem Pvt. Ltd, English–Indian Clays (40% owned by ECC), West Coast Minerals and Chemicals, and The Hindustan Mineral Products Co. Pvt. Ltd (HMP). The Indian Aluminium Co. Ltd (Indal) has plans to mine a deposit, with an estimated resource of more than 10 Mt, at Lohardaga in Bihar State, in northeast India (Industrial Minerals, 1991, 1996).

Ashapura Minechem Pvt. Ltd produces 25 000 tpa of kaolin from three mines, for use in the ceramic and rubber industries. English–Indian Clays produces 30 000 tpa of kaolin for the domestic paper industry from its mine near Trivandrum in Kerala State. West Coast Minerals and Chemicals has a processing plant with a current capacity of 5000 tpa of kaolin in the form of paper filler and coating grades, catalyst grade material, and rubber filler kaolin. HMP operates two processing facilities in Bombay, and another in Ankleshwar in Gujarat State, with a combined capacity of 15 000 tpa. At present about 6000 tpa of HMP's production is used in the paint and rubber industries, mostly in the domestic market.

Indonesia

The production of kaolin in Indonesia in 1996 was 50 000 t (Coope, 1997). However, Skillen (1996b) has quoted a figure of 780 000 tpa, which presumably is the production of raw kaolin and would therefore include lower grade material.

Indonesia is possibly ASEAN's key kaolin producer, with production centred on the island of Belitung, off the eastern coast of Sumatra (Skillen, 1996b). Kaolin deposits are also found on Bangka Island, east of Palembang in Sumatra. This island contains several large-scale weathered granitic deposits, as well as a reasonable quantity of smaller, kaolinized metasediments that are being worked by a number of small operators. The kaolinitic material derived from the metasediments is mainly consumed by the tile industry, with some material used in other ceramic products.

There are 12 companies extracting kaolin in Indonesia, and of these the main producer is PT Alter Abadi, which operates six separate sites on Belitung Island. In 1995, the company produced around 70% of the country's total output. In addition, the company supplies 70% of the filler grade material consumed within Indonesia in ceramics, paper, and paints. The domestic and export markets for the company's kaolin products are split equally. Export markets include Japan, Taiwan, South Korea, Thailand, the Philippines, Sri Lanka and Pakistan, as well as other countries in South East Asia.

Other companies producing kaolin in Indonesia (based on 1993 data) include PT Multi Mascot with a mine at Minahasa, North Sulawesi; PT Kencana Kaolin with a mine at Tanjung Indah, Kab. Belitung; PT Fajar Perdana Permai with a mine at Sungai Liat, Bangka; PT Daya Waruna Indragiri with a mine at Pekanbaru, Riau; PT Binakaolin Anugrah with a mine at Stasiun, Bangka; and PT Bangka Kaolin Industri Indonesia Trepadu with a mine at Kec. Belinyu, Bangka.

Australia

Australia is about the 14th largest producer of kaolin in the world, and produced approximately 190 000 t of kaolin in 1996 (Table 8). It was a major exporter of paper coating kaolin until the closure of the Weipa deposit in Queensland in 1997. Queensland is the main producer of kaolin in Australia, although all other states also produce appreciable quantities of variable grade kaolin. However, production from Tasmania appears to be dwindling due to the lack of demand. The Northern Territory has had no recorded production of kaolin in recent years.

Queensland

Most of the production in Australia has been from the Weipa deposit, located on the western side of Cape York Peninsula in Queensland. In 1996–97, the production from Queensland was 64 068 t, which was valued at $9 million (Bruwell, Geological Survey of Queensland, pers. comm., 1998). However, Comalco Kaolin (part of the Rio Tinto Group), the owner of the Weipa deposit, has stopped kaolin production at this operation as a result of a restructuring and rationalization plan to overhaul the company's bauxite operations at Weipa (Industrial Minerals, 1997c). The kaolin plant was placed on a care-and-maintenance basis towards the end of 1996. The kaolin deposit is located beneath the well-known Weipa lateritic bauxite of Tertiary age. The clay zone is 8–12 m thick and averages 40–70% kaolin. Kaolin from the deposit was processed to produce a fine No. 1 coating clay product with excellent high-shear viscosity. The plant was established in 1986 with an initial capacity of 100 000 tpa of product, but in 1995 the capacity was increased to 200 000 tpa to meet the growing demand for paper coating clay in Asia. The resources at Weipa are estimated at 9.2 Mt of proven and 47 Mt of probable reserves (Cooper et al., 1996).

However, Queensland will continue to play a significant role in world kaolin markets with the development of the Skardon River deposit, located 100 km north of Weipa. There is no production from the deposit as yet, but the proposed plan is to produce a minimum of 75 000 tpa of premium grade calcined kaolin and 100 000 tpa of hydrous kaolin, with an expected mine life of at least 13 years. The operator, Australian Kaolin Ltd (formerly Venture Exploration NL), established an operating pilot plant at Cairns in 1993, and is proceeding with the development of the deposit at a capital cost of $65 million. The company aims to start production in the middle of 1998, following the construction of mining, processing, and shipping facilities. Three major international trading houses, Chemag Aktiegensellschaft of Germany, Nissho Iwai Corporation of Japan, and Lomas International of the USA, have made a commitment to take a total of

60 000 t of calcined kaolin in the first year of operation (Queensland Government Mining Journal, 1997a,b).

Drilling of the Skardon River deposit has defined two clay-rich zones consisting of a channel-fill sequence of sediments comprising clay and sand in varying proportions, and an underlying altered shale. A detailed grade-control program conducted in 1997, together with the build up of a stockpile, has enabled a detailed analysis of the resource for the first three years of production. The material from the deposit is ideal for paper coating grades because of its high brightness. The deposit contains proven reserves of 2.6 Mt at an average clay grade of 93.8%, yielding kaolin of an average brightness of 89.1%. In addition, there is an indicated resource of 22 Mt with a clay grade of 92.01%. The beneficiation process for the kaolin is based on the physical separation of the fine kaolin followed by dewatering and drying to produce the final products. The kaolin slurry from the wet plant at the mine site will be pumped a distance of 16 km to the drying plant located at the Skardon River port site (Waterman, 1997; Minerals Gazette, 1997; Keys, 1998).

Other kaolin deposits in Queensland include those containing over 3 Mt around Kingaroy, about 200 km northwest of Brisbane, which are worked by Nyora Mining. These are transported deposits underlying Tertiary basalt, and are probably derived from kaolinized granites and kaolin-rich sediments. Kingaroy Kaolin operates a relatively small plant of about 15 000 tpa capacity, using kaolin resources supplied by Nyora Mining.

South Australia

Current kaolin production in South Australia is relatively small and is from operations located close to Adelaide. Around 50 000 tpa of semi-plastic kaolin is produced from pits at Golden Grove and One Tree Hill. The Golden Grove deposit, located 20 km northeast of Adelaide, is a large transported deposit with an indicated resource estimated at 15 Mt. Clays from Golden Grove and One Tree Hill are used mostly by Nubrik and PGH as a plastic component in brick-clay blends, but small tonnages are also used for refractory bond clay and ceramics.

Approximately 5000 tpa is produced from mixed kaolin–sillimanite ore mined at Williamstown, 40 km northeast of Adelaide. This is a unique high-alumina kaolin deposit mined by Commercial Minerals Ltd for the manufacture of refractories and ceramic insulators. These orebodies are within a shear zone, 800 m wide, containing highly deformed lenses of coarse-grained schist, gneiss, and quartzite.

Around 5000 tpa of high-grade kaolin is mined selectively near Birdwood. The deposit has an indicated resource of 0.2 Mt, and is mined by Adelaide Brighton Cement Ltd for the manufacture of specialty white cement, and by Commercial Minerals Ltd for use as a filler in paint and rubber.

There is a small production of silty kaolin from Woodside, which is used by Heat Containment Industries Ltd for refractory clay blends.

In addition to the above deposits, four large deposits of variable grade kaolin have been outlined by drilling granitic and gneissic terrains in the Gawler Craton on the Eyre Peninsula. These deposits are Mount Hope, Poochera, Mount Sturt, and Kimba. However, development of these deposits will depend on commercial factors such as quality, beneficiation and transport costs, and market availability (Mines and Energy South Australia, 1995).

The Mount Hope deposit, located on the southwestern part of the Eyre Peninsula, is in deeply weathered schist and gneiss, and has an indicated resource of 11 Mt of ore averaging 10 m thickness, below 5–12 m of calcareous sand and sandy clay overburden. The clay resource comprises 40–60% kaolin, mostly present as well-crystallized kaolinite, together with medium-grained sugary quartz, minor muscovite, and traces of anatase and iron oxides. The Poochera deposit, located on the northern Eyre Peninsula, has an inferred resource of 30 Mt of kaolin clay, and comprises 3–20 m-thick kaolin beds below 9–30 m of overburden. The Mount Sturt deposit covers an area of 10 km^2, but test results from drilling indicate discouraging results with the kaolin having a low yield, poor brightness, and poor rheological properties. Test results of kaolin from the Kimba deposit indicate that the material is unsuitable for high-quality paper, ceramic, or refractory grades.

Victoria

The production of kaolin (including ball clay) in recent years is around 145 000 tpa. Kaolin is used in both its crude and refined forms in the manufacture of a number of products such as ceramics, paper, floor and wall tiles, fireclay products, and stoneware. Commercial deposits of kaolin in Victoria are of both residual and transported types (McHaffie and Buckley, 1995).

Residual deposits in Victoria are large and are expected to satisfy industry needs for 20–50 years at the current rate of consumption. Residual kaolin, resulting from the weathering of a Devonian granite, is mined at Pittong (near Ballarat) by Kaolin Australia Pty Ltd, a wholly owned subsidiary of English China Clays International Ltd (ECC). The kaolin is generally of a uniform cream colour, with occasional pink-red patches of hematite staining. An orange rust coloration of goethite also occurs locally. The impurities present include quartz, mica, minor montmorillonite, and iron and titanium minerals. The quartz is coarse and readily removed in an on-site wet-processing plant. Free iron oxides and hydroxides can be readily reduced, but goethite, which produces a yellow stain, is more difficult to remove. Product sizing is achieved by a combination of hydrocycloning, centrifuging, and residue attrition. The company produces around 40 000 tpa of wet-processed kaolin. Approximately 50–60% of the kaolin produced from this deposit is used as a paper filler and coating clay, and most of this is exported. Kaolin from this deposit is also used as a source of alumina in the manufacture of fibreglass, as a filler in paint, rubber and plastics, and in the manufacture of ceramics. Other residual deposits in Victoria that have been worked in the past include those at Hallam (to the southeast of Melbourne), the Ballan–Lal Lal area, in the vicinity of Gordon, at Ringwood, and near Bulla. Residual kaolin deposits are also known in the Pyalong area (Keeling, 1997; McHaffie and Buckley, 1995).

Transported deposits of kaolin are mined at Axedale by R. R. & A. E. Osterfield Pty Ltd and by Axedale Ballclay Pits. The clays are Tertiary in age and were deposited in a restricted fluvial environment, possibly in a series of lakes or abandoned channels. Ball clay from these deposits is used in the manufacture of tiles, insulators, and various whiteware and ceramic products. A number of other localities in Victoria are known for their transported kaolin deposits. Deposits that have been recently worked are located in the Latrobe Valley (underlying Morwell No. 1 coal seam), in the Parwan Valley near Rowsley, at Enfield, and at Napoleons. The deposit in the Latrobe Valley is known as Morwell 1B clay bed and has been intermittently worked by various end-users. The current operators in the Parwan Valley are Hine Bros and Boral, with Hine Bros producing semi-ball clay suitable for use in various ceramic applications and in firebrick manufacture. The production by Boral is mainly for brickmaking. Boral also extracts kaolin from pits at Rowsley for use in the manufacture of low-grade refractory bricks. Clay from the deposits at Enfield is used in face bricks, roofing tiles and pottery, whereas clay from deposits at Napoleons is mainly used for ceramic applications (McHaffie and Buckley, 1995).

The Lal Lal Kaolin Mine, located approximately 20 km east of Ballarat on the western side of the Moorabool River, is an underground mine that has been in operation since around 1880. This mine produces high-grade kaolin for many uses such as ceramic bodies and glazes, porcelain, cosmetics, and as a filler for paper, paint, rubber, and plastics. The kaolin is derived from a weathered feldpspathic dyke and is obtained from three working levels by means of an inclined shaft.

New South Wales

In 1996, New South Wales produced 13 066 t of kaolin and ball clay. In addition, 2538 t of halloysite and 2818 t of refractory clay were also produced.

Most of the high-quality kaolin produced in New South Wales, for use as fillers and in ceramic whiteware, is mined from Tertiary transported deposits in the Gulgong–Home Rule–Puggoon area and in the Coorabin–Oaklands area. Lower grade kaolin, used for refractories or house bricks, is also extracted from these deposits as well as from Tertiary transported deposits at Barraba, Port Stephens, Bungonia, and Adaminaby. The clay from Port Stephens and Adaminaby, and from unworked transported deposit at South Rocks, could also be used in ceramic whiteware, as a filler, and in refractories (Baker and Uren, 1982).

Lower grade transported kaolin, for use in refractories and house bricks, is also mined from Permian sediments in the Illawarra, Newcastle, and Muswellbrook areas, from Triassic sediments near Sydney, and from Jurassic sediments in the Merrygoen area.

Residual kaolin deposits are mined at Buckaroo, near Mudgee, for use in refractories and sanitary ware, and near Goulburn for use in house bricks. Kaolin from deposits at Elsmore, Tichborne, and Goulburn has potential for use as a filler, in ceramic whiteware, and in refractories.

Australian Kaolin NL has purchased a kaolin deposit at Elsmore that contains high-quality kaolin capable of being processed for the paint, rubber, and plastics markets (Australia's Paydirt, 1997). The deposit has a measured resource of 752 000 t and an indicated resource of 1.3 Mt, with the company aiming to produce 24 000 tpa of calcined kaolin. However, production from this deposit is not expected before 1999, until after the Skardon project in Queensland is commissioned and all marketing commitments for that project are met (Industrial Minerals, 1998).

Tasmania

Kaolin suitable for use as paper filler has been extracted from several localities in Tasmania. The production during 1995–96 was 28 425 t.

Current production is limited to a deposit at Tonganah (located in the State's northeast near Scottsdale), which is operated by the Ballarat Clay Company. This operation is presently wound down because the Australian Paper mill at Burnie, which uses kaolin from this deposit, has begun using calcium carbonate as a filler instead of kaolin (C. Bacon, Tasmania Department of Mines, pers. comm., 1998). The kaolin from the deposit is residual, and is derived from weathering of a granite in situ.

Other localities of past production of kaolin in Tasmania include Surges Bay in the southern coastal region and South Mount Cameron in the State's northeast. Production from both localities has been used as a paper filler (Bacon, 1992).

Western Australia

In Western Australia, the production of kaolinitic clay is classified under three categories: kaolin, ball clay, and fireclay. The production data given in this Bulletin for each category are classified on the basis of 'as received' by the Department of Minerals and Energy from the producer.

Kaolin production in the State showed very low levels up until operations at Mount Kokeby expanded in 1975. Levels gradually declined until Mount Kokeby stopped its production in 1983 (Fig. 4). This coincided with the start of the mining of kaolin at Greenbushes in 1984. Since then, kaolin production in the State has averaged around 3500 tpa. The total recorded production of kaolin in the State from 1939 to 1997 amounts to 60 586 t with a total value of approximately $2.5 million (Tables 11 and 12). Although the production of kaolin in Western Australia is comparatively low, there are prospective areas for large deposits of high-grade kaolin in the South West region of the State, and these localities are discussed in Chapter 5.

During the period 1932–97, the State also produced 715 355 t of ball clay, valued at approximately

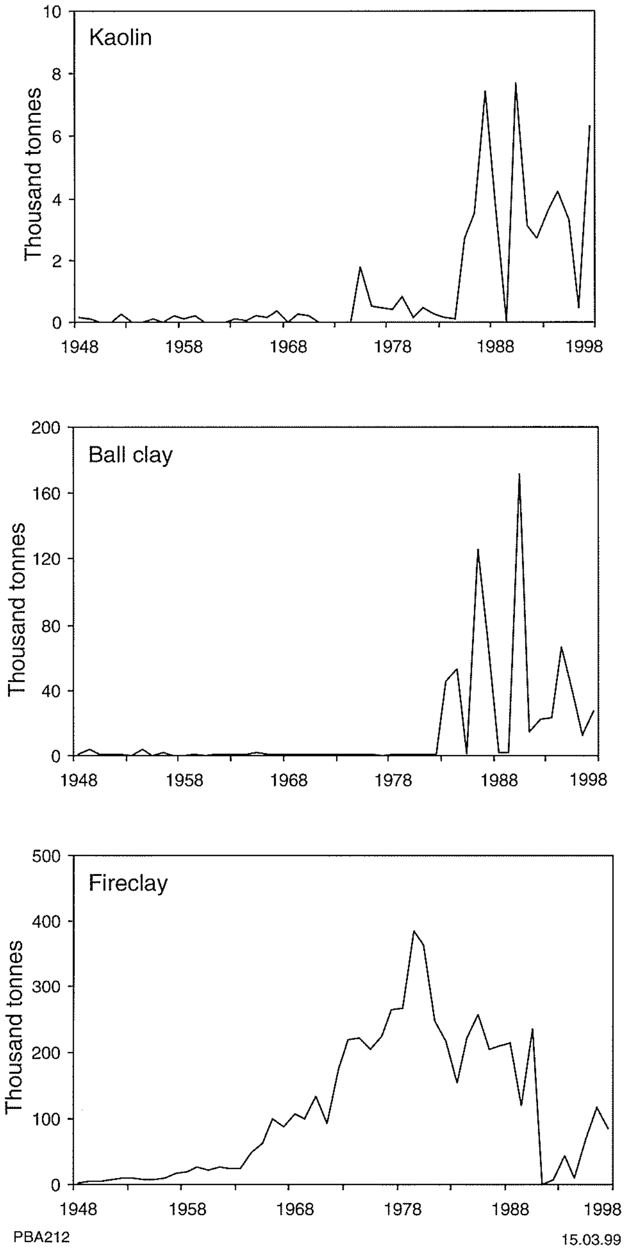

Figure 4. Production of kaolin, ball clay, and fireclay in Western Australia, 1948–1997

$4.8 million (Tables 13 and 14), with the main production centre being Jarrahdale (469 092 t). However, the clay classified as ball clay is not of uniform grade, and may not strictly fall within the definition of ball clay given earlier in this Bulletin. The classification of the clay produced is primarily based on information provided from the various producers. White clays that have been produced from the Jarrahdale and Swan Valley regions are also included in the category of ball clay, as previous production from these localities has been reported as ball clay. The reported ex-mine values of this white clay are similar to those of ball clay reported previously. The ball clay production trend indicates a sharp increase from 1983 onwards, coinciding with the start of production from Jarrahdale, with a peak production of around 171 400 t in 1990 (Fig. 4).

Production of variable grade fireclay in Western Australia from 1922 to 1997 totalled 5.7 Mt. Of this, more than 4 Mt was produced from Bullsbrook (Tables 15 and 16). The production trend indicates a significant increase, from around 100 000 t in 1966 to around 387 000 t in 1979 (Fig. 4), coinciding with production from Bullsbrook, Clackline, and Byford. In 1997, production amounted to 84 688 t.

Prices and markets

Prices

The vast number of kaolin grades on the market makes it difficult to obtain precise pricing information. Coope (1997) provided ex-works price ranges as an indication of 1996 levels for various grades, but it should be noted that prices fluctuate within these broad bands (Table 17).

In terms of dollar value of the day, the unit value of Western Australian kaolin has increased from $1.50 per tonne in 1939 to around $43 per tonne in 1997. The graph of unit value of ex-mine production of kaolin shows that, in real terms, kaolin prices declined for almost 30 years until the closure of Mount Kokeby in 1983, after which prices recovered to be within the range of $40–140 per tonne after production from Greenbushes commenced (Fig. 5).

The trend in unit value of ball clay production shows that, in real terms, prices have declined steadily over the last 50 years (Fig. 5). This reinforces the interpretation that the problem is related to inappropriate classification of the product. Similarly to ball clay, a graph of the real unit price of fireclay (Fig. 5) shows a long period of decline, again interpreted to be from original classification problems of the clay. The average price of fireclay has remained low, at less than $1.50 per tonne over the last few years.

To overcome classification problems of industrial minerals, as discussed previously, Driessen (1996) proposed a uniform code of nomenclature based on end-uses. This proposal has been accepted in principle by all the relevant organizations in Australia, including the Department of Minerals and Energy of Western Australia (DME). Preliminary steps have been taken by the DME for implementation of this proposal.

Markets

The primary consumer of kaolin is the paper industry, accounting for over 80% of the total consumption. Although kaolin has lost market share to other white minerals over the years, particularly calcium carbonate and talc, the demand for coating and filler grades in the paper industry has been sufficiently strong for kaolin operators to continue successfully. Only a small number of deposits in the world are suitable for the production of high-quality paper coating grades of kaolin, with the main countries having such deposits being the USA, UK, Brazil, and Australia. However, Pleeth (1997) stated that

Table 11. Production of kaolin in Western Australia (tonnes)

Year	*Glen Forrest (MC 189)*	*Mount Kokeby (MC 247)*	*Piyawanning (MC 240)*	*Nynaania (PP)*	*Cue (PP)*	*Mukinbudin (MC 70/2110)*	*Greenbushes (M 01/1)*	*Goomalling (M 70/162)*	*Total*
1939	415	–	–	–	–	–	–	–	**415**
1940	1 675	–	–	–	–	–	–	–	**1 675**
1941	672	20	–	–	–	–	–	–	**692**
1942	–	51	–	–	–	–	–	–	**51**
1943	–	68	406	–	–	–	–	–	**474**
1944	–	126	–	–	–	–	–	–	**126**
1945	–	55	–	–	–	–	–	–	**55**
1946	–	–	–	–	–	–	–	–	**0**
1947	–	590	–	–	–	–	–	–	**590**
1948	–	148	–	–	–	–	–	–	**148**
1949	–	81	–	–	–	–	–	–	**81**
1950	–	–	–	–	–	–	–	–	**0**
1951	–	–	–	12	–	–	–	–	**12**
1952	–	217	–	12	42	–	–	–	**272**
1953	–	20	–	–	–	–	–	–	**20**
1954	–	20	–	–	–	–	–	–	**20**
1955	–	77	–	–	–	–	–	–	**77**
1956	–	–	–	–	–	–	–	–	**0**
1957	–	206	–	–	–	–	–	–	**206**
1958	–	80	–	–	–	–	–	–	**80**
1959	–	188	–	–	–	–	–	–	**188**
1960	–	–	–	–	–	–	–	–	**0**
1961	–	–	–	–	–	–	–	–	**0**
1962	–	–	–	–	–	–	–	–	**0**
1963	–	127	–	–	–	–	–	–	**127**
1964	–	62	–	–	–	–	–	–	**62**
1965	–	194	–	–	–	–	–	–	**194**
1966	–	152	–	–	–	–	–	–	**152**
1967	–	338	–	–	–	–	–	–	**338**
1968	–	–	–	–	–	–	–	–	**0**
1969	–	263	–	–	–	–	–	–	**263**
1970	–	190	–	–	–	–	–	–	**190**
1971	–	–	–	–	–	–	–	–	**0**
1972	–	–	–	–	–	–	–	–	**0**
1973	–	–	–	–	–	–	–	–	**0**
1974	–	–	–	–	–	–	–	–	**0**
1975	–	1 763	–	–	–	16	–	–	**1 779**
1976	–	408	–	–	–	116	–	–	**524**
1977	–	425	–	–	–	57	–	–	**482**
1978	–	353	–	–	–	55	–	–	**408**
1979	–	827	–	–	–	–	–	–	**827**
1980	–	163	–	–	–	–	–	–	**163**
1981	–	440	–	–	–	–	–	–	**440**
1982	–	235	–	–	–	–	–	–	**235**
1983	–	169	–	–	–	–	–	–	**169**
1984	–	–	–	–	–	–	85	–	**85**
1985	–	–	–	–	–	–	2 685	–	**2 685**
1986	–	–	–	–	–	–	3 540	–	**3 540**
1987	–	–	–	–	–	–	7 460	–	**7 460**
1988	–	–	–	–	–	–	3 891	–	**3 891**
1989	–	–	–	–	–	–	–	–	**0**
1990	–	–	–	–	–	–	7 701	–	**7 701**
1991	–	–	–	–	–	–	3 100	–	**3 100**
1992	–	–	–	–	–	–	2 692	–	**2 692**
1993	–	–	–	–	–	–	3 611	–	**3 611**
1994	–	–	–	–	–	–	3 347	864	**4 211**
1995	–	–	–	–	–	–	134	3 163	**3 297**
1996	–	–	–	–	–	–	440	–	**440**
1997	–	–	–	–	–	–	6 334	–	**6 334**
Total	**2 762**	**8 059**	**406**	**24**	**42**	**244**	**45 020**	**4 027**	**60 586**

Table 12. Value of kaolin production in Western Australia (Aus $)

Year	*Glen Forrest (MC 189)*	*Mount Kokeby (MC 247)*	*Piyawanning (MC 240)*	*Nynaania (PP)*	*Cue (PP)*	*Mukinbudin (MC 70/2110)*	*Greenbushes (M 01/1)*	*Goomalling (M 70/162)*	*Total Aus $ value of the day*
1939	623	–	–	–	–	–	–	–	**623**
1940	2 557	–	–	–	–	–	–	–	**2 557**
1941	1 020	50	–	–	–	–	–	–	**1 070**
1942	–	150	–	–	–	–	–	–	**150**
1943	–	670	400	–	–	–	–	–	**1 070**
1944	–	1 240	–	–	–	–	–	–	**1 240**
1945	–	540	–	–	–	–	–	–	**540**
1946	–	–	–	–	–	–	–	–	**0**
1947	–	620	–	–	–	–	–	–	**620**
1948	–	584	–	–	–	–	–	–	**584**
1949	–	320	–	–	–	–	–	–	**320**
1950	–	–	–	–	–	–	–	–	**0**
1951	–	–	–	38	–	–	–	–	**38**
1952	–	2 148	–	44	414	–	–	–	**2 606**
1953	–	200	–	–	–	–	–	–	**200**
1954	–	200	–	–	–	–	–	–	**200**
1955	–	760	–	–	–	–	–	–	**760**
1956	–	–	–	–	–	–	–	–	**0**
1957	–	2 030	–	–	–	–	–	–	**2 030**
1958	–	790	–	–	–	–	–	–	**790**
1959	–	1 850	–	–	–	–	–	–	**1 850**
1960	–	–	–	–	–	–	–	–	**0**
1961	–	–	–	–	–	–	–	–	**0**
1962	–	–	–	–	–	–	–	–	**0**
1963	–	570	–	–	–	–	–	–	**570**
1964	–	275	–	–	–	–	–	–	**275**
1965	–	965	–	–	–	–	–	–	**965**
1966	–	900	–	–	–	–	–	–	**900**
1967	–	2 164	–	–	–	–	–	–	**2 164**
1968	–	–	–	–	–	–	–	–	**0**
1969	–	1 505	–	–	–	–	–	–	**1 505**
1970	–	1 113	–	–	–	–	–	–	**1 113**
1971	–	–	–	–	–	–	–	–	**0**
1972	–	–	–	–	–	–	–	–	**0**
1973	–	–	–	–	–	–	–	–	**0**
1974	–	–	–	–	–	–	–	–	**0**
1975	–	10 435	–	–	–	316	–	–	**10 751**
1976	–	2 433	–	–	–	2 711	–	–	**5 144**
1977	–	2 546	–	–	–	1 254	–	–	**3 800**
1978	–	2 104	–	–	–	1 210	–	–	**3 314**
1979	–	4 960	–	–	–	–	–	–	**4 960**
1980	–	978	–	–	–	–	–	–	**978**
1981	–	2 639	–	–	–	–	–	–	**2 639**
1982	–	1 412	–	–	–	–	–	–	**1 412**
1983	–	1 014	–	–	–	–	–	–	**1 014**
1984	–	–	–	–	–	–	3 199	–	**3 199**
1985	–	–	–	–	–	–	85 148	–	**85 148**
1986	–	–	–	–	–	–	131 580	–	**131 580**
1987	–	–	–	–	–	–	241 564	–	**241 564**
1988	–	–	–	–	–	–	197 740	–	**197 740**
1989	–	–	–	–	–	–	–	–	**0**
1990	–	–	–	–	–	–	472 291	–	**472 291**
1991	–	–	–	–	–	–	204 400	–	**204 400**
1992	–	–	–	–	–	–	172 726	–	**172 726**
1993	–	–	–	–	–	–	248 699	–	**248 699**
1994	–	–	–	–	–	–	201 531	25 920	**227 451**
1995	–	–	–	–	–	–	34 941	135 481	**170 422**
1996	–	–	–	–	–	–	61 527	–	**61 527**
1997	–	–	–	–	–	–	269 653	–	**269 653**
Total	**4 201**	**48 164**	**400**	**82**	**414**	**5 491**	**2 324 999**	**161 401**	**2 545 152**

Table 13. Production of ball clay in Western Australia (tonnes)

Year	*Goomalling (ML 5 PP)*	*Kalgoorlie (PA 5306E)*	*Jarrahdale (MC 21374, M 70/41, 42 170, 145)*	*Swan Valley*	*Total*
1932	77	–	–	–	**77**
1934	56	–	–	–	**56**
1947	3 963	–	–	–	**3 963**
1948	751	–	–	–	**751**
1949	4 197	–	–	–	**4 197**
1950	610	–	–	–	**610**
1951	1 118	–	–	–	**1 118**
1952	793	–	–	–	**793**
1953	465	–	–	–	**465**
1954	4 064	–	–	–	**4 064**
1956	2 124	–	–	–	**2 124**
1959	1 021	–	–	–	**1 021**
1961	764	20	–	–	**784**
1962	667	26	–	–	**693**
1963	731	76	–	–	**807**
1964	557	22	–	–	**579**
1965	1 408	55	–	–	**1 463**
1966	977	51	–	–	**1 028**
1967	731	20	–	–	**751**
1968	964	–	–	–	**964**
1969	694	–	–	–	**694**
1970	864	–	–	–	**864**
1971	667	–	–	–	**667**
1972	915	–	–	–	**915**
1973	549	–	–	–	**549**
1974	719	–	–	–	**719**
1975	575	–	–	–	**575**
1976	555	–	–	–	**555**
1977	323	–	–	–	**323**
1978	519	–	–	–	**519**
1979	619	–	–	–	**619**
1980	1 131	–	–	–	**1 131**
1981	946	–	–	–	**946**
1982	1 176	–	–	–	**1 176**
1983	994	–	44 766	–	**45 760**
1984	978	–	52 156	–	**53 134**
1985	846	–	–	–	**846**
1986	866	–	125 187	–	**126 053**
1987	–	–	72 176	–	**72 176**
1988	–	–	1 697	–	**1 697**
1989	–	–	1 709	–	**1 709**
1990	–	–	171 401	–	**171 401**
1991	–	–	–	14 611	**14 611**
1992	–	–	–	22 575	**22 575**
1993	–	–	–	22 984	**22 984**
1994	–	–	–	67 077	**67 077**
1995	–	–	–	38 596	**38 596**
1996	–	–	–	13 003	**13 003**
1997	–	–	–	27 175	**27 175**
Total	**39 971**	**271**	**469 092**	**206 021**	715 355

Table 14. Value of ball clay production in Western Australia (Aus $)

Year	*Goomalling (ML 5 PP)*	*Kalgoorlie (PA 5306E)*	*Jarrahdale (MC 21374, M 70/41, 42 170, 145)*	*Swan Valley*	*Total Aus $ value of the day*
1932	95	–	–	–	**95**
1934	138	–	–	–	**138**
1947	9 750	–	–	–	**9 750**
1948	2 956	–	–	–	**2 956**
1949	16 524	–	–	–	**16 524**
1950	2 400	–	–	–	**2 400**
1951	6 600	–	–	–	**6 600**
1952	6 000	–	–	–	**6 000**
1953	3 526	–	–	–	**3 526**
1954	32 000	–	–	–	**32 000**
1956	16 320	–	–	–	**16 320**
1959	8 040	–	–	–	**8 040**
1961	6 016	118	–	–	**6 134**
1962	7 904	156	–	–	**8 060**
1963	5 752	450	–	–	**6 202**
1964	4 384	132	–	–	**4 516**
1965	11 088	324	–	–	**11 412**
1966	7 696	300	–	–	**7 996**
1967	5 752	60	–	–	**5 812**
1968	7 592	–	–	–	**7 592**
1969	7 738	–	–	–	**7 738**
1970	9 631	–	–	–	**9 631**
1971	7 432	–	–	–	**7 432**
1972	10 812	–	–	–	**10 812**
1973	6 480	–	–	–	**6 480**
1974	6 881	–	–	–	**6 881**
1975	6 792	–	–	–	**6 792**
1976	6 552	–	–	–	**6 552**
1977	3 230	–	–	–	**3 230**
1978	6 228	–	–	–	**6 228**
1979	7 428	–	–	–	**7 428**
1980	11 094	–	–	–	**11 094**
1981	11 952	–	–	–	**11 952**
1982	12 750	–	–	–	**12 750**
1983	11 500	–	134 298	–	**145 798**
1984	9 287	–	148 645	–	**157 932**
1985	8 936	–	–	–	**8 936**
1986	6 599	–	356 783	–	**363 382**
1987	–	–	209 528	–	**209 528**
1988	–	–	20 364	–	**20 364**
1989	–	–	20 503	–	**20 503**
1990	–	–	1 529 000	–	**1 529 000**
1991	–	–	–	160 718	**160 718**
1992	–	–	–	225 745	**225 745**
1993	–	–	–	249 946	**249 946**
1994	–	–	–	656 898	**656 898**
1995	–	–	–	385 960	**385 960**
1996	–	–	–	130 030	**130 030**
1997	–	–	–	262 310	**262 310**
Total	**311 855**	**1 540**	**2 419 121**	**2 071 607**	**4 804 123**

Table 15. Production of fireclay in Western Australia (tonnes)

Year	*Collie (ML 87)*	*Clackline (MC 304^H 379, 380, M 70/240)*	*Bedfordale MC 504^H, 505^H)*	*Byford (MC 522^H, 523^H, 1302^H, 685^H)*	*Glen Forrest (Loc. 84, Lot 157, MC 585^H, 732^H, 1114^H)*	*Bullsbrook (ML 435^H, 436^H, M 70/635)*	*Bakers Hill (ML 53, PA 312, 4)*	*Metro area (unspecified localities)*	*Piawaning (M 70/240)*	*Nanamoolan (M 70/827)*	*Total*
1922	689	–	–	–	–	–	–	–	–	–	**689**
1928	379	–	–	–	–	–	–	–	–	–	**379**
1939	–	429	–	–	–	–	–	–	–	–	**429**
1940	–	1 445	–	–	–	–	–	–	–	–	**1 445**
1941	–	730	–	–	–	–	–	–	–	–	**730**
1942	–	759	–	–	–	–	–	–	–	–	**759**
1943	–	1 651	–	–	–	–	20	–	–	–	**1 671**
1944	–	1 381	–	–	–	–	–	–	–	–	**1 381**
1945	–	1 567	–	–	–	–	–	–	–	–	**1 567**
1946	–	1 821	–	–	–	–	–	–	–	–	**1 821**
1947	–	1 690	–	–	–	–	–	–	–	–	**1 690**
1948	–	2 040	–	–	–	–	1 016	–	–	–	**3 056**
1949	–	4 189	–	–	1 372	–	–	–	–	–	**5 561**
1950	–	4 129	–	–	1 194	–	610	–	–	–	**5 933**
1951	–	6 144	–	–	2 120	–	–	–	–	–	**8 265**
1952	–	7 962	–	–	1 800	–	–	–	–	–	**9 762**
1953	–	7 512	–	–	1 448	–	–	–	–	–	**8 959**
1954	–	5 624	–	–	1 222	–	–	–	–	–	**6 846**
1955	–	6 131	–	–	892	–	–	–	–	–	**7 023**
1956	–	7 222	–	1 372	995	–	–	–	–	–	**9 588**
1957	–	5 588	2 180	6 697	3 464	–	–	–	–	–	**17 930**
1958	–	3 048	–	14 461	3 027	–	–	–	–	–	**20 536**
1959	–	1 901	1 016	19 073	4 632	–	–	–	–	–	**26 623**
1960	–	1 640	–	15 662	3 371	–	–	–	–	–	**20 673**
1961	–	2 053	–	19 108	5 646	–	–	–	–	–	**26 807**
1962	–	1 966	2 835	16 688	3 693	–	–	–	–	–	**25 182**
1963	–	4 029	–	14 045	7 329	–	–	–	–	–	**25 403**
1964	–	2 932	–	26 001	19 077	–	–	–	–	–	**48 010**
1965	–	3 315	–	7 444	31 328	–	–	19 996	–	–	**62 083**
1966	–	3 417	1 283	26 370	29 432	–	–	39 565	–	–	**100 068**
1967	–	5 055	–	34 553	41 773	–	–	6 033	–	–	**87 413**
1968	–	2 299	–	51 381	38 529	–	–	13 459	–	–	**105 668**
1969	–	4 804	1 593	55 802	31 678	5 610	–	188	–	–	**99 675**
1970	–	2 997	–	101 378	2 025	19 786	–	6 722	–	–	**132 909**
1971	–	–	–	41 752	–	49 185	–	1 564	–	–	**92 501**
1972	–	1 016	–	62 474	–	108 569	–	–	–	–	**172 058**
1973	–	2 642	–	73 367	–	143 021	–	–	–	–	**219 029**
1974	–	1 728	–	42 325	–	176 890	–	–	–	–	**220 943**
1975	–	1 905	–	52 350	–	149 839	–	–	–	–	**204 094**
1976	–	1 805	–	–	–	220 718	–	–	–	–	**222 523**
1977	–	4 831	–	51 431	–	207 445	–	–	–	–	**263 707**
1978	–	6 420	–	97 847	–	162 436	–	–	–	–	**266 703**

Table 15. (continued)

Year	*Collie (ML 87)*	*Clackline (MC 304^{H} 379, 380, M 70/240)*	*Bedfordale MC 504^{H}, 505^{H})*	*Byford (MC 522^{H}, 523^{H}, 1302^{H}, 685^{H})*	*Glen Forrest (Loc. 84, Lot 157, MC 585^{H}, 732^{H}, 1114^{H})*	*Bullsbrook (ML 435^{H}, 436^{H}, M 70/635)*	*Bakers Hill (ML 53, PA 312, 4)*	*Metro area (unspecified localities)*	*Piawaning (M 70/240)*	*Nanamoolan (M 70/827)*	*Total*
1979	–	6 176	–	122 120	–	258 672	–	–	–	–	**386 968**
1980	–	5 887	–	95 774	–	262 947	–	–	–	–	**364 608**
1981	–	4 347	–	68 046	–	174 432	–	–	–	–	**246 825**
1982	–	938	–	–	–	215 504	–	–	–	–	**216 442**
1983	–	910	–	–	–	151 644	–	–	–	–	**152 554**
1984	–	252	–	–	–	221 518	–	–	–	–	**221 770**
1985	–	1 336	–	–	–	255 257	–	–	100	–	**256 693**
1986	–	–	–	–	–	203 597	–	–	–	–	**203 597**
1987	–	–	–	–	–	206 567	–	–	2 064	–	**208 631**
1988	–	–	–	–	–	212 703	–	–	1 830	–	**214 533**
1989	–	–	–	–	–	119 478	–	–	300	–	**119 778**
1990	–	–	–	–	–	234 367	–	–	–	–	**234 367**
1991	–	–	–	–	–	0	–	–	–	–	**0**
1992	–	–	–	–	–	6 508	–	–	–	–	**6 508**
1993	–	–	–	–	–	43 813	–	–	–	–	**43 813**
1994	–	–	–	–	–	10 812	–	–	–	–	**10 812**
1995	–	–	–	–	–	67 802	–	–	–	–	**67 802**
1996	–	–	–	–	–	104 850	–	–	–	12 000	**116 850**
1997	–	–	–	–	–	84 688	–	–	–	–	**84 688**
Total	**1 068**	**147 663**	**8 908**	**1 117 523**	**236 046**	**4 078 658**	**1 646**	**87 527**	**4 294**	**12 000**	**5 695 331**

Table 16. Value of fireclay production in Western Australia (Aus $)

Year	*Collie (ML 87)*	*Clackline (MC 304H 379, 380, M 70/240)*	*Bedfordale MC 504H, 505H)*	*Byford (MC 522H, 523H, 1302H, 685H)*	*Glen Forrest (Loc. 84, Lot 157, MC 585H, 732H, 1114H)*	*Bullsbrook (ML 435H, 436H, M 70/635)*	*Bakers Hill (ML 53, PA 312, 4)*	*Metro area (unspecified localities)*	*Piawaning (M 70/240)*	*Nanamoolan (M 70/827)*	*Total Aus $ value of the day*
1922	1 292	–	–	–	–	–	–	–	–	–	**1 292**
1928	184	–	–	–	–	–	–	–	–	–	**184**
1939	–	420	–	–	–	–	–	–	–	–	**420**
1940	–	1 422	–	–	–	–	–	–	–	–	**1 422**
1941	–	718	–	–	–	–	–	–	–	–	**718**
1942	–	748	–	–	–	–	–	–	–	–	**748**
1943	–	1 625	–	–	–	–	78	–	–	–	**1 703**
1944	–	1 380	–	–	–	–	–	–	–	–	**1 380**
1945	–	1 542	–	–	–	–	–	–	–	–	**1 542**
1946	–	1 792	–	–	–	–	–	–	–	–	**1 792**
1947	–	1 664	–	–	–	–	–	–	–	–	**1 664**
1948	–	2 008	–	–	–	–	2 100	–	–	–	**4 108**
1949	–	4 123	–	–	2 514	–	–	–	–	–	**6 637**
1950	–	4 064	–	–	2 148	–	1 260	–	–	–	**7 472**
1951	–	7 776	–	–	3 764	–	–	–	–	–	**11 540**
1952	–	15 672	–	–	3 368	–	–	–	–	–	**19 040**
1953	–	14 786	–	–	2 717	–	–	–	–	–	**17 503**
1954	–	11 070	–	–	2 286	–	–	–	–	–	**13 356**
1955	–	12 068	–	–	1 668	–	–	–	–	–	**13 736**
1956	–	14 216	–	3 803	1 860	–	–	–	–	–	**19 879**
1957	–	11 000	5 340	18 566	6 726	–	–	–	–	–	**41 632**
1958	–	6 000	–	40 090	4 780	–	–	–	–	–	**50 870**
1959	–	3 742	3 000	52 875	7 075	–	–	–	–	–	**66 691**
1960	–	3 228	–	44 519	5 277	–	–	–	–	–	**53 024**
1961	–	4 042	–	50 535	6 843	–	–	–	–	–	**61 420**
1962	–	3 870	8 270	40 996	4 480	–	–	–	–	–	**57 616**
1963	–	7 930	–	36 731	7 515	–	–	–	–	–	**52 177**
1964	–	5 772	–	61 263	19 037	–	–	–	–	–	**86 072**
1965	–	6 526	–	17 802	30 833	–	–	29 174	–	–	**84 335**
1966	–	6 726	2 715	72 370	28 967	–	–	58 412	–	–	**169 190**
1967	–	9 950	–	34 007	41 113	–	–	2 840	–	–	**87 910**
1968	–	4 526	–	50 570	19 558	–	–	6 471	–	–	**81 125**
1969	–	9 456	4 939	56 921	23 578	2 761	–	102	–	–	**97 756**
1970	–	5 900	–	99 777	997	9 739	–	3 639	–	–	**120 051**
1971	–	–	–	40 093	–	24 204	–	1 826	–	–	**66 123**
1972	–	2 000	–	61 487	–	43 693	–	–	–	–	**107 180**
1973	–	5 200	–	72 208	–	34 844	–	–	–	–	**112 252**
1974	–	3 400	–	41 657	–	43 520	–	–	–	–	**88 577**
1975	–	3 767	–	51 523	–	36 871	–	–	–	–	**92 161**
1976	–	3 504	–	–	–	137 932	–	–	–	–	**141 436**
1977	–	9 594	–	50 931	–	39 571	–	–	–	–	**100 096**
1978	–	12 748	–	97 847	–	24 856	–	–	–	–	**135 451**

Table 16. (continued)

Year	*Collie (ML 87)*	*Clackline (MC 304ᴴ 379, 380, M 70/240)*	*Bedfordale MC 504ᴴ, 505ᴴ)*	*Byford (MC 522ᴴ, 523ᴴ, 1302ᴴ, 685ᴴ)*	*Glen Forrest (Loc. 84, Lot 157, MC 585ᴴ, 732ᴴ, 1114ᴴ)*	*Bullsbrook (ML 435ᴴ, 436ᴴ, M 70/635)*	*Bakers Hill (ML 53, PA 312, 4)*	*Metro area (unspecified localities)*	*Piawaning (M 70/240)*	*Nanamoolan (M 70/827)*	*Total Aus $ value of the day*
1979	–	12 266	–	122 120	–	37 273	–	–	–	–	**171 659**
1980	–	11 774	–	95 774	–	39 442	–	–	–	–	**146 990**
1981	–	8 694	–	68 046	–	45 723	–	–	–	–	**122 463**
1982	–	1 876	–	–	–	258 607	–	–	–	–	**260 483**
1983	–	1 820	–	–	–	181 971	–	–	–	–	**183 791**
1984	–	504	–	–	–	265 822	–	–	–	–	**266 326**
1985	–	2 672	–	–	–	306 309	–	–	200	–	**309 181**
1986	–	–	–	–	–	244 317	–	–	–	–	**244 317**
1987	–	–	–	–	–	247 881	–	–	4 128	–	**252 009**
1988	–	–	–	–	–	405 629	–	–	3 660	–	**409 289**
1989	–	–	–	–	–	143 373	–	–	600	–	**143 973**
1990	–	–	–	–	–	457 335	–	–	–	–	**457 335**
1991	–	–	–	–	–	0	–	–	–	–	**0**
1992	–	–	–	–	–	7 810	–	–	–	–	**7 810**
1993	–	–	–	–	–	52 576	–	–	–	–	**52 576**
1994	–	–	–	–	–	12 975	–	–	–	–	**12 975**
1995	–	–	–	–	–	81 363	–	–	–	–	**81 363**
1996	–	–	–	–	–	125 820	–	–	–	120 000	**245 820**
1997	–	–	–	–	–	101 626	–	–	–	–	**101 626**
Total	**1 476**	**265 579**	**90 390**	**1 316 383**	**227 103**	**3 413 842**	**3 438**	**102 463**	**8 588**	**120 000**	**5 549 263**

Table 17. Ex-works price ranges (1996) for various grades of kaolin

Grade	*Price (US$/tonne)*
Paper coating	90–180
Paper filling	70–100
Ceramic grades	60–120
Calcined pigment	400–500

SOURCE: Coope (1997)

investment in new kaolin projects cannot easily be justified as there appears to be an abundant oversupply of kaolin around the world, thus increasing the opportunities to lift marginal production by improving the capacity and profitability of existing plants, rather than opening costly new mines.

By early 1998, the oversupply of kaolin on world markets had become a reality with the arrival of new companies in the market place, particularly from the Rio Capim region in Brazil. This has hit European producers badly, causing falls in prices and profitability of kaolin fillers supplying the paper and paint industries.

Since that time, there has been a move towards consolidation and globalization of the industry, typified by the takeover bid in January 1999 for English China Clays PLC by the French-based Imetal S.A. If successful, the takeover would give Imetal an estimated 20% of world market share for white pigment minerals. These moves are seen by producers as a way of putting greater leverage on raw material purchases, and at the same time, achieving greater efficiencies and costs associated with research and development, sales, distribution and operations (Industrial Minerals, 1999).

Until the second half of 1997, the demand for kaolin in the ceramics industry was steady and even showing signs of improvement in many countries, particularly in South East Asia in countries such as Japan, Taiwan, Malaysia, Indonesia, and China. The increased demand even attracted a number of potential Western joint venture participants. About this time, the onset of currency crises in a number of South East Asian countries caused a stabilization or even downturn in demand for ceramic grade kaolin, which is likely to remain subdued for sometime.

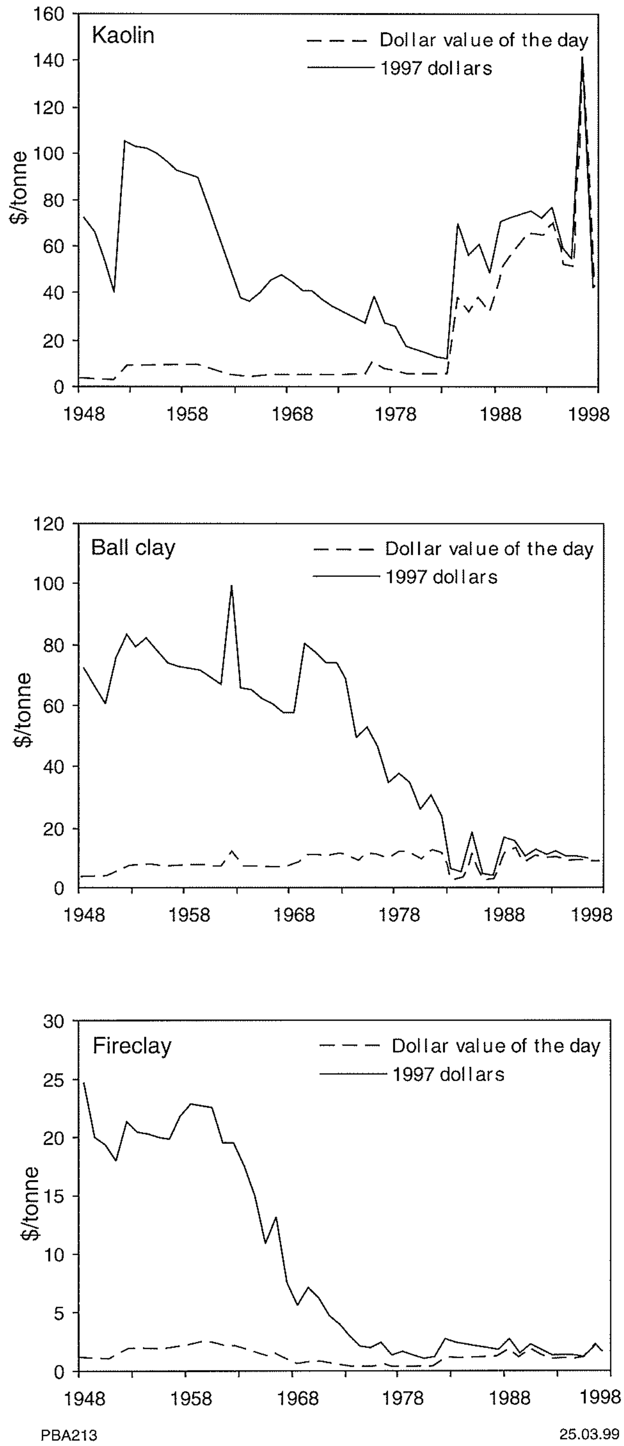

Figure 5. Unit value of Western Australian kaolin, ball clay, and fireclay (dollar value of the day and adjusted to 1997 dollars)

The Asia–Pacific region

Loughbrough (1993) stated that the Asia–Pacific region (taken to include the Indian subcontinent, Australasia and the Far East) is the major growth market of the future for kaolin. Harvey (1997) grouped white-burning clays in the ASEAN region on the basis of price, quality, mineralogy, chemical composition, and/or physical properties as follows:

(a) Category 1 — high-quality, high-priced, intensively processed kaolinite predominantly to supply the paper industry;

(b) Category 2 — high-quality, high-priced, intensively processed halloysite focused on the ceramics industry;

(c) Category 3 — moderate quality, moderately priced, moderately processed ball clays and kaolin clays for the ceramics and whiteware markets;

(d) Category 4 — lower priced variable quality clays that are typically sold 'as mined' for use in a range of ceramic applications, including tiles.

Category 1 and 2 clays have sufficient profitability to justify imports from outside the ASEAN region, whereas clays of Categories 3 and 4 are shipped extensively throughout the region in bulk, in supersacks or in 25–40 kg bags.

Japan imports in excess of 1 Mt of kaolin per annum. About 80% of this is used in the paper industry as coating clays and fillers, whereas the remainder is consumed by ceramics and speciality markets such as plastics and paints. The demand for paper grade kaolin in Japan is increasing. Japan currently imports paper coating grade kaolin from the USA, Brazil, and Australia, and filler grade from Malaysia and Indonesia. Ceramic grade is imported from China, and North and South Korea, whereas clay of high brightness (halloysite) is imported from New Zealand. Japan also imports kaolin from the UK, mainly for use in speciality markets (O'Driscoll, 1992). Taiwan imports around 0.5 Mt of kaolin annually, from countries such as China, Malaysia, and Indonesia (O'Driscoll, 1995).

The use of kaolin in the paper industry in South Korea is declining due to a changeover to the alkaline process that uses ground calcium carbonate (GCC) and precipitated calcium carbonate (PCC) in place of kaolin. However, at least 50% of the industry still uses the acid paper-making process that requires kaolin. There is a demand for around 1.8 Mt of kaolin, of which 0.22 Mt is imported (O'Driscoll, 1993).

Significant producers of kaolin in the Asian region are Indonesia, Malaysia, Thailand, and India. A substantial amount of kaolin produced in Indonesia and Malaysia is used in growing domestic industries, but a significant portion is exported to a number of other Asian countries including Japan, Taiwan, South Korea, Thailand, and the Philippines. In Malaysia, the paper industry is the largest consumer of domestically produced kaolin. In addition, an expected increase in the number of export-oriented ceramic plants, a move towards using water-based paints, a booming domestic building industry, and a growing plastics sector will result in a stronger demand for kaolin in Malaysia. Most of the production in India is consumed domestically. Although China produces a large quantity of kaolin, it still depends on imports to meet its refined kaolin requirements for paper coating.

In times of increasing demand for high-grade kaolin in South East Asia, especially for the paper industry, Australia is well positioned to capture some of these growing markets.

Other factors

Many factors are pertinent when contemplating new projects. Pleeth (1997) has documented the main feasibility findings that were considered in the decision to develop a US$180 million greenfield project in Brazil (Pará Pigmentos SA). These findings were as follows:

1. Growth in kaolin consumption can still be related to the world-economy growth forecast. For example, above average growth will be seen in South East Asia and the transition economies;
2. Kaolin production will expand in the known high-quality deposits in the world;
3. Competitive substitution pigments such as calcium carbonate will make further inroads into the kaolin market; and
4. Major capital investments will only be contemplated where unique properties and special conditions enable product differentiation to be realised.

Chapter 4

Geomorphological and geological aspects related to kaolin mineralization in Western Australia

Geological and geomorphological aspects, such as weathering, physiography, drainage history, and palaeochannels, influence the development of kaolin deposits. Therefore, a knowledge of these aspects in Western Australia promotes an understanding of known deposits and helps in delineating probable areas of kaolin mineralization.

Geomorphology

Physiography

Western Australia consists of a number of narrow coastal plains, and a broad plateau that rises to about 1200 m above sea level, but which is largely at an elevation of less than 600 m and forms a vast gently undulating surface known as the Great Plateau of Western Australia (also referred to as the Old Plateau) (Jutson, 1950). There are a few ranges above the general plateau level, the most notable of which are the King Leopold Ranges (Mount Ord, 921 m) in the north, the Hamersley Range (Mount Meharry, 1231 m) in the northwest, and the Stirling Range (Bluff Knoll, 1092 m) in the south.

The Great Plateau of Western Australia is bounded to the west by the Darling Fault scarp, which rises sharply from the coastal plain to between 240 and 300 m above sea level. The Darling Fault scarp can be traced from Pemberton, near the south coast, to northeast of Geraldton, a distance of some 640 km. Except for steep cliffs along the coastline of the Eucla Basin and the Kimberley highlands, the plateau surface grades gently to the sea.

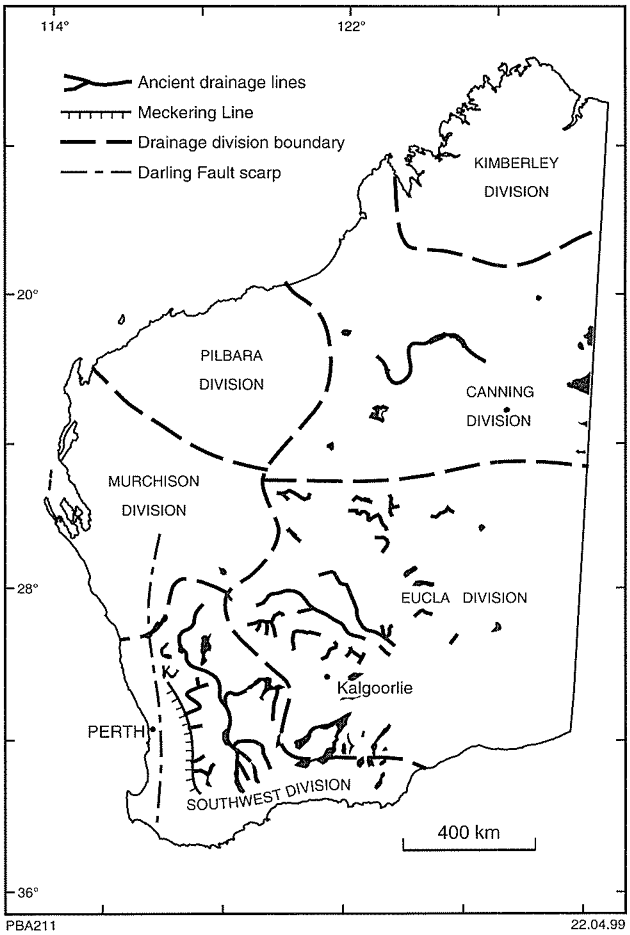

Figure 6. The major drainage divisions of Western Australia (after Mulcahy and Bettenay, 1972)

Drainage

On the basis of river classification, direction of flow, and characteristic soil landscapes, Mulcahy and Bettenay (1972) divided Western Australia into six major drainage divisions (Fig. 6). These are as follows:

- Southwest Drainage Division
- Eucla Drainage Division
- Murchison Drainage Division
- Pilbara Drainage Division
- Canning Drainage Division
- Kimberley Drainage Division

The most relevant areas for transported kaolin resources are the Southwest Drainage Division and western parts of the Eucla Drainage Division, since these areas contain relatively older drainages that are likely to contain thick sequences of clayey sediments.

Southwest Drainage Division

The Southwest Drainage Division is bounded by the Darling Fault scarp (elevation of 240–300 m) on the west and slopes gently to the Southern Ocean. Inland, it rises to a maximum elevation of 600 m. The annual rainfall in this drainage division varies from in excess of 125 cm near the coast to less than 25 cm in the interior.

Drainages and river systems

There have been several periods of drainage rejuvenation in the Southwest Drainage Division. Gregory (1914) described salt lake systems in this division as ancient river systems that are now blocked and distorted in various ways. Woolnough (1919) regarded the valleys in which salt lakes occur as having been cut into the uplifted lateritized Tertiary Old Plateau of Western Australia, following rejuvenation of the drainage of an almost flat peneplain. Mulcahy and Hingston (1961) and Bettenay and Hingston (1964) have shown that these valleys contain thin, but extensive, connected layers of relatively unweathered sediments, which overlie deep lateritic pallid zones.

Mulcahy (1967) has shown that the downstream limit of the incised valleys is marked by a change to a more intensive drainage, and argued that the line marking this limit, the 'Meckering Line' (Fig. 6), indicates the extent of rejuvenation. These more intensive drainage areas appear to coincide with the young drainage system identified by Bettenay and Mulcahy (1972), who described three principal classes of drainage and valley forms of young, mature, and old (Fig. 7) in the Southwest Drainage Division. The old drainage and valley systems change downstream to mature and then young forms. The old valley form of the Great Plateau is the most extensive valley form in the southwestern part of the State. In these valleys, the ancient landscape with its deep zone of chemical alteration is extensively preserved, both on the uplands and buried beneath younger deposits in the valley floors. Large areas are occupied by extensive sandy uplands, and underlain by lateritic mottled and pallid kaolinitic zones. The residual kaolin deposits occur, almost without exception, over granitic rocks in areas drained by streams in old or mature valleys.

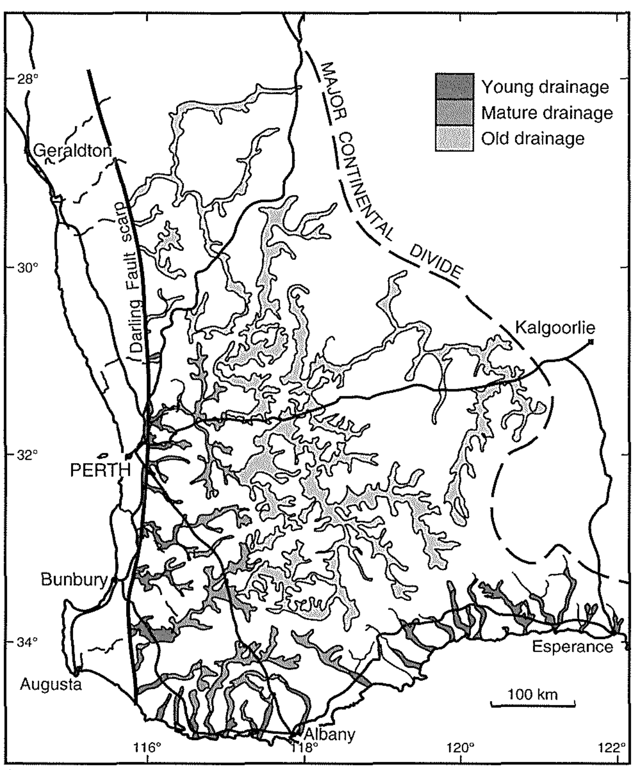

Figure 7. The Southwest Drainage Division showing the extent of young, mature, and old drainage (after Bettenay and Mulcahy, 1972)

Palaeochannels

Salama (1994), based on a detailed satellite imagery study, identified the presence of a widespread system of palaeochannels on the higher reaches of the area east of the Darling Fault scarp, which equates with the western region of the Yilgarn River catchment area (Fig. 8). These palaeochannels are as follows:

1. The palaeodrainages that once flowed southward from the Mortlock River;
2. The palaeodrainage system that is flowing west from the Salt River. This system shows that the original Yilgarn River used to flow west across the Darling Range in a path that is north of the existing Helena River;
3. A palaeochannel system flowing in a northwesterly direction, indicating the possible easterly migration of the channels as uplift of the scarp progressed.

Salama (1997) suggested that continuous uplift caused the damming of all rivers flowing towards the sea and the formation of internal drainage systems. This resulted in the recapturing of streams, the development of new systems, and the formation of large inland lakes that occupied the present area of Yenyening Lakes (Fig. 9). The continuous presence of water along palaeochannels in this area led to weathering, transportation, and redeposition over large areas, and the formation of sedimentary sequences such as the Salt River Group (Figs 9 and 10). The Salt River Group (Salama, 1997) includes the sediments and sedimentary rocks that are preserved within the palaeochannels of the Salt River, and comprises the South Caroline Clay (possibly Pliocene), the Yenyening Formation (not older than Miocene), and the Quairading Sandstone (Early Oligocene or Miocene).

Eucla Drainage Division

This division has a low, intermittent rainfall spread throughout the year, except towards the south coast where there is a slight increase in rainfall during winter. Sand and lateritic remnants are common in the westerly areas of the division. Ancient drainage lines are fairly extensively developed in the areas north and south of Kalgoorlie.

Drilling carried out for hydrogeological investigations in the Kalgoorlie area intersected a number of palaeochannels containing kaolin horizons ((Fig. 11; Commander et al., 1992), and this will be discussed in

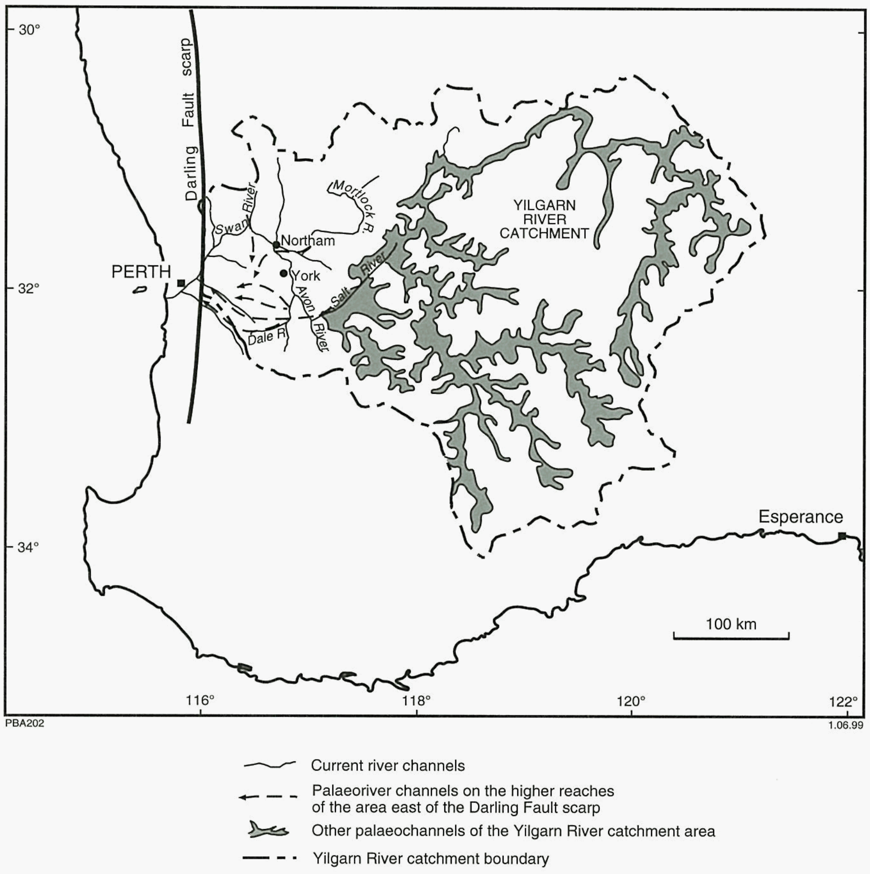

Figure 8. Palaeochannels of the Yilgarn River catchment area (after Salama, 1997)

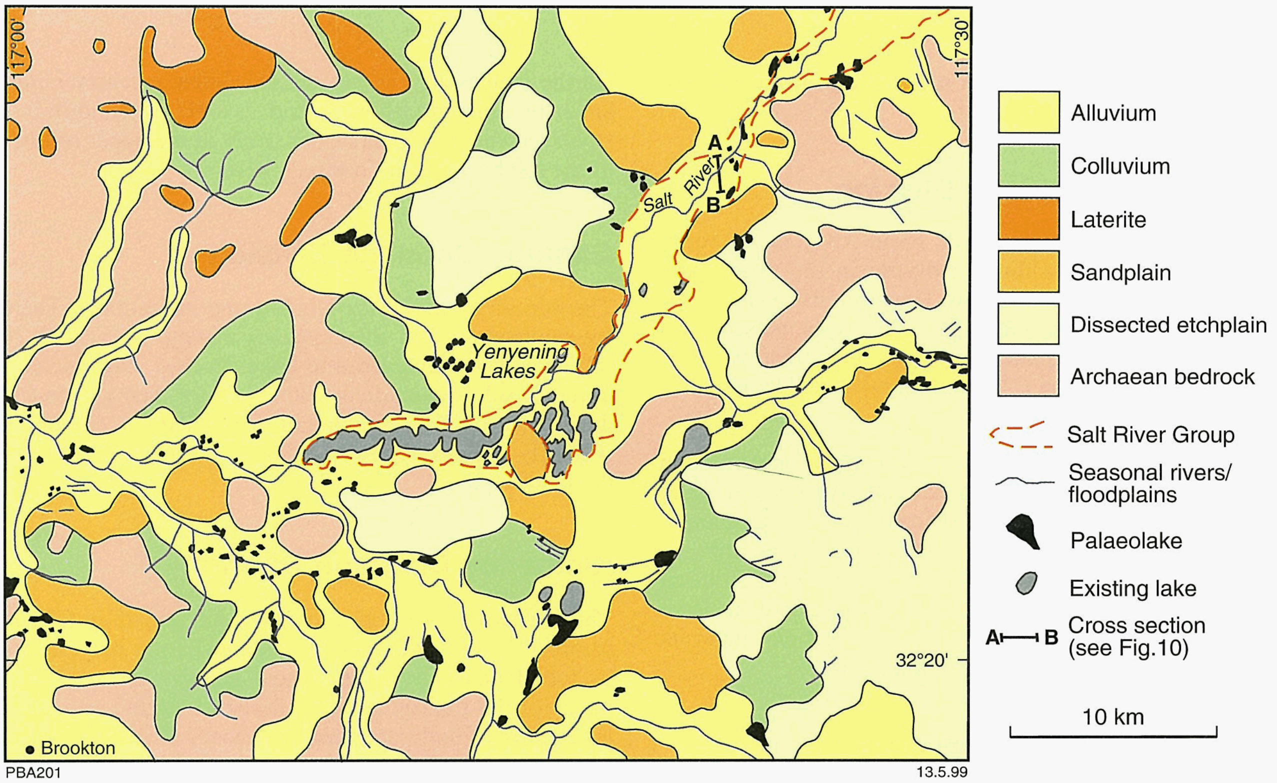

Figure 9. Distribution of palaeolakes in the area around Yenyening Lakes (after Salama, 1997)

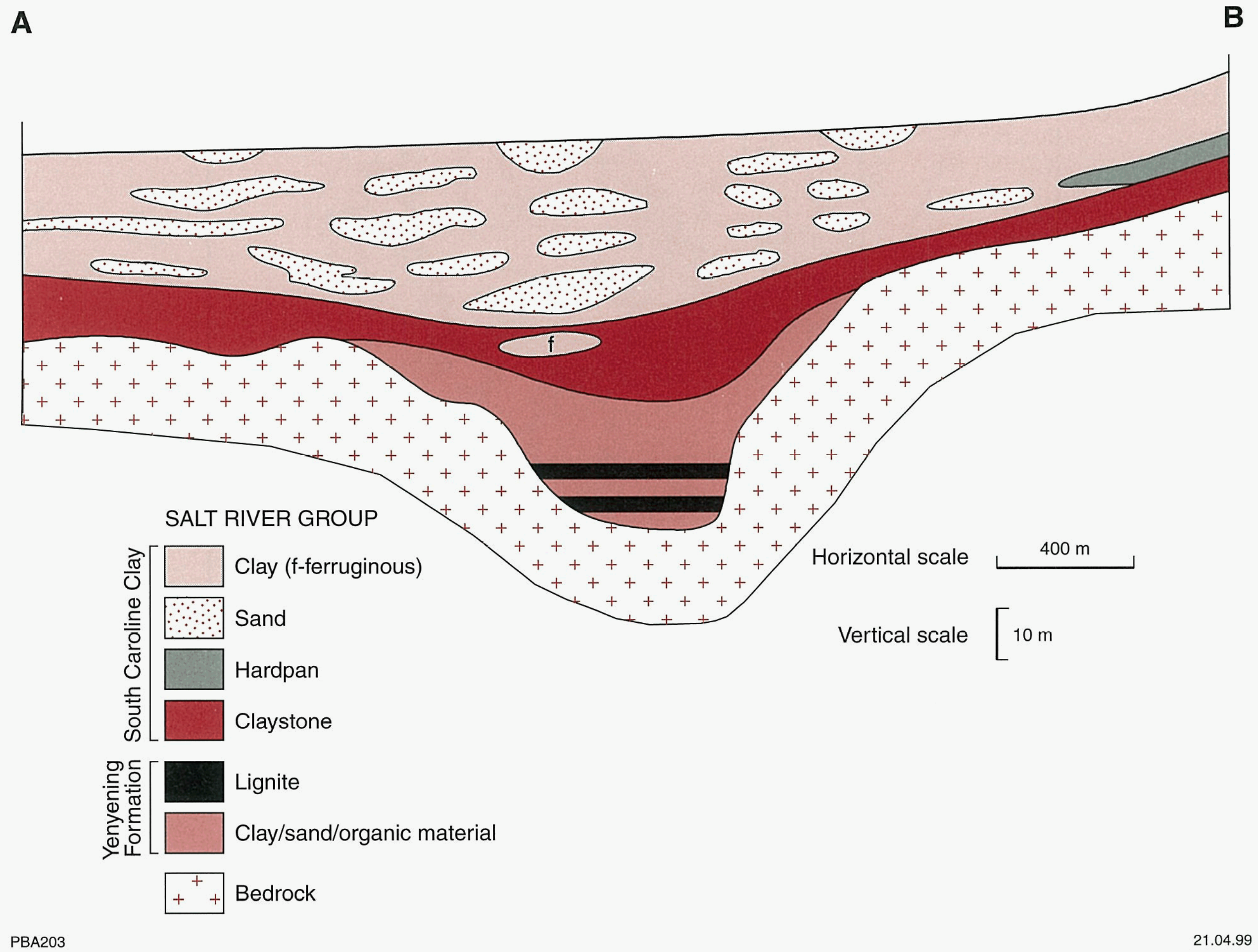

Figure 10. Cross section showing the relationship of the South Caroline Clay and Yenyening Formation (after Salama, 1997)

more detail in Chapter 5, in the section on the Eastern Goldfields terranes.

Murchison Drainage Division

This division extends from the Irwin River in the south to the Gascoyne–Ashburton divide in the north, and contains no permanent streams. However, its river courses are, in the main, fully functional and sharply incised, with their upper courses marked by calcrete formations. The rainfall in this division is low, intermittent, and largely falls in winter.

Unlike the Southwest division, the zone of deep chemical weathering has been extensively removed. Sand and lateritic remnants are restricted, and are frequently confined to relatively small areas above the scarps, or breakaways marking the limits of the Old Plateau (Mulcahy and Bettenay, 1972). Below the plateau level there are broad outwash plains where surficial deposits increase in depth towards the drainage lines.

Pilbara Drainage Division

The rainfall in this division is low and largely falls in summer. There are no permanent streams in this division, but the valleys are sharply incised. There are only minor areas of deep weathering and associated sandplains. However, calcrete occurs extensively in the upper reaches of the Ashburton and Fortescue Rivers.

Canning Drainage Division

The rainfall in this division is low and intermittent. There are remnants of old river systems marked by a chain of salt lakes from Lake Dora to Lake Percival, and calcretes in the broad, low-gradient drainage lines. Sandplains and dune fields overlay the zone of deep chemical alteration, which is seldom exposed owing to the gentle nature of the landscape.

Kimberley Drainage Division

This division has a high rainfall which generally falls in summer. Most of the main rivers are sharply incised into its tablelands and ranges. There are extensive alluvial plains of the Fitzroy and Ord Rivers. Lateritic remnants, in the form of both sandplains and zones of deep chemical alteration, occur more extensively in the southwest of the division, fringing the Fitzroy River and Great Sandy Desert.

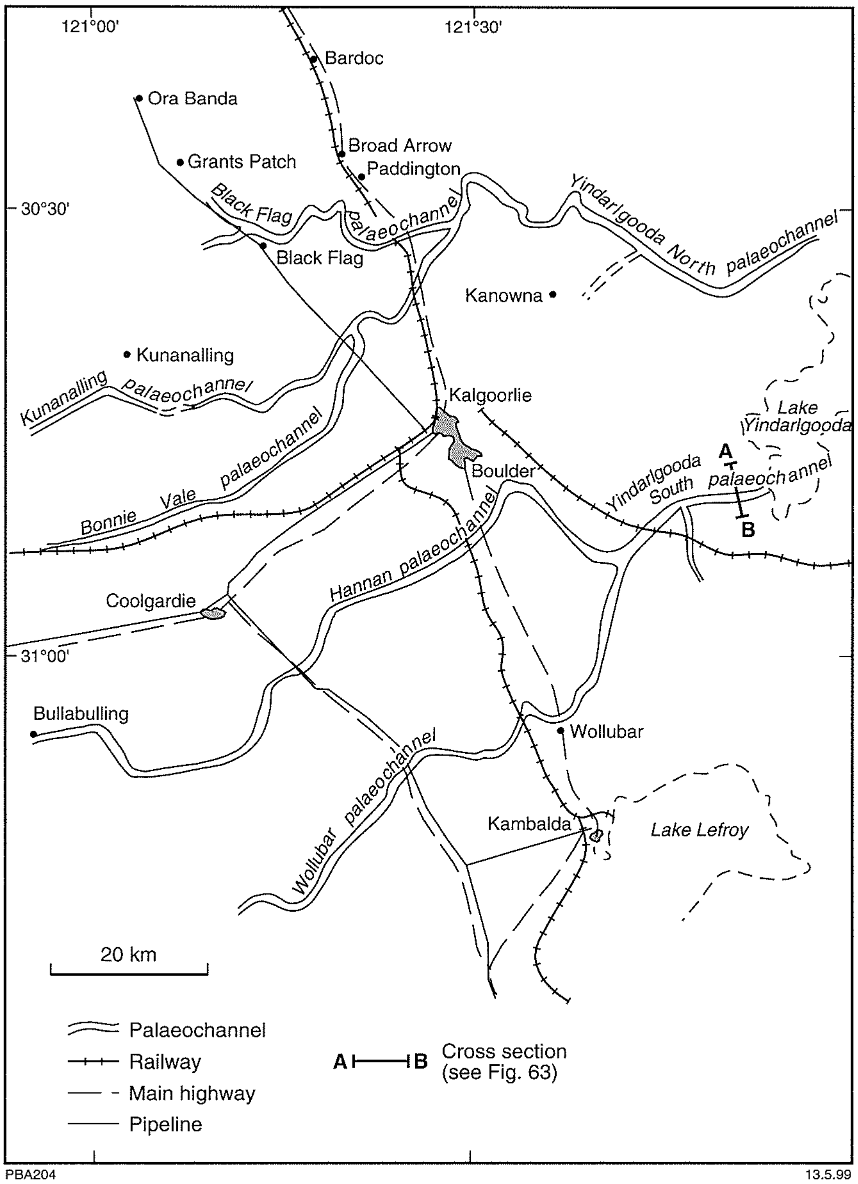

Figure 11. Palaeochannels in the Kalgoorlie region (after Commander et al., 1992)

Regional geology

The known kaolin deposits in Western Australia are largely limited to the Yilgarn Craton and the Albany–Fraser Orogen (Fig. 12). The geology of the Yilgarn Craton is favourable for the development of significant deposits of residual kaolin as it contains extensive bodies of granite and granitic gneiss that have formed deep weathering profiles. Also, the mature drainage systems and palaeochannels in the Southwest Drainage Division, as previously discussed, are potential areas for the accumulation of thick horizons of transported clay. The pallid zones of these weathering profiles and palaeochannels generally contain thick sequences of variable grade clay.

Significant kaolin deposits of both residual and transported origin occur in the southwestern region of the State. The residual deposits are associated mostly with large granitic bodies and gneisses of Precambrian age. Examples of these are the Gabbin deposit, located 140 km northeast of Perth, and the Jubuk deposit, which is located approximately 200 km east of Perth (Fig. 12). Large residual kaolin deposits are also known that are associated with pegmatite bodies. Such a deposit is located at Greenbushes, 250 km south of Perth.

Transported deposits of kaolin occur in palaeodrainage areas and lacustrine environments. Some of the notable deposits are the Mount Kokeby deposit situated approximately 100 km east-southeast of Perth, and the Goomalling deposit situated approximately 130 km northeast of Perth. Although economic kaolin deposits have not yet been discovered in palaeochannels, thick kaolin beds are known in such environments in the Eastern Goldfields.

Figure 12. Known kaolin deposits and occurrences in Western Australia (except for Roebuck Bay, Canning Basin)

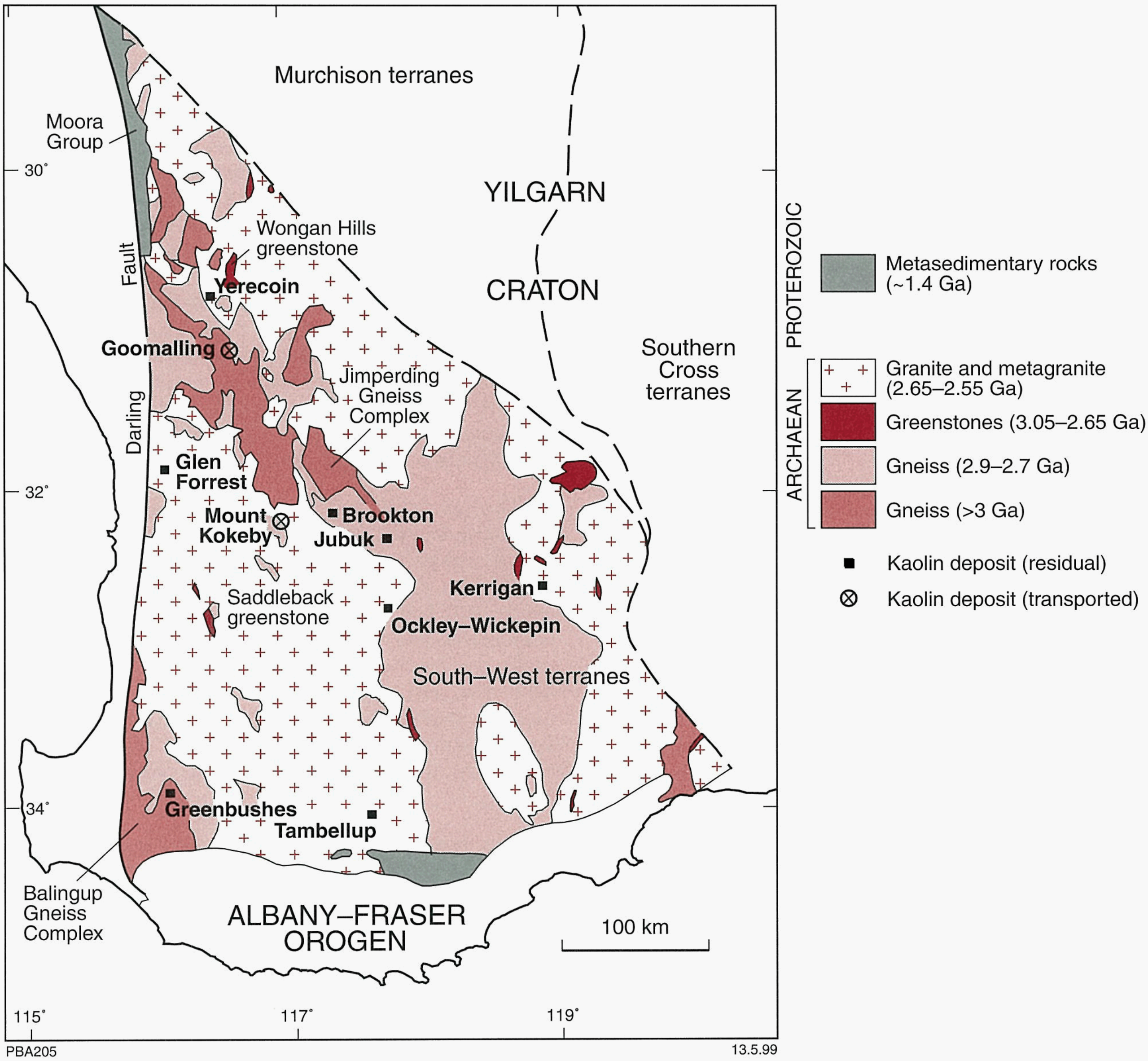

Figure 13. Regional geology of the South-West terranes, Yilgarn Craton

In the next chapter, the kaolin deposits in the State are grouped into the following tectonic units:

- South-West terranes, Yilgarn Craton
- Murchison terranes, Yilgarn Craton
- Southern Cross terranes, Yilgarn Craton
- Eastern Goldfields terranes, Yilgarn Craton
- Albany–Fraser Orogen

The following section deals with the regional geology of the above tectonic units. This information provides a useful background to the kaolin deposits that will be discussed in the next chapter.

South-West terranes, Yilgarn Craton

The South-West terranes are bounded by the Albany–Fraser Orogen to the south, the Southern Cross terranes to the east, the Murchison terranes to the north, and the Darling Fault and Moora Group to the west (Fig. 13).

The main geologic units within the South-West terranes are granite, gneiss, and the Jimperding and Balingup Gneiss Complexes. The most widespread rock type in the South-West terranes is granite, which intrudes the Jimperding and Balingup Gneiss Complexes. The granitic rocks are partly recrystallized in 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. The metasediments are mainly fuchsite-bearing quartzite, quartz–feldspar–biotite–garnet gneiss, andalusite and sillimanite schist, banded iron-formation, and minor calc-silicate rocks. The Balingup Gneiss Complex consists mainly of metasedimentary rocks, quartzofeldspathic gneisses, amphibolites, calc-silicate gneiss, and ultramafic rocks (Wilde, 1980). The metasediments are mainly interlayered quartzite, quartz–mica schist and quartz–feldspar–biotite–garnet gneiss, and banded iron-formation. The Balingup Gneiss Complex has been metamorphosed to amphibolite facies, although localized assemblages of granulite facies metamorphism are also present.

The Saddleback greenstone belt, located in the southwestern portion of the South-West terranes, consists of metamorphosed siltstones, felsic lava, pyroclastic rocks, and basalt (Wilde and Pidgeon, 1986).

Murchison terranes, Yilgarn Craton

The Murchison terranes encompass the northwestern portion of the Yilgarn Craton. They are bounded by the Perth Basin to the west, the Narryer Terrane to the northwest, the Bryah and Padbury Basins to the north, the Southern Cross terranes to the east, and the South-West terranes to the south (Fig. 12).

The greenstone sequences in these terranes are the Luke Creek Group (Fig. 14) and the overlying Mount Farmer Group, which together form the Murchison Supergroup (Watkins, 1990). The Luke Creek Group is divided into two (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 Golconda Formation, which consists of banded iron-formation (BIF) and interlayered mafic rocks. The upper sequence, consisting of 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 terranes. 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 volcaniclastic 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-filling 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, iron-rich tholeiites are more abundant and there is less of a compositional gap between the mafic and felsic rocks. In the Mount Farmer Group there is a higher proportion of felsic rocks.

Four suites of granitoid rocks have been distinguished in the Murchison terranes. These are pegmatite-banded gneiss, recrystallized monzogranite, and two compositionally diverse suites of post-folding granitoids. These 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 terranes (Fig. 14), and generally occurs as 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, interlayered 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 terranes than in the western part. The pegmatite-banded gneiss contains quartz, oligoclase, K-feldspar, and biotite, with accessory white mica, epidote, sphene, apatite, zircon, and opaques. The pegmatite bands contain coarse-grained quartz, microcline, and oligoclase, with less than 1% mica phases.

The recrystallized monzogranite, along with the pegmatite-banded gneiss and Murchison Supergroup, was 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 in the recrystallized monzogranite are similar to those in the pegmatite-banded gneiss.

Fifty-seven plutons of post-folding granitoid have been recognized in the Murchison terranes. 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 terranes and suite II to the southwestern half. Suite I consists predominantly of tonalite and monzogranite, while 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 opaques, 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.

Southern Cross terranes, Yilgarn Craton

The Southern Cross terranes of the Yilgarn Craton are unconformably overlain by the Yerrida Basin to the north and are in tectonic contact with the Albany–Fraser Orogen to the south (Fig. 12). They are bounded to the east by the Eastern Goldfields terranes and to the west by the South-West and Murchison terranes. The boundaries between these terranes are not well defined.

Granitoid and gneiss dominate the Southern Cross terranes, but are poorly exposed and form isolated pavements within extensive areas of sandy soil (Fig. 15).

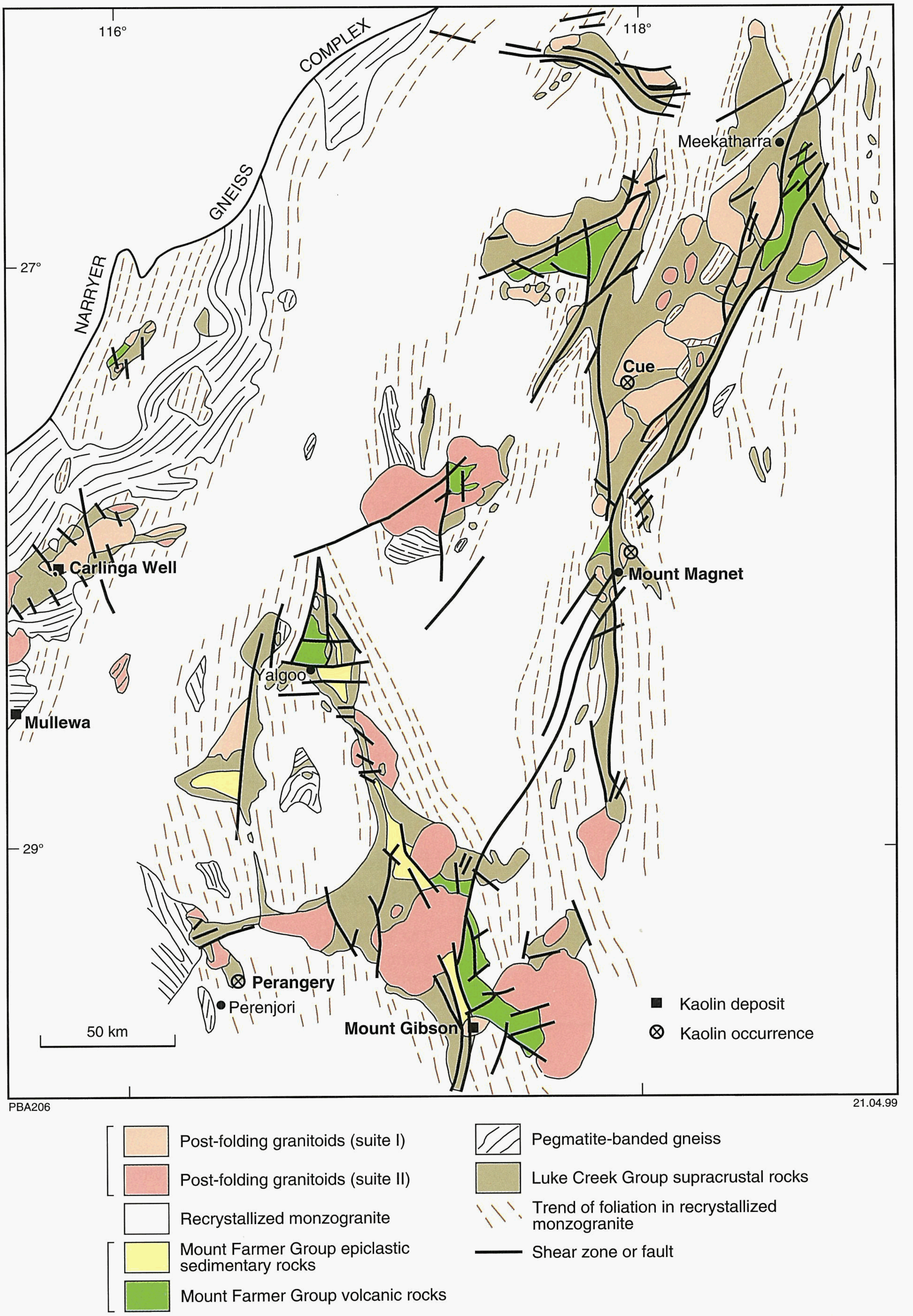

Figure 14. Simplified geology of the area north of Mount Gibson in the Murchison terranes, Yilgarn Craton (after Watkins, 1990)

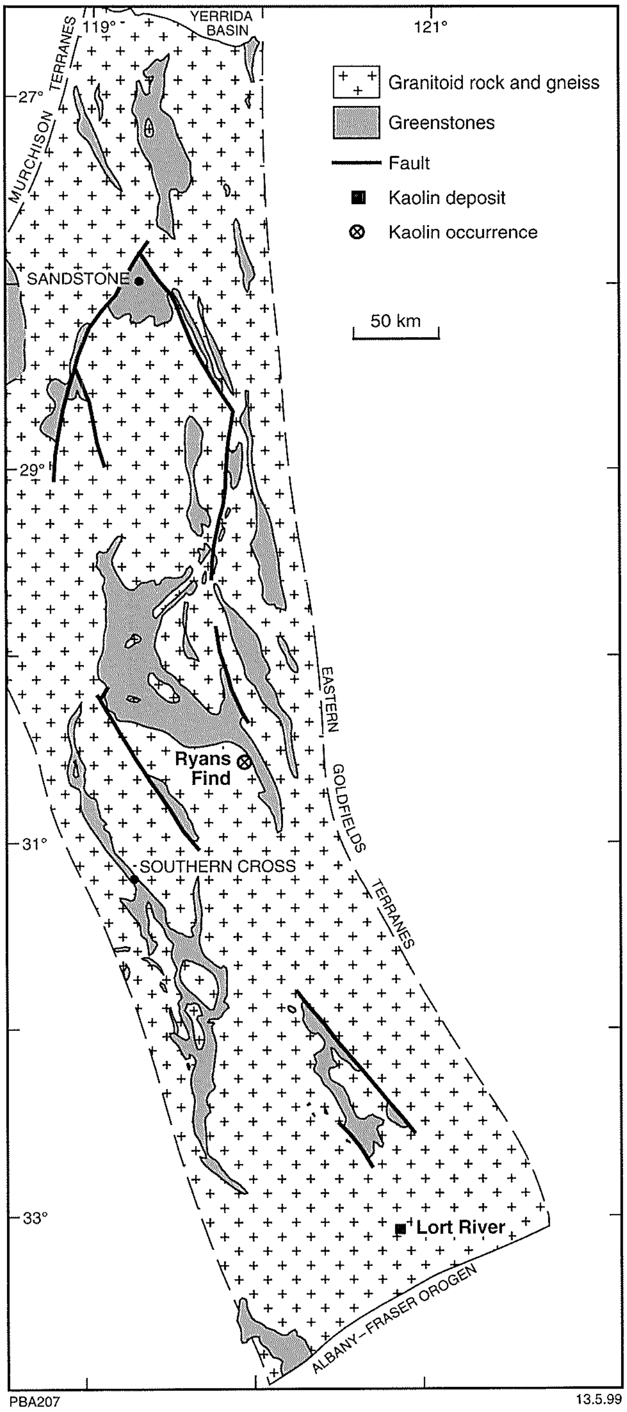

Figure 15. Generalized geology of the Southern Cross terranes, Yilgarn Craton (modified from Griffin, 1990a)

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 region contains gneiss and granitoid metamorphosed to granulite facies. The contacts between gneiss or granitoid and greenstone are generally sheared or strongly foliated (Walker and Blight, 1983; Stewart et al., 1983). Gneissic rocks are of two types: foliated gneiss and massive gneiss. These are predominantly feldspar–quartz–biotite rocks ranging in composition from tonalite to syenogranite. The majority of the rocks are monzogranite to syenogranite. Foliated to weakly foliated granitoid dominates the large areas between the greenstone belts. Biotite monzogranite is the most abundant type, but syenogranite and granodiorite are also present. 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, plagioclase (zoned), 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 of these phases are intruded by veins and small masses of granitoid, pegmatite, and aplite.

The greenstones consist of an upper and a 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 rocks and minor felsic volcanic rocks occur near and at the top of this lower sequence. The upper sequence occurs only in the centre of the region and consists of clastic sedimentary rocks and felsic volcanic rocks that unconformably overly the lower sequence.

Both granitoids and greenstones are strongly deformed with evidence of polyphase deformation, and have a dominant north-northwesterly trend similar to those of the Eastern Goldfields terranes. Greenstones, gneisses, and granitoids of the Southern Cross terranes all range in age from 3.1 to 2.5 Ga (Griffin, 1990a).

Eastern Goldfields terranes, Yilgarn Craton

The Eastern Goldfields terranes form a typical Archaean granite–greenstone terrane, which occupies the eastern portion of the Yilgarn Craton. They consist of large areas of granitic rocks and linear to arcuate belts of greenstone, mainly with a north-northwesterly trend (Fig. 16). The greenstones exhibit various degrees of deformation, and have mainly undergone metamorphism to greenschist facies (Griffin, 1990b). The region is unconformably overlain by sedimentary rocks of the Earaheedy Basin in the north and northeast, and by sedimentary rocks of the Gunbarrel Basin in the east. In the south and southeast, it is bounded by the Albany–Fraser Orogen. The boundary between the Eastern Goldfields and Southern Cross terranes is not well defined, and is located in a narrow zone of unexposed granitic rocks. In general, the granitoid rocks are more poorly exposed than the greenstone belts. The main granitoid varieties recognized are granitic gneiss, foliated and unfoliated granites, and small discordant granitoid stocks. In the greenstone belts, the lowest parts are mostly mafic to ultramafic volcanic rocks overlain by felsic volcanic rocks and clastic sedimentary

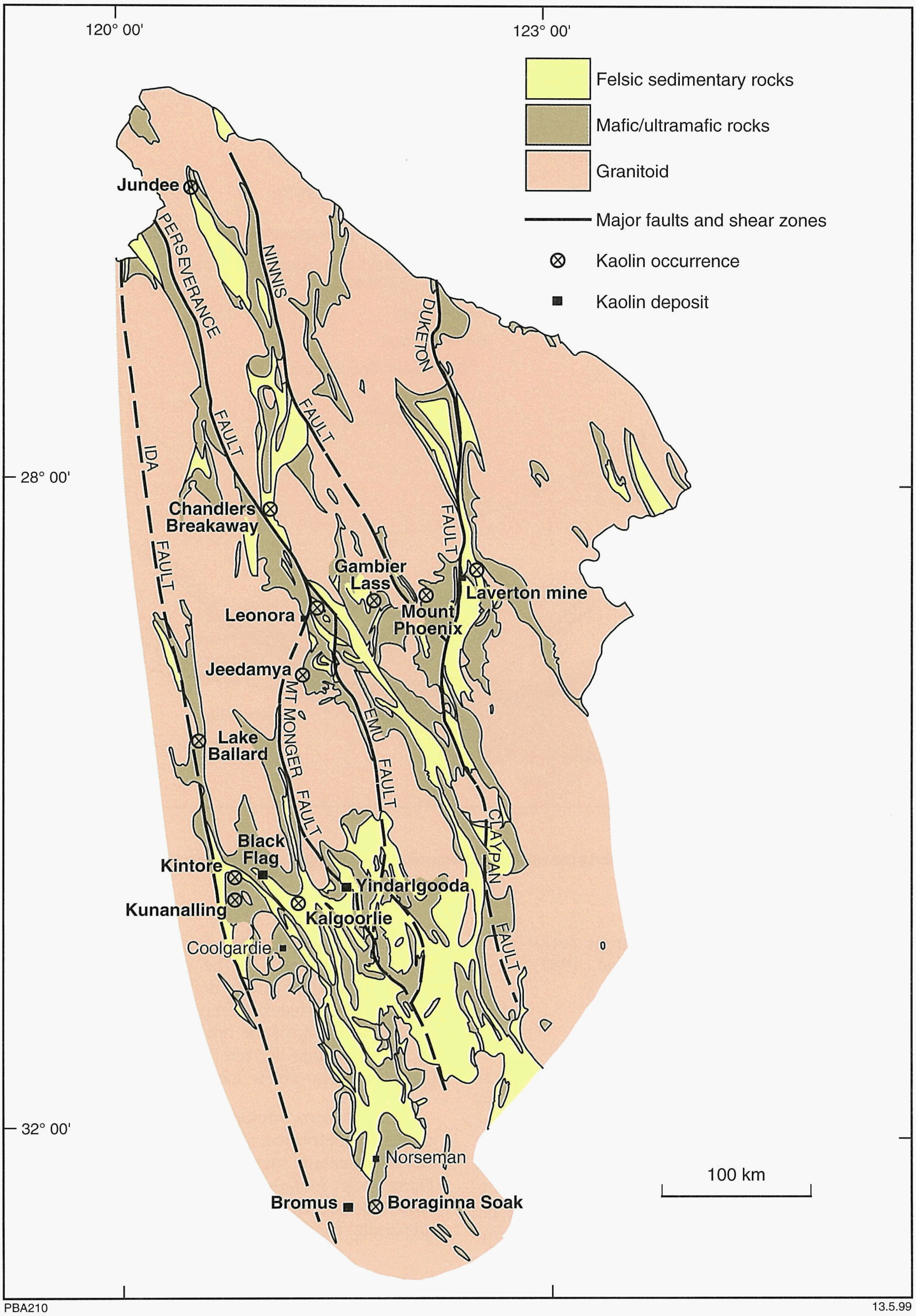

Figure 16. Main lithologic units of the Eastern Goldfields terranes, Yilgarn Craton (modified from Griffin, 1990b)

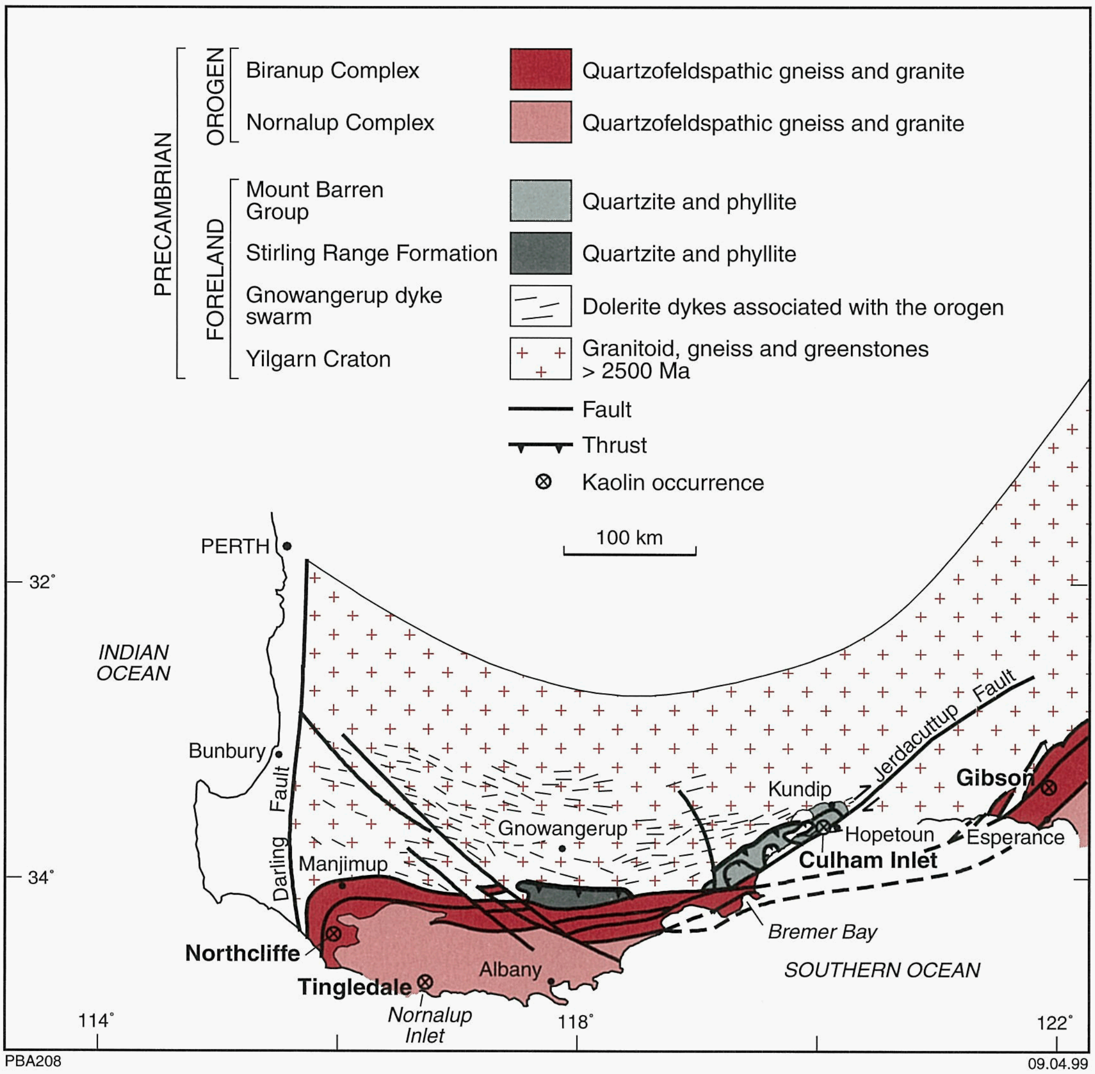

Figure 17. Simplified geology of the area west of Esperance in the Albany–Fraser Orogen (after Myers, 1990)

rocks. The age of the granite–greenstone rocks in the region is 2800–2600 Ma (McCulloch et al., 1983).

Albany–Fraser Orogen

The Albany–Fraser Orogen borders the southeastern margin of the Yilgarn Craton and is characterized by high-grade gneiss and granitoid intrusions that have the potential to act as parental material for large deposits of clay. The orogen can be divided into two parts (Myers, 1990). These are 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 parasgenesis, intruded by sheets of granite at about 1.1 Ga, and collectively called the Nornalup Complex (Fig. 17).

The Biranup Complex forms a belt in the north and northwestern part of the orogen, and consists of quartzofeldspathic gneiss derived from mainly granitoid rocks. The Nornalup Complex forms the southern and southeastern part of the orogen, and consists of quartzofeldspathic gneiss derived from granitic rocks and mainly pelitic and semi-pelitic metasedimentary rocks.

The northern foreland of the Albany–Fraser Orogen comprises deformed psammitic and subordinate pelitic metasedimentary rocks, generally of greenschist facies. These rocks include the Stirling Range Formation and Mount Barren Group. A dense swarm of dolerite dykes subparallel to the orogen intrudes the northern foreland.

Chapter 5

Kaolin resources in Western Australia

South-West terranes, Yilgarn Craton

The majority of known kaolin deposits in Western Australia are found in the South-West terranes of the Yilgarn Craton and the largest recorded production of kaolin in the State is from one of these deposits located at Greenbushes. Other large deposits in the South-West terranes include Jubuk, Ockley–Wickepin, Kerrigan, and Tambellup. These deposits are almost exclusively of residual origin, but none of them have yet been mined.

Residual deposits

Greenbushes

Greenbushes is situated approximately 250 km south of Perth, with access from the South Western Highway. The kaolin occurs in a deeply weathered pegmatite body, which is mined by Gwalia Consolidated Ltd (now part of Sons of Gwalia Ltd) for tantalum, tin, and spodumene. The mine produces around 4000 t of kaolin biennially as a raw mine product and is the largest kaolin mine in the State at present. The small mining town of Greenbushes has most facilities, and is connected by a railway line to the port at Bunbury, which is located about 80 km to the northwest.

Geology

The kaolin occurs as a residual deposit formed by the weathering of numerous steeply dipping pegmatites, which intruded a zone of amphibolite and quartz–feldspar–biotite gneiss and granofels (Fig. 18). The pegmatites contain quartz, albite, K-feldspar, muscovite, and tourmaline, in addition to the economically important minerals of tantalite, stibiotantalite, spodumene, kaolin, and cassiterite. The albite- and spodumene-enriched pegmatites contain xenoliths of granofels and amphibolite, and are cross-cut by dolerite and narrow biotite-rich dykes in some locations (Davidson, D., Gwalia Consolidated Ltd, 1998, pers. comm.).

Kaolin mineralization

The kaolin deposits occur in a north–south zone that follows the major pegmatite lode and, prior to mining, were generally covered with a few metres of surficial material consisting of laterite, lateritized alluvium, laterite rubble, sand, gravel, clay, and colluvial loamy soil. Kaolin has formed due to weathering of the feldspar and spodumene, with weathering extending to a depth of 35–50 m below the surface. The kaolin is concentrated in several small lenses, presumably reflecting the original concentrations of feldspar and spodumene (Davidson, D., 1998, pers. comm.). The thickest deposit of economically viable kaolin at Greenbushes occurs in the southern area of a major pegmatite, and extraction of kaolin is from a 'soft rock' openpit, 25–30 m deep, located south of the main mine area (Figs 18 and 19).

Production

Production of kaolin from Greenbushes began in 1984, with the total output from 1984 to 1997 being 45 020 t (Tables 11 and 12). This is more than 74% of the State's production of 60 586 t, from 1939 to 1997, and 92% of the State's production for the period 1984–97. Most of the current production of kaolin is exported to Asian destinations, including Japan, with small amounts being sold to local consumers. The company appears to have been holding stockpiles of around 10 000 t of kaolin at any given time (Fig. 20), but as at August 1998 the stockpile contained 4000 t.

Resources

Willsteed (1988) estimated an indicated resource of 2.3 Mt in the Greenbushes deposit, but this figure is no longer considered to be of practical relevance because at present the high-grade kaolin is confined to the main pegmatite zone, which is estimated to contain a measured resource of 40 000 t (Davidson, D., 1998, pers. comm.). However, according to company sources the area has not been fully evaluated, and there are plans to carry out a drilling program to assess in detail the potential kaolin resources within the company's leases (Gwalia Consolidated Ltd, 1997, pers. comm.).

Quality

The kaolin in the stockpiles is fine to medium grained, conspicuously white, and relatively soft. Three samples (GSWA 145108–10) from these stockpiles, when studied under XRD and SEM (using a -10 μm fraction), showed

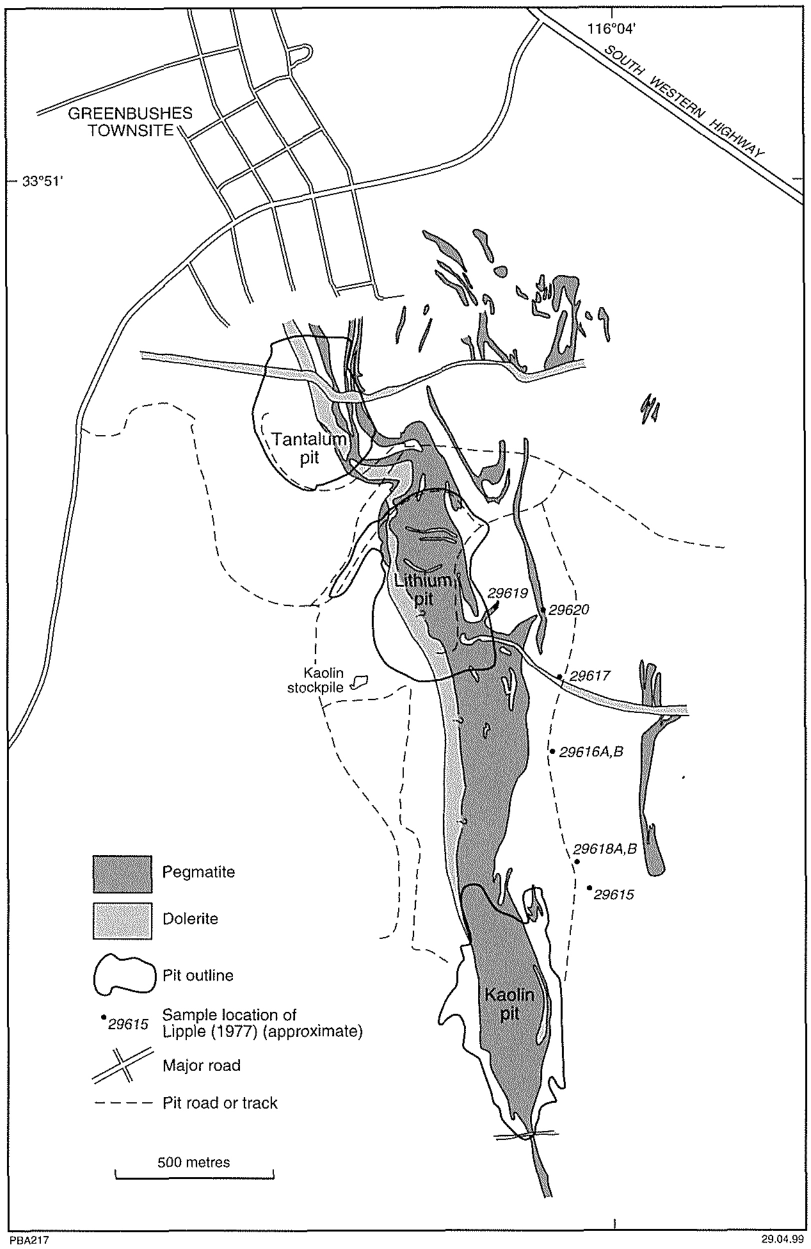

Figure 18. Geology around the Greenbushes kaolin deposits (after Lipple, 1977)

that the material contains greater than 50% kaolinite, 10–50% halloysite, and traces of quartz, mica, and halite (Fig. 21; Table 18).

Three samples from the stockpiles gave ISO brightness values above 85% (Table 18). Lipple (1977) quoted an average brightness (at 457 mμ) of 81.5%, based on previous testing done by Greenbushes NL during 1971–72. He also stated that five samples tested for brightness (at 457 mμ) showed an improvement of 2.1% after bleaching (average of 79.9 to 82.0%). Brightness (at 457 mμ) measurements on eight samples from the -2 μm fractions collected by Lipple (1977) gave values above 84.9% (Table 19).

The chemical composition of the three samples collected from the stockpiles, along with partial chemical analyses of five other samples (Tables 20 and 21), indicate that the clay has a high alumina content, and is low in iron oxide, titania, potash, and soda. These results suggest that the brightness and chemical composition of this material are acceptable for high-grade applications such as the manufacture of ceramics.

Fractionation test results obtained by Greenbushes NL indicated that the average yield was 29% for -5 μm material, with individual results ranging from 7 to 55% (Lipple, 1977). Particle-size fractionation results of eight samples indicated that the average yield of the -2 μm fraction was 31% (Table 19). These values appear to be low for high-grade applications. However, some individual values, such as 74% at -2 μm, suggest that high-grade material would be available in some parts of the deposit. Particle-size test results for three raw samples from the

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Figure 19. The Greenbushes kaolin openpit
Top: Northern portion of the openpit — approximately 2 m of kaolin occurs below waterlevel (looking west)
Lower: Flooded southern portion of the pit (looking west)

Figure 20. A stockpile of kaolin at the Greenbushes mine

stockpiles are also given in Table 19, and these showed that 28–39% of the kaolinitic clay is -45 µm.

The above tests indicate that parts of this deposit contain kaolin suitable for high-grade uses such as ceramics, but the presence of significant quantities of halloysite would make the material unsuitable for paper grade applications. Lipple (1977) concluded, based on partial tests on about 60 samples, that most of the kaolin from this deposit would be unsuitable for paper coating applications.

Jubuk

The Jubuk kaolin project, owned by Summit Resources NL (formerly Summit Gold NL), is located 20 km southwest of Corrigin, which is approximately 200 km east of Perth, (Figs 12 and 22). An abandoned quarry in the eastern portion of the deposit, near Ling Homestead, is presumed to be the site of clay extraction earlier this century. This quarry is now used as a water reservoir for stock. During 1989–90, Summit explored the area. Its work included the drilling of 34 reconnaissance aircore drillholes, totalling 570 m, on the Jubuk lease. In 1998, a further 192 aircore holes were drilled in the Guinness deposit.

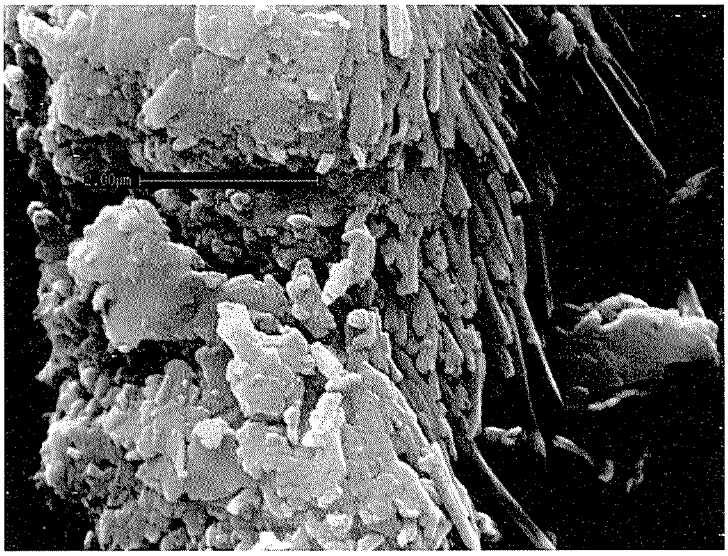
Geology

Poorly exposed Archaean granite and adamellite that are deformed, recrystallized, and porphyritic underlie the area. Fresh granite and adamellite outcrop in a number of localities within the tenement area E70/2023 (formerly E70/888) (Fig. 23). In other places, 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. Kaolin is best developed in the pallid zone of the weathering profile, which also contains quartz, and minor feldspar and micaceous minerals.

Kaolin mineralization

The kaolin deposits of main interest to Summit Resources lie topographically in a mid-slope position between the lateritic ridges and the break of slope just above the present drainage lines (Summit Gold NL, 1994). These deposits are subparallel to the present ground surface and are ‘pan-shaped’. Drilling indicated that the thickness of the pallid-zone clays ranged from 5 to 20 m beneath a sandy overburden 2–4 m thick. Within this pallid zone, white or pale-cream clay horizons range from 1 to 30 m and appear to consist almost entirely of kaolinite with variable amounts of quartz.

Within the Jubuk project, deposits at Guinness, Top Valley, South Guinness, and Homestead have been investigated by detailed drilling (Fig. 23). The average thickness of kaolin drilled is 10 m. Other prospects have also been identified in the area, and exploration is continuing. Laboratory tests indicate that kaolin in the Guinness deposit is of better quality than the Top Valley, South Guinness, and Homestead deposits, although the



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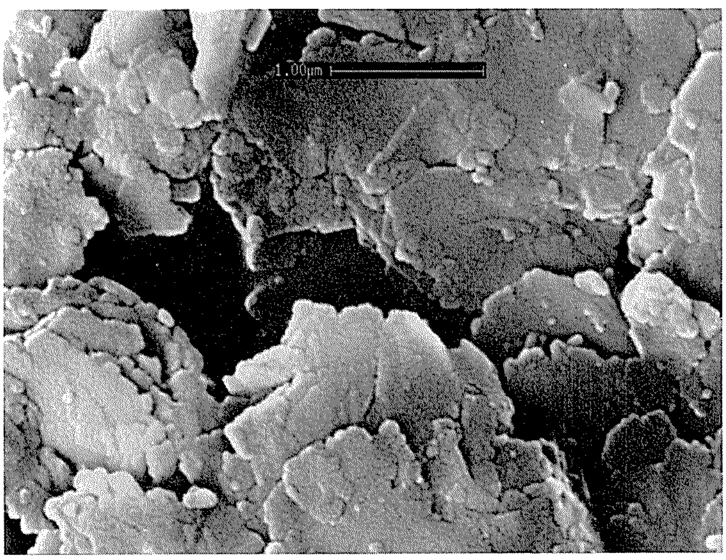

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Figure 21. Scanning electron micrographs of the Greenbushes kaolin (GSWA 145110)
Top: Fine-textured kaolinite intergrown with halloysite tubes
Lower: Coarse, ragged kaolinite platelets

Table 18. Mineralogy, brightness, and crystallinity of kaolin samples from stockpiles at Greenbushes

GSWA no.	*Kaolinite*	*Halloysite*	*Quartz*	*Mica*	*Microcline*	*Halite*	*Brightness*	*Crystallinity (under SEM)*
				Percentage				
145108	>50	10–50	2–10	<2	<2	<2	85.16	Subhexagonal, moderately thick platelets of kaolin and tubular halloysite
145109	>50	10–50	<2	–	–	<2	85.56	Fine to medium sized aggregates of subhexagonal kaolin platelets with tubular halloysite
145110	>50	10–50	<2	–	–	<2	85.56	Fine textured kaolinite intergrown with halloysite fibres (Fig. 21).

NOTE: All tests on -10 μm fractions

Table 19. Brightness and particle-size fractionation results for kaolin from Greenbushes

Sample no.	*Brightness (-2 μm fraction)*	*Size fractions*							
		-2 μm	*2–53 μm*	*53–75 μm*	*+75 μm*	*+45 μm*	*+106 μm*	*+500 μm*	*H_2O*
				Percentage					
29615	90.3	25	33	2	40	–	–	–	–
29616A	87.3	25	16	6	55	–	–	–	–
29616B	85.8	20	16	6	55	–	–	–	–
29617	88.6	20	53	<1	26	–	–	–	–
29618A	84.9	24	19	2	49	–	–	–	–
29618B	90.8	37	19	2	49	–	–	–	–
29619	91.6	22	–	–	–	–	–	–	–
29620	94.2	74	16	1	9	–	–	–	–
GSWA 145108	85.2	–	–	–	–	38.5	49.9	90.8	19.65
GSWA 145109	85.6	–	–	–	–	35.2	42.9	67.9	19.17
GSWA 145110	85.6	–	–	–	–	28.1	34.3	61.7	13.43

SOURCE: Lipple (1977)

Table 20. Chemical analyses of kaolin samples from stockpiles at Greenbushes

GSWA no.	*145108*	*145109*	*145110*
		Percentage	
Al_2O_3	37.40	38.20	37.80
SiO_2	46.00	45.40	45.70
TiO_2	0.12	<0.01	0.01
Fe_2O_3	0.42	0.31	0.35
MnO	<0.01	<0.01	<0.01
CaO	0.07	0.06	0.07
K_2O	0.08	0.03	0.04
MgO	0.20	0.13	0.19
P_2O_5	0.02	0.02	0.03
SO3	0.07	0.06	0.05
Na_2O	0.09	0.09	0.12
LOI	15.54	15.97	16.30
Total	**100.01**	**100.27**	**100.66**

NOTE: All tests on -10 μm fractions

Table 21. Partial chemical composition of five samples from Greenbushes

	Average	*Range*
	Percentage	
SiO_2	45.0	44.6–45.6
Al_2O_3	39.4	38.8–39.8
Fe_2O_3	0.27	0.21–0.32
MgO	0.05	0.0–0.1
TiO_2	0.05	0.01–0.09
Ignition Loss	15.0	14.7–15.2

SOURCE: Lipple (1977)

possibility of good quality kaolin in other prospects has not been fully ruled out.

Quality

Test results for drill samples taken during the drilling program of 1989–90 are summarized in Table 22. The kaolin from the Guinness deposit was further tested via the processing of a 100 t bulk sample in a pilot plant at Kwinana. A 200 kg sample of -2 µm material was produced using 3 t of the 100 t bulk sample. Further test work was carried out in the USA, where a sample of 1 kg was processed through a 'superconducting HGMS' magnetic separator and the resultant product showed an improvement in brightness of at least 2%. Brightness testing of a sample, after leaching in sodium dithionite solution at the University of Western Australia, showed an improvement of 2%. Further test work carried out in the USA on an unprocessed 200 kg sample showed that a high-quality product with 93.7% brightness, suitable for premium paper coating grade, could be produced. These encouraging results led to the collection of a second bulk sample of 18 t from the Guinness deposit by drilling on grids of 50 m × 50 m and 50 m × 100 m. As of July 1998, the testing of this material was due to commence on a pilot plant scale (Summit Resources NL, 1998).

Resources

Based on the drilling carried out in 1998, the Guinness deposit is estimated to contain a measured resource of 8 Mt. This is within an inferred resource of 14.9 Mt as originally estimated at the Guinness prospect, based on drilling during 1989–90 (Summit Gold NL, 1994; Summit Resources NL, 1998). There is a high potential for conversion of additional portions of the inferred resource to reserves. In addition, the adjacent Top Valley, South Guinness, and Homestead deposits contain inferred resources estimated at 3.5 Mt, 2.9 Mt, and 9.9 Mt respectively. The estimates are based on four drillholes and one farm dam exposure, one drillhole and two farm dam exposures, and three drillholes and two farm dam exposures respectively. The total inferred resources in the above deposits are estimated at 31.2 Mt. Another four prospects (Smiths, Grylls, Wrens, and Ling) within the tenement area (E70/2023) are estimated to contain a resource of 20 Mt, which (at best) might be classified in the inferred category.

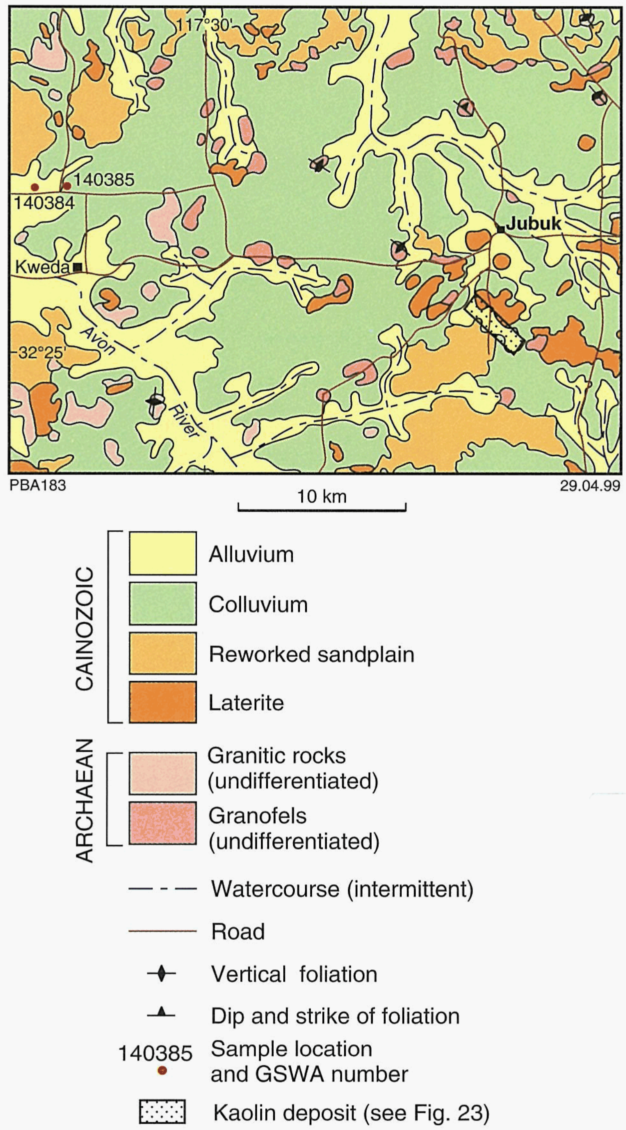


Figure 22. Regional geology of the Jubuk area (modified from Muhling and Thom, 1979)

Ockley–Wickepin

CRA Exploration Pty Ltd (now Rio Tinto Exploration Pty Ltd) has carried out extensive exploration activities in the Ockley–Wickepin area. A number of areas investigated by drilling have been found to contain kaolin of high brightness, with the most important high-quality kaolin resource (Sparks) located 15 km east of Wickepin (Fig. 24), near Uleling Hill (Williams, 1996a, 1997a).

Geology

As demonstrated by material exposed in many farm dam diggings, the area around the Sparks deposit appears to be extensively underlain by porphyritic granite and adamellite, and leucocratic granofels of granite–adamellite composition. In many places, these granitic rocks have undergone intense weathering to produce leached pallid zones that contain zones of kaolin under a lateritic duricrust. The surface material mainly consists of Cainozoic alluvial, colluvial, and reworked sandplain deposits (Fig. 25). Kaolin exposures are common in breakaways, around the edges of lateritic uplands, and in farm dams.

Drilling at the Sparks deposit has indicated that the kaolin horizon has a thickness varying from 2 to 32 m, with an overburden typically 2 to 10 m thick. Textures of the parent rock are preserved in kaolin outcrops, showing that the deposit is a result of weathering in situ of Archaean granitic rocks. A typical cross section of the Sparks kaolin deposit is given in Figure 26.

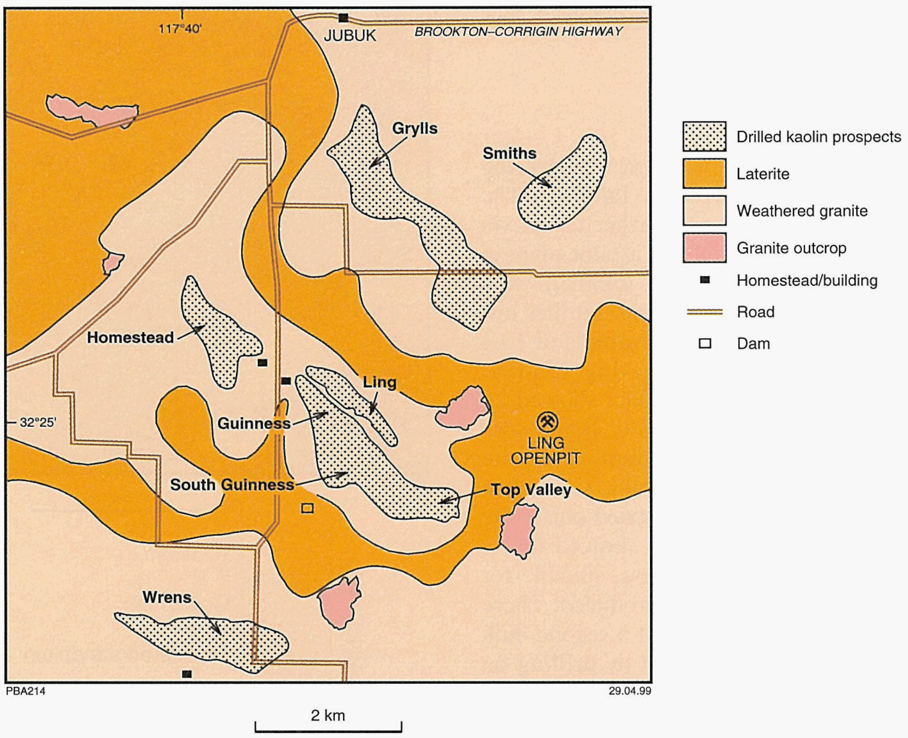


Figure 23. Location map of the kaolin deposits and main geological units at Jubuk (modified from Summit Gold, 1994)

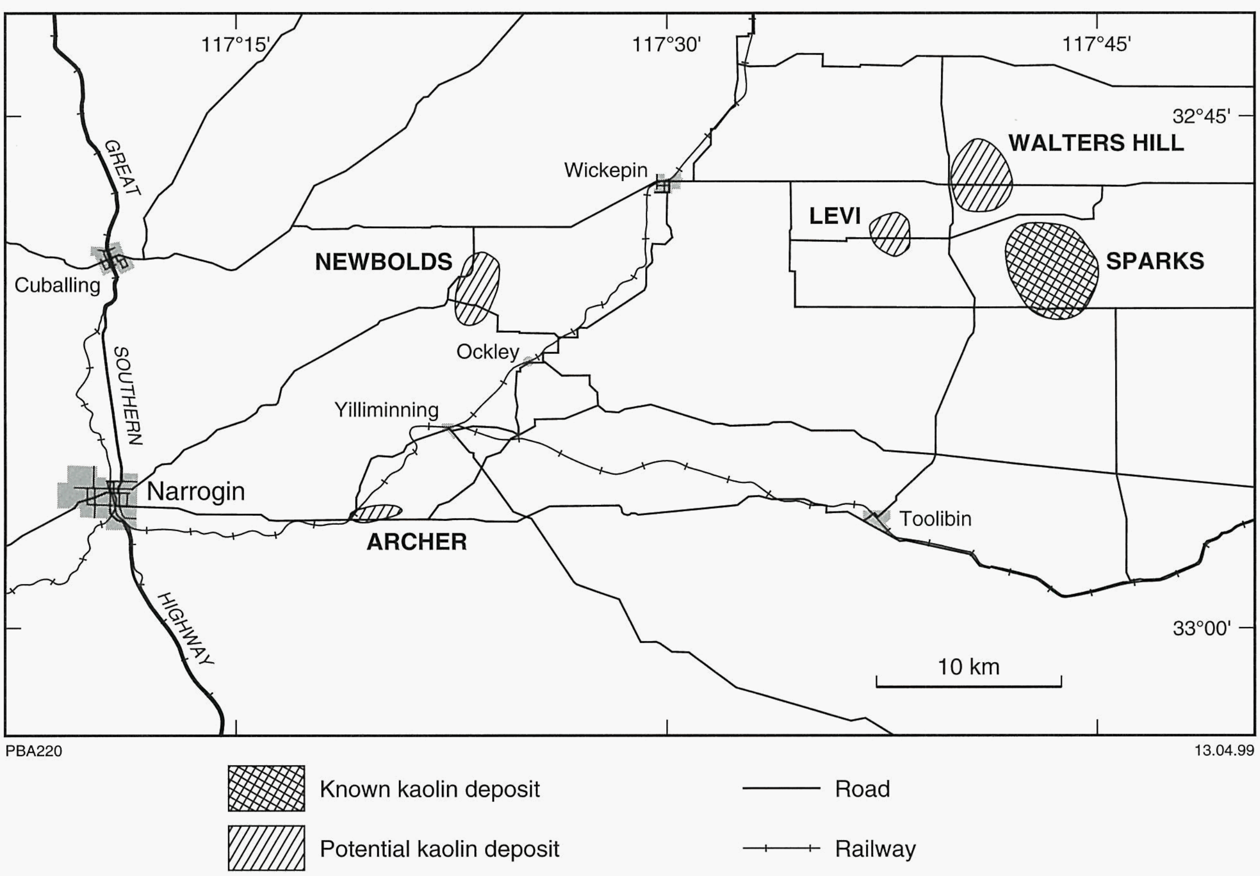


Figure 24. Potential kaolin deposits in the Ockley–Wickepin area (after Williams, 1997)

Table 22. Test results for kaolin from the Jubuk area

Deposit	Grit (%)	Brightness (at 570 mμ) (%) Raw	Degritted	Oxidized	Demagnetized	Abrasion factor (mg)
Guinness	38.3	83.1	85.7	88.4	90.1	21
Top Valley	52.5	78.6	83.0	85.7	89.5	64
South Guinness	35.4	72.5	78.1	80.6	82.3	16
Homestead	49.0	81.1	84.4	86.4	88.0	34
Smiths	44.1	79.9	83.1	86.8	89.0	18
Wrens	56.4	75.3	79.6	82.5	83.9	38
Grylls	61.3	74.9	80.1	83.2	84.8	17
Ling	45.6	71.8	78.0	80.6	83.0	56

Quality

The kaolin in the Sparks deposit is of high quality and capable of producing paper coating grade material (Williams, 1997a). The kaolin has an ISO brightness of 88.8% after magnetic separation, a Brookfield viscosity of 289 centipoise, and a clay fraction (-2 μm) of 28%.

Resources

An in situ indicated resource of 29 Mt (dry) of kaolin, capable of producing a slurry at 71% solids as required by the TAPPI Standard, has been estimated. The resource estimate is based on 43 holes drilled on a grid of 200 m × 200 m, and also on observation of a pit exposure in the deposit. This resource contains 12 Mt of Premium Bright feedstock yielding a 90.5% ISO brightness. The average thickness of the kaolin is 11.5 m, while the average overburden thickness is 6.1 m.

Test results

Six samples, collected by the authors from a number of localities bounded by Yealering, Boyning Gully, Borning Soak, and Jitarning (Fig. 25), were tested to determine their chemical and mineral compositions (Tables 23 and 24). In addition, some of the samples were tested for ISO brightness and particle size (Tables 25 and 26) and were also studied under SEM (Figs 27 and 28). The test results suggest that kaolin from these samples would be suitable for ceramic, refractory, and other commercial applications, and therefore the area in general appears to be a good target for further exploration work.

Kerrigan

Prospector J. Tucker from Graphite Holdings Pty Ltd first investigated exceptionally white clays in the general area of Location 2524 south of the Kerrigan deposit, 350 km east of Perth and approximately 25 km southeast of Karlgarin. In 1992, he approached CRA Exploration Pty Ltd (now Rio Tinto Exploration Pty Ltd) with preliminary laboratory results on material from the above areas with a view to a possible joint venture. CRA Exploration Pty Ltd advised Mr. Tucker to collect more representative samples, preferably by drilling.

This led to the drilling of 47 holes in the area by Graphite Holdings Pty Ltd, which intersected large lenses of exceptionally bright clay in an area designated as 'Bradley' within the Kerrigan deposit (Fig. 29). Similar clay intersections to those found in the Bradley deposit were also encountered in nearby areas. In June 1993, Rio Tinto Exploration Pty Ltd carried out a more detailed investigation under a commercial arrangement with Graphite Holdings Pty Ltd.

Geology

Bedrock in the area consists of Archaean porphyritic granite and adamellite, and leucocratic granofels of granite–adamellite composition. Weathering in situ of these rocks has given rise to the kaolin deposit. Over much of the area, the rocks are deeply weathered, forming a well-leached kaolinized zone under a lateritic duricrust, as can be seen in a north–south cross section of the Bradley deposit (Fig. 30). However, in some areas laterite lies directly above relatively fresh granite. Exposures of leached zones are common in breakaways around the edges of the lateritic uplands. Aeromagnetic features and drillhole intersections show that mafic dykes intrude the Archaean rocks.

Kaolin mineralization

The kaolin occurs as a matrix between quartz crystals, and is derived from the breakdown of potash and soda feldspar. Preserved textures in outcrops show that the kaolin is definitely of residual origin.

The overburden, consisting of nodular lateritic duricrust grading into ferruginous mottled clays, averages about 4 m in thickness. At the top of the pallid zone, which comprises well-leached kaolin and off-white and slightly discoloured kaolin, is an irregular layer of well-cemented, siliceous kaolin up to 2 m thick. The pallid zone is up to 30 m thick, with an average of 16 m, and contains lenses of highly leached kaolin referred to as 'high white' (Kristensen, 1994; Williams, 1996b; Williams and Bisset, 1996).

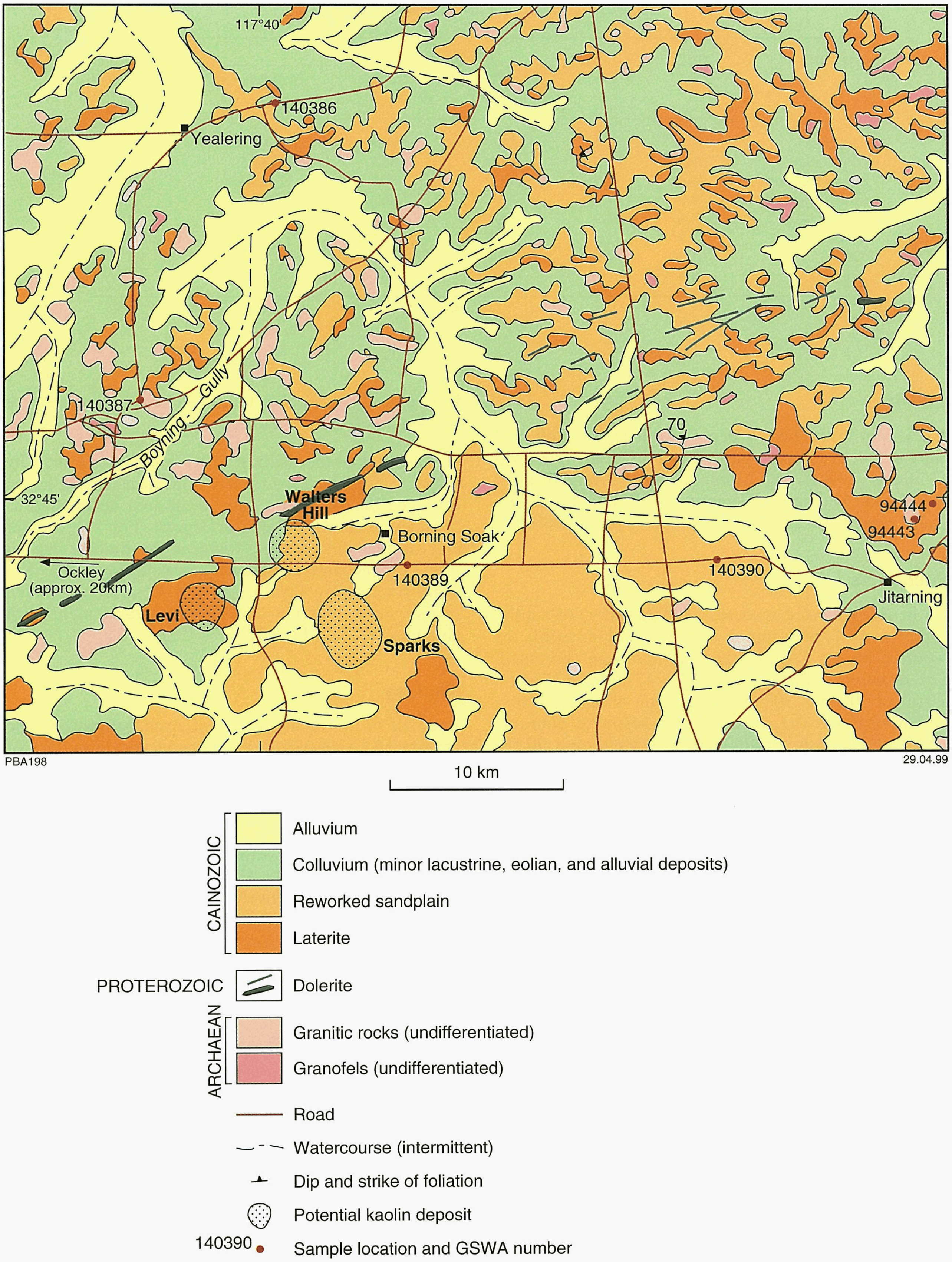


Figure 25. Regional geology around the Sparks kaolin deposit (modified from Muhling and Thom, 1985)

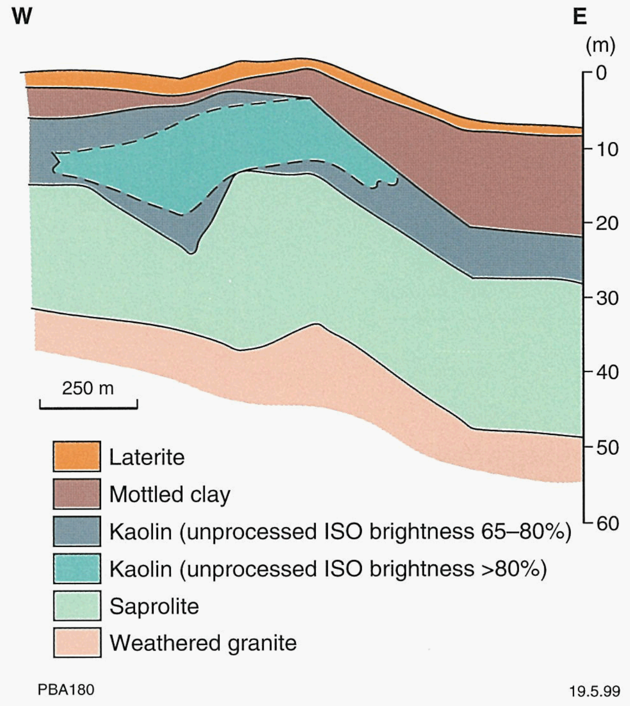


Figure 26. Typical east–west cross section of the Sparks kaolin deposit (after Williams, 1997)

Table 23. Chemical analyses of kaolin samples from the Ockley–Wickepin area

Locality *GSWA no.*	*Yealering* *140386*[(a)]	*Boyning Gully* *140387*[(a)]	*Borning Soak* *140389*[(a)]	*Jitarning* *140390*[(a)]	*Jitarning* *94443*	*Jitarning* *94444*
			Percentage			
Al_2O_3	34.70	35.90	33.30	34.60	22.00	28.20
SiO_2	47.40	45.80	50.90	48.60	68.40	56.20
TiO_2	0.34	1.05	0.40	0.22	0.42	2.11
Fe_2O_3	1.71	1.13	1.33	1.55	0.32	1.04
MnO	<0.01	<0.01	<0.01	<0.01	<0.01	0.01
CaO	0.08	0.03	0.04	0.02	<0.01	<0.01
K_2O	2.51	0.20	0.21	0.46	0.21	0.07
MgO	0.51	0.13	0.15	0.23	0.05	0.04
P_2O_5	0.02	0.08	0.01	<0.005	<0.01	0.08
SO_3	0.06	0.12	0.17	0.25	<0.01	0.01
Na_2O	0.32	0.55	0.54	0.77	0.59	0.73
LOI	12.72	14.92	13.57	14.24	8.78	12.00
Total	**100.37**	**99.91**	**100.62**	**100.94**	**100.77**	**100.49**

NOTE: (a) Analyses on -10 µm fractions

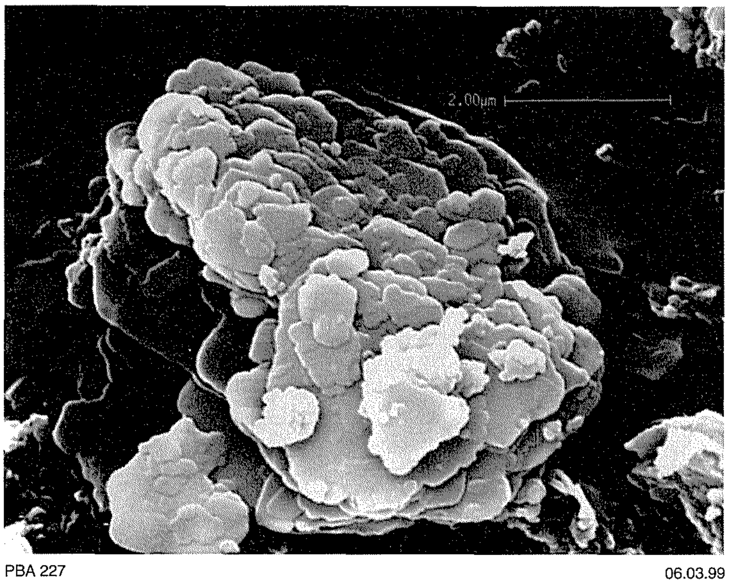
Table 24. Semi-quantitative mineral estimates for kaolin samples from the Ockley–Wickepin area

GSWA no.	*Locality*	*Kaolinite*	*Quartz*	*Mica*	*Microcline*	*Halite*
				Percentage		
140386[(a)]	Yealering	>50	<2	2–10	–	<2
140387[(a)]	Boyning Gully	>50	<2	<2	–	<2
140389[(a)]	Borning Soak	>50	<2	<2	trace	<5
140390[(a)]	Jitarning	>50	<2	<2	trace	<5
94443	Jitarning	dominant	40–50	trace	–	–
94444	Jitarning	dominant	15–25	–	–	–

NOTE: (a) Tests on -10 µm fractions

Table 25. Brightness of samples from the Ockley–Wickepin area

Location	*GSWA no.*	*Brightness (ISO) (%)*
Yealering	140386	74.6
Boyning Gully	140387	70.6
Borning Soak	140389	66.3
Jitarning	140390	74.0
Jitarning	94443–44	not available



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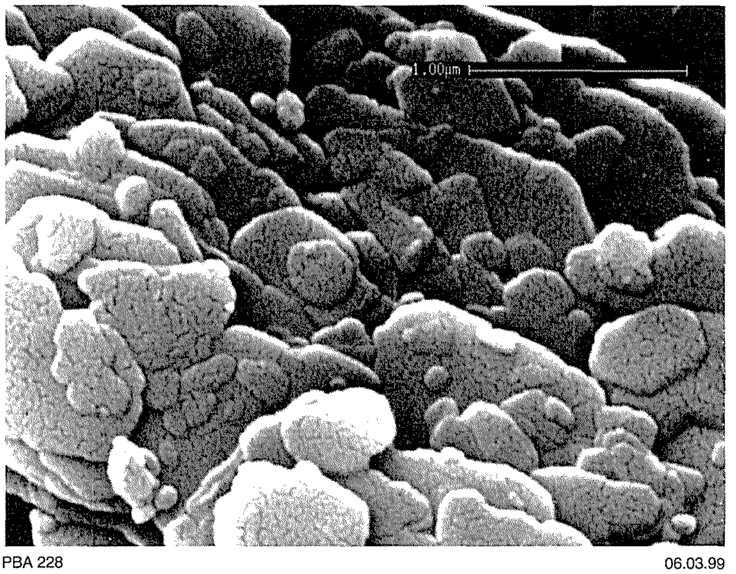

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Figure 27. Scanning electron micrographs of kaolin from Borning Soak
Top: Polycrystalline aggregates of fine kaolinite resulting from secondary recrystallization
Lower: Enlargement of the above photomicrograph

Table 26. Particle-size fractionation results of raw samples from the Ockley–Wickepin area

GSWA no.	*Locality*	*<500 µm*	*<106 µm*	*<45 µm*	*H_2O*
			Percentage		
140386	Yealering	71.4	47.4	43.1	6.4
140387	Boyning Gully	73.6	44.2	37.3	5.1
140389	Borning Soak	43.2	25.3	21.3	10.1
140390	Jitarning	51.6	31.5	27.0	7.6

Quality

Preliminary analytical results indicated that the kaolin is of exceptionally high quality, requiring little or no beneficiation other than size separation (Kristensen, 1994). The Bradley deposit contains extensive high-quality kaolin with potential for use in paper manufacture.

Kaolin from the Bradley deposit was found to have an average -10 µm yield of 45%, an unbeneficiated ISO brightness of 85.4–89.1%, a quartz content of less than 1%, and a -2 µm yield of 42–83% (average of 74%). Large variations in the -2µm fraction are thought to be due to sample size and intervals.

Resources

Based on 115 holes drilled in the area during 1993–94 (mostly in the Bradley deposit), CRA Exploration Ltd estimated inferred resources in the Bradley deposit to be about 80 Mt, over an area of about 3 km^2. The resource estimate is based on drill spacings of 200–400 m. Kaolin in the deposit is up to 27 m thick, with an average of 16 m, and with an average overburden thickness of 4 m. The average thickness of the 'high white' lenses within the pallid zone is about 8 m.

Other testing in the Kerrigan area

Three surface grab samples (GSWA 140394–96) were collected by the authors from an area west of the Kerrigan deposit (Fig. 29), and were tested for mineral composition, brightness, particle size, and chemical composition (Tables 27 to 29). Within the sampled area, there are numerous breakaways exposing kaolin horizons associated with either laterite or granite. Some profiles indicate the development of kaolin during lateritization (Fig. 31). The dominant rock type distinguished in the area is granite, which is generally covered with laterite and/or sandplain and/or alluvial material. Sample GSWA 140394 was a quartz-rich kaolin developed below a laterite profile exposed in a road cutting, and sample GSWA 140395 was from a kaolin horizon exposed at another road cutting further south. The third sample was a quartz-rich kaolin collected from a farm dam. These samples were tested using the -10 µm fraction.

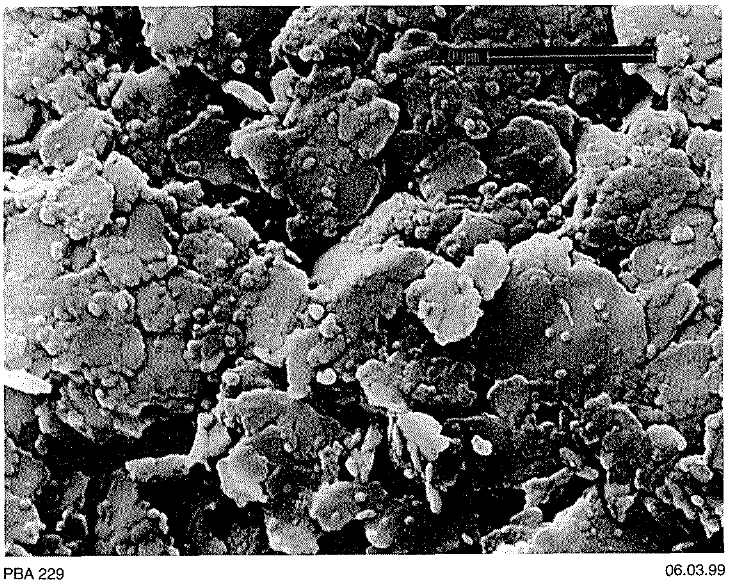

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Figure 28. Scanning electron micrograph of kaolin from Jitarning (GSWA 140390) showing kaolinite flakes with fine globular ?kaolinite scattered on the surface

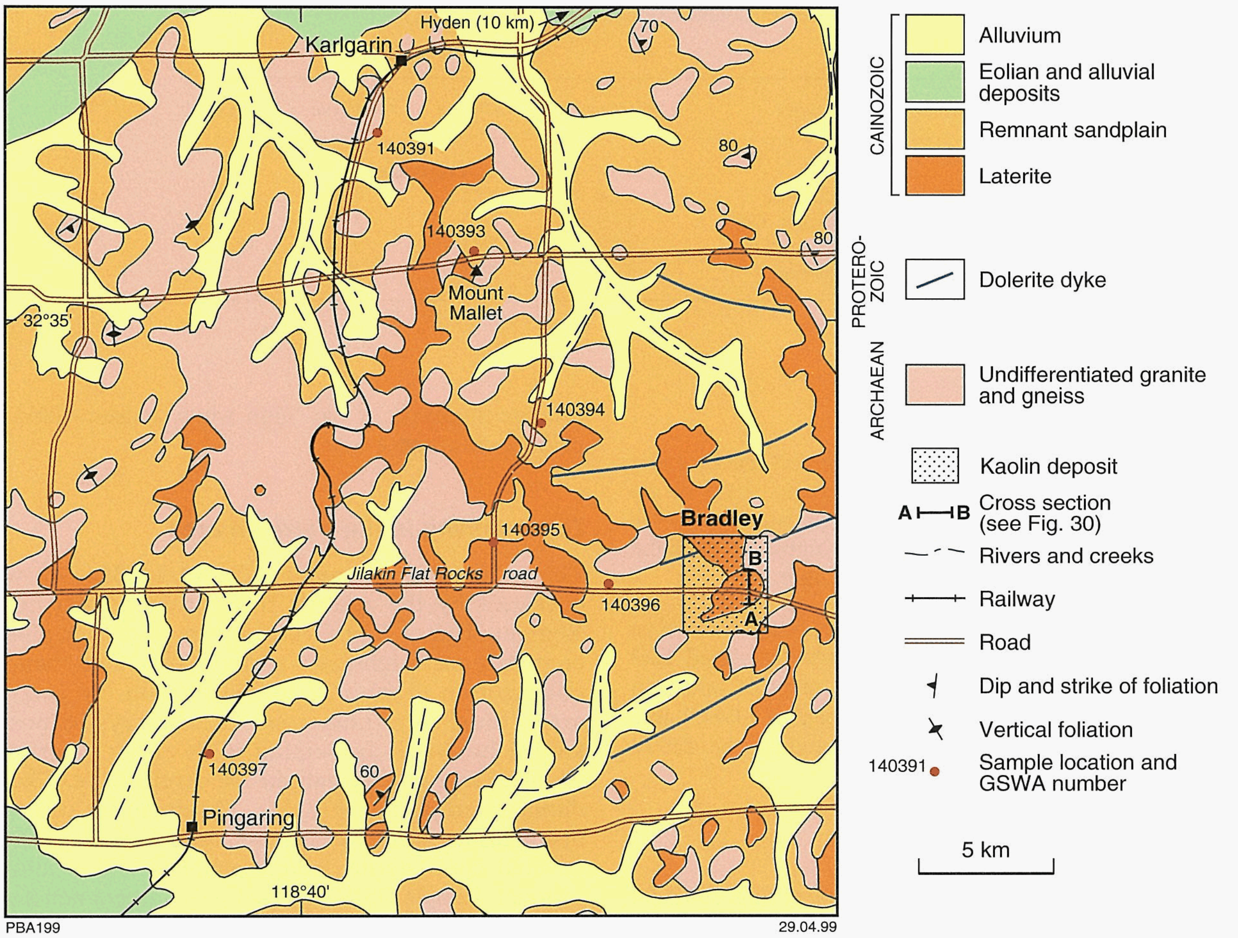


Figure 29. Regional geology around the Kerrigan kaolin deposit (modified from Chin et al., 1984)

All samples showed kaolinite as the dominant mineral with trace to minor amounts of quartz, mica, feldspar, and halite. The ISO brightness of the samples was high, ranging from 80 to 86%, which implies the presence of material suitable for both paper coating and filler grades. These values could possibly be improved by beneficiation. SEM studies indicated subhexagonal to hexagonal kaolinite in thin- to thick-stacked platelets. Particle-size fractionation studies of the raw samples indicated a low proportion of fine kaolin, with only 22.4–26.8% less than 45 µm.

Chemical analyses indicated that sample GSWA 140394 had a composition typical of paper coating grade kaolin, whereas the other two had marginally low Al_2O_3 for such applications. The fact that these three samples were collected from localities more than 5 km apart suggests the possibility of an extensive resource of high-grade kaolin within the general area, in addition to the Kerrigan kaolin deposit.

Tambellup

The kaolin deposit at Tambellup is located between 4 and 18 km west of Tambellup, which is 335 km southeast of Perth (Figs 12 and 32). The area was first held by Gilba Pastoral Company in 1971 under Mineral Claims MC 12106, 12108, 12926, 12099, and 12930. Tenure to the area was then taken up by Portman Mining Ltd in 1993 under Exploration Licence E 70/1120, which covered an area of 84.41 km^2 but was surrendered in May 1994.

Gilba Pastoral Company explored the area west of Tambellup in 1971 by drilling more than 100 auger holes and digging test pits; results were considered encouraging. This work identified four prospective areas for kaolin with the best area being Saddlers property. Other prospective areas identified were Newings property, Hulls property, and Lot 7338, located approximately 5 km west of Saddlers property (Fig. 32).

In 1993, further sampling of farm dams by Portman Mining confirmed the presence of high-quality kaolin on Saddlers, Newings, and Hulls properties, and identified kaolin on Lots 758 and 2704. Saddlers, Newings, and Hulls properties were further explored by 161 reverse-circulation aircore drillholes, totalling 1944 m (Holmes, 1993).

In addition to the above exploration activities, CRA Exploration Pty Ltd secured a large area surrounded by Tambellup, Katanning, and Kojonup, including an area approximately 150 km north of Katanning. The company has carried out regional exploration activities in these areas, but the results remain confidential.

Geology

Kaolin deposits in the Tambellup area have formed due to weathering in situ of biotite adamellite, which is the predominant rock type in the area (Fig. 32). The degree of weathering is related to structural features such as jointing and deformation. Although even-grained adamellite is abundant in outcrops in the eastern part of the area investigated by Portman Mining, some exposures of coarse-grained granodiorite and fine-grained aplitic adamellite–gneiss also occur. On Saddlers property, north–south and east–west cross sections indicate that well-leached white clays containing kaolin formed within the residual weathered profile of Archaean granitoid (Fig. 33).

Resources and quality

Drilling by Portman Mining Ltd is summarized in Table 30. An indicated resource of 7.1 Mt (wet basis) of clay material (-2 µm) is estimated to be present within the Saddlers and Hulls properties.

Test results on selected samples from Tambellup are given in Tables 31 and 32. The brightness of the samples was found to be of an acceptable grade for many uses. A brightness of greater than 90% (at 570 mµ) was obtained for 10 out of 11 samples tested, and a brightness (at 457 mµ) value of greater than 88% for 7 out of 11 samples. The chemical composition of a sample (GSWA 145107) collected from a farm dam close to Saddlers property indicated that the material is of moderately high grade, although the Al_2O_3 appears to be marginally low for paper grade material (Table 32). However, this sample may not be representative of the drilled area. Sample GSWA 145107 contained 30.1% material less than 45 µm (Table 33). Testing for viscosity, using samples of variable solids contents, produced results considered unacceptable for coating grades of kaolin (Vivian, 1994).

Brookton

The Brookton kaolin deposit is situated on the southern edge of the saline Yenyening Lakes, 26 km east-southeast of Brookton, which is approximately 140 km from Perth (Fig. 12). Undulating hills and several small perennial freshwater swamps and lakes surround the lake area. Fresh groundwater occurs beneath the non-perennial streams. The area has been investigated for kaolin by Longreach Metals NL (Lipple, 1977). In 1972, Longreach Metals NL drilled thirty-three percussion holes totalling 776 m, and discovered four deposits, which in this publication have been labelled A to D for ease of reference (Fig. 34).

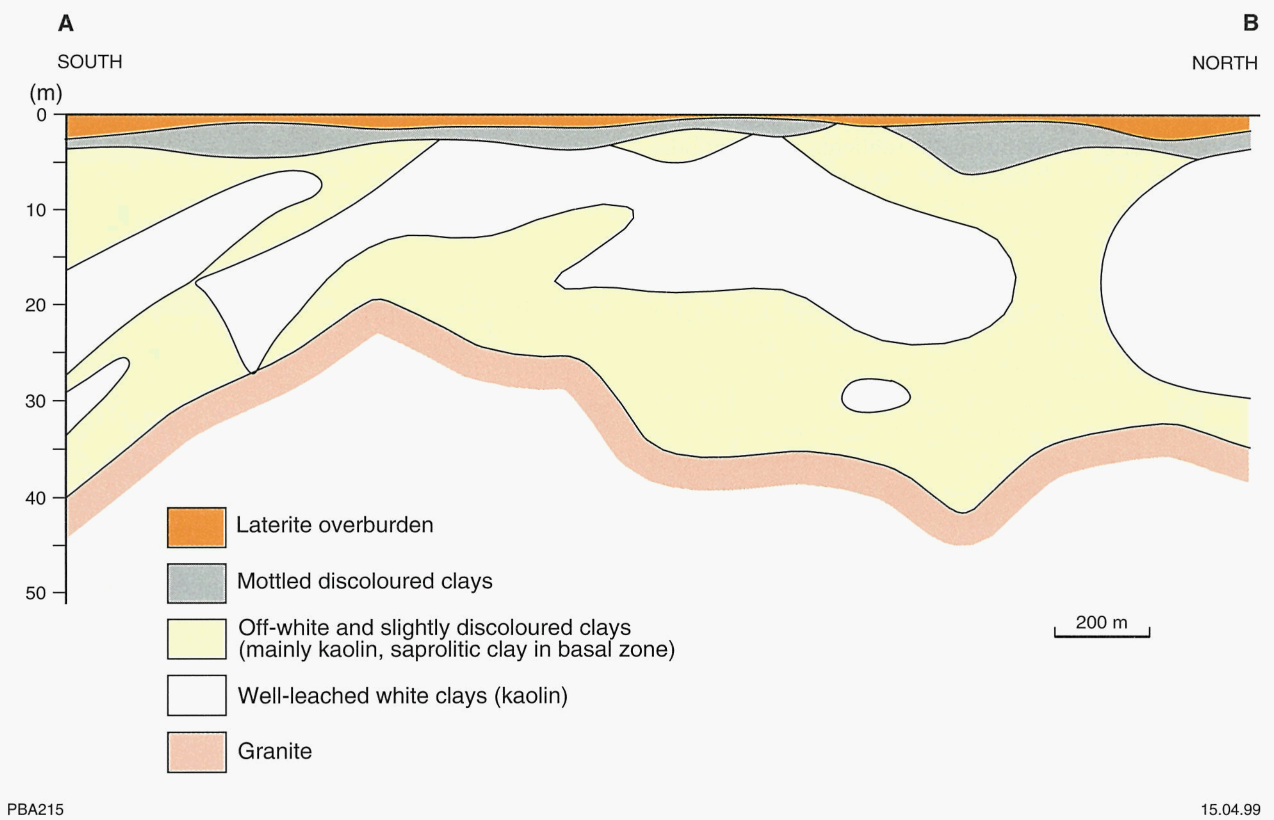


Figure 30. North–south cross section of the Bradley kaolin deposit at Kerrigan (modified from Kristensen, 1994)

Table 27. Mineralogy, brightness, and crystallinity of kaolin samples from the Kerrigan area

GSWA no.	*Kaolinite*	*Quartz*	*Mica*	*Feldspar*	*Halite*	*Brightness (ISO)*	*Crystallinity (using SEM)*
				Percentage			
140394	>50	2–10	<2	–	<2	80.22	Coarse- to medium-grained sub-hexagonal platelets of kaolin
140395	>50	2–10	–	–	<2	80.29	Medium- to coarse-grained sub-hexagonal platelets of kaolin
140396	>50	<2	<2	<2	<2	86.02	Relatively thick, coarse-grained sub-hexagonal to hexagonal platelets of kaolin

NOTE: All tests on -10 µm fractions

Table 28. Particle-size fractionation results for kaolin samples from the Kerrigan area

GSWA no.	*<500 µm*	*<106 µm*	*<45 µm*	H_2O
		Percentage		
140394	59.1	32.6	25.7	5.6
140395	53.5	28.5	22.4	8.3
140396	52.4	31.6	26.8	5.2

Table 29. Chemical analyses for kaolin samples from the Kerrigan area

GSWA no.	*140394*	*140395*	*140396*
		Percentage	
Al_2O_3	37.60	35.00	35.10
SiO_2	47.00	49.80	48.90
TiO_2	0.28	0.44	0.25
Fe_2O_3	0.67	0.76	0.70
MnO	<0.01	<0.01	<0.01
CaO	0.03	0.02	0.04
K_2O	0.10	0.09	1.34
MgO	0.04	0.07	0.24
P_2O_5	0.01	<0.005	<0.005
SO_3	0.04	0.05	0.05
Na_2O	0.16	0.14	0.27
LOI	14.37	14.16	13.38
Total	**100.3**	**100.53**	**100.27**

NOTE: All analyses on -10 µm fractions

Geology

The main rock type in the area is medium- to coarse-grained Archaean biotite adamellite that has intruded fine-grained biotite granodiorite (Fig. 34). The granodiorite contains numerous mafic schlieren and xenoliths from a nearby medium-grained amphibolite. Drilling showed that the amphibolite forms a large subcrop extending northeast and northwest beneath 25 to 35 m of overburden.

Overlying the Archaean rocks are surficial deposits up to 40 m thick, containing clay, sandy clay, clayey sand, yellow eolian sand, and minor limonitic gravel. Kaolin is not exposed in the area, although some farm dams reveal its presence beneath sand and gritty discoloured clay. The thickness of the clay beds in the kaolin deposits varies from 3 to 16 m, while the average overburden of these deposits varies from 4 to 10 m (Table 34).

Quality

Samples from the drill chips were tested for clay yield, particle-size distribution, and brightness of both bleached and unbleached -5 µm and 5–44 µm fractions. The tests indicated 25–30% of -5 µm kaolinite of good crystallinity that contained only traces of quartz and mica. However, the brightness values (at 457 mµ) were low, with only nine samples having a brightness of more than 80%. Viscosity was high and usually equivalent to a solids loading of less than 65%. Based on these tests, the commercial potential of the Brookton deposit was considered to be very low (Lipple, 1977).

Clackline

The Clackline deposit, located about 80 km east-northeast of Perth and 5 km west of the Clackline townsite (Fig. 12), has a reputation as one of the best deposits of refractory clay in Western Australia. There has been a recorded production of 147 663 t, from 1939 to 1985, and this has been mainly used in the manufacture of refractory firebricks, boiler linings, seatings, and whiteware. In 1996, 12 000 t of fireclay was produced from the nearby deposit of Nanamoolan, but in 1997 there was no reported production from this location.

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

Figure 31. Development of kaolin during laterization in the Kerrigan area (Lat. 32°37'00"S, Long. 118°45'40"E)

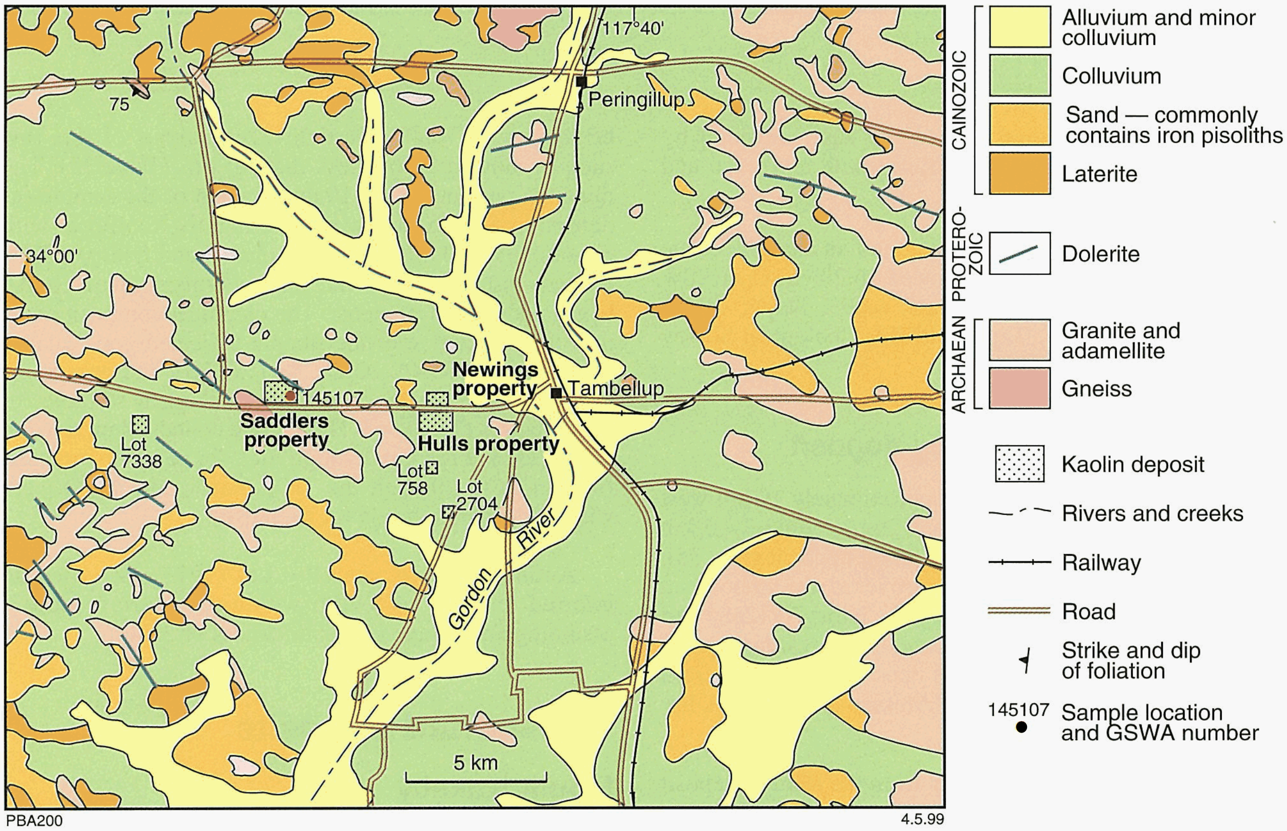


Figure 32. Regional geology and locations of kaolin deposits around Tambellup (modified from Muhling et al., 1984; Brakel et al., 1985)

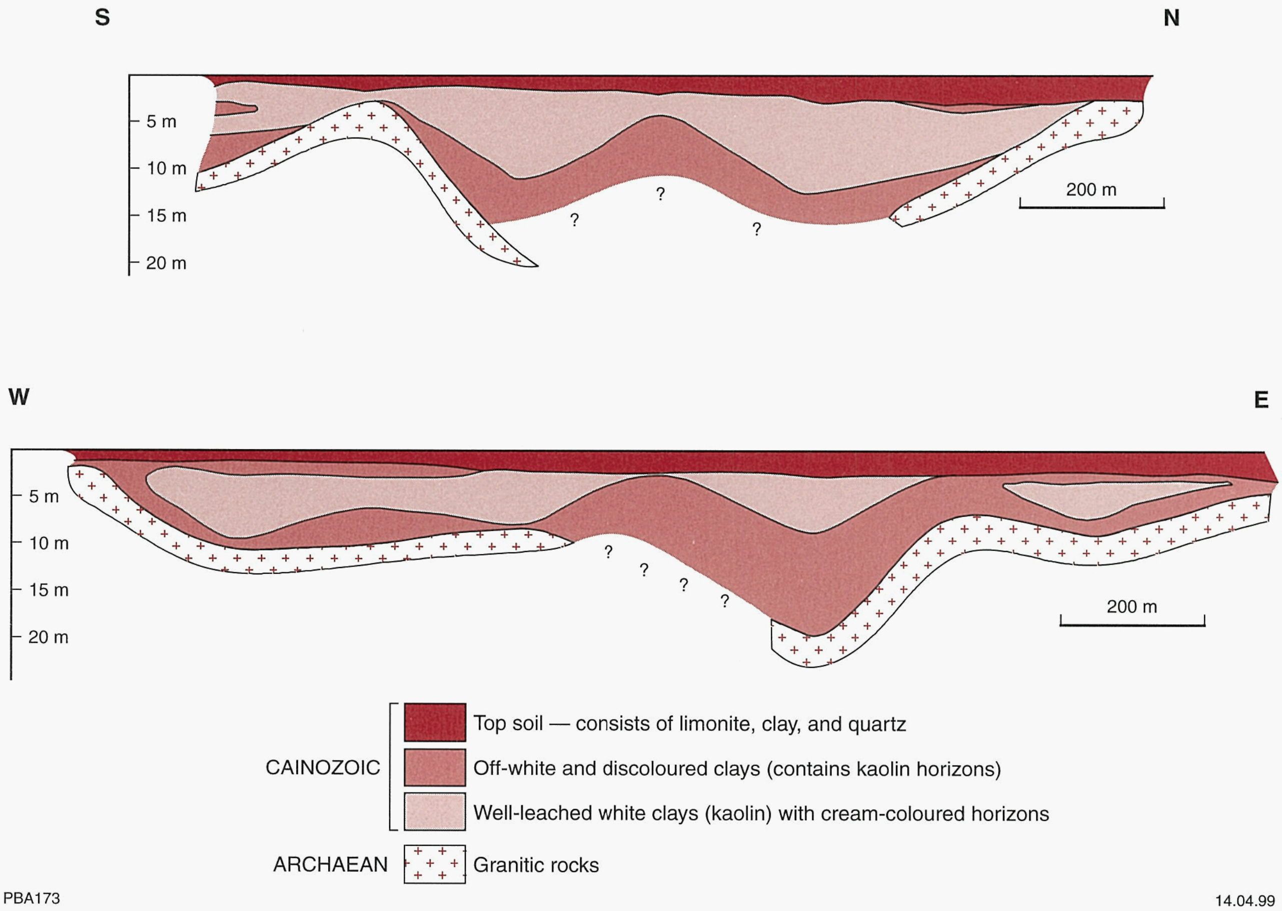


Figure 33. North–south and east–west cross sections of Saddlers property in the Tambellup kaolin deposit (based on drilling data from Holmes, 1993)

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.

The clay is white and grit-free, and an analysis of the kaolinized sillimanite schist showed 26.2% Al_2O_3, 63.8% SiO_2, 0.60% Fe_2O_3, 0.22% MgO, 0.09% Na_2O, 1.76% K_2O, and 0.58% TiO_2 (Lipple, 1976a; Geological Survey of Western Australia, 1980).

Mount Kokeby – Murray deposit

The Murray deposit is located approximately 10 km west of Mount Kokeby townsite and approximately 2 km northeast of the Mount Kokeby kaolin opencut (Fig. 35). King Mountain Mining NL discovered the deposit in 1971. This deposit is within Mineral Claims 70/12685 and 70/12686. The deposit is considered to be residual kaolin on granite, and the extent of the deposit, as inferred from drilling, is shown on Figure 35 (Aminco & Associates Pty Ltd, 1971; Lipple, 1977).

Bruce (1987) stated that clay from the Murray deposit should be suitable for whiteware and possibly for refractory bricks. White fine-grained, platy kaolin (sample GSWA 140383) from the diggings of a farm dam at the northern corner of the Murray deposit had an ISO brightness of 79.4%. Particle-size analysis of this raw sample showed 33.6% less than 45 µm (Table 35). The minerals present in the -10 µm fraction of the sample (as determined by XRD) were dominantly kaolinite, with minor halite and traces of mica, quartz, and feldspar. SEM studies indicated that the kaolin consisted of coarse hexagonal platy fragments. The chemical composition of the -10 µm fraction of the sample indicated good quality kaolinite with 35.4% Al_2O_3, 48.1% SiO_2, and acceptable levels of TiO_2, Fe_2O_3, and MgO, making it suitable for ceramic uses (Table 36). The sample contained marginally low Al_2O_3 and marginally high SiO_2 for paper coating and filler grades, although the TiO_2, Fe_2O_3, and MgO were within acceptable levels for such uses.

Aminco & Associates Pty Ltd (1971) estimated an inferred resource of 5.9 Mt within the Murray deposit, assuming an average kaolin thickness of 2.74 m.

Transported deposits

Mount Kokeby

The Mount Kokeby kaolin deposit is situated approximately 100 km east-southeast of Perth (Fig. 12), and 13 km southwest of the Mount Kokeby townsite. Kaolin

Table 30. Summary of drilling and related data for the Saddlers, Newings, and Hulls properties at Tambellup

Property	*Number of drillholes*	*Average depth of drillhole (m)*	*Average thickness of kaolinized zone (m)*	*Comments*	*Resource*
Saddlers	84	11.4	9.6	The width of the kaolinized zone is approximately 600 m	An indicated resource of 3.3 Mt (wet tonnes) of -2 µm clay is estimated. An additional resource (probably inferred) of 0.4 Mt is also estimated on Lots 654 and 657
Newings	41	12.51	11.10	Most potential for kaolin is within Lot 2713 in the central area of the property	Not estimated
Hulls	36	16.57	10.22	Bedrock is at an average depth of 20 m	An indicated resource of 3.8 Mt (wet tonnes) of -2 µm clay is estimated

was extracted from the deposit from 1941 to 1983, but the deposit is not currently worked.

Feldtmann (1919), Joplin (1959), Kalix (1973), and Lipple (1977) have described the kaolin deposit in this locality. The area investigated is located between the Avon River to the east and the Dale River (a tributary of the Avon River) to the west.

In 1916, three boreholes (Fig. 35) were put down in the Mount Kokeby area on the recommendation of Mr H. P. Woodward, who was the current Assistant Government Geologist, to check for the presence of coal, oil, or commercial clay in the area (Feldtmann, 1919). These boreholes passed through 65 to 70 m of sediments containing lenticular beds of kaolin, sand, sandstone, and blue clay overlying weathered granite, although there were no indications of coal or oil (Fig. 36).

According to Lipple (1976b, 1977), the uppermost kaolin layer, which averages 2.3 m in thickness, has been mined. The kaolin layer is covered with an overburden of 3 to 6 m of loose sand, laterite nodules, and gritty clay. The early workings northeast of borehole No. 1 extended over a length of 55 m in a northerly direction, and consisted of opencuts and shallow (6 m) shafts leading to short drives.

Geology

The area has an undulating topography, with broad valleys and low hills rising to 300 m above sea level. Most of the area is covered with thin colluvial sand and limonitic gravel, overlying gritty clay and laterite and sandy soil, which in turn generally overlie kaolin. The country rock exposed to the west and north of the kaolin deposit is an Archaean, medium- to coarse-grained, porphyritic biotite adamellite, with later intrusions of dolerite. In the Mount Kokeby opencut area, kaolin formed as transported lacustrine deposits, and according to Feldtmann (1919) the kaolin was deposited within Pliocene sediments in a deep valley extending northeast from the Dale River towards the Avon River, just south of the Mount Kokeby township. The Pliocene sediments contain granular quartz, grey shale, drift sand, carbonaceous shale, sandstone, and blue clay, in addition to fairly pure kaolin.

Mining and production

The kaolin was first mined by J. B. Linton in 1941. This was followed with mining by Universal Milling Co., with kaolin being extracted from several shallow shafts and later from an opencut. Mining of these deposits was normally during the dry season of the year, and the brackish water that collected during the rainy season had to be pumped out. Mining by Universal Milling Co. ceased in 1983. The total recorded production to date is 8059 t. This locality has been the second largest producer of kaolin in Western Australia.

Quality

Simpson (1952) described the clay as a semi-ball type, containing 78% kaolinite, 7% mica, and 12% quartz. Particle-size analysis showed 3.5% greater than 20 µm, 38.5% material -20+1 µm and 58% less than 1 µm.

Brightness (at 457 mµ) values of four samples from stockpiles ranged from 73.2 to 75.5% (Lipple, 1977) Chemical analysis of a sample from the mined area indicated that the kaolin was of moderate to good quality (Table 37). The quality approached ceramic and possibly paper grade, provided that the brightness of the material could be improved to acceptable levels.

According to Joplin (1959), the clay has been used as a colour plasma, for leather dressing, and in the manufacture of insecticide dusts, and some was exported to Malaysia for rubber plantations. Later, Mount Kokeby clay was used in the paint and synthetic rubber industries. Lipple (1977) described the clay as potentially useful for earthenware products, including whiteware, and stated that nearly half of all Western Australian kaolin production for filler material, at that time, had been from Mount Kokeby.

Table 31. Test results for the Tambellup kaolin

Sample no.	*727741*	*727012*	*726024*	*726198*	*726790*	*726880*	*726248*	*727811*	*726840*	*727934*	*726198*
Moisture content (%)	15.3	16.5	16.6	12.4	46.4	17.6	24.1	25.6	16.3	13.2	12.4
Dry yield (%)	13.3	31.1	31.0	21.0	–	–	24.4	23.5	17.9	16.4	21.0
Undried yield (%)	11.3	25.9	25.8	18.3	29.5	22.9	18.5	17.5	15.0	14.2	18.3
-2 µm (%) (refined sample)	–	–	–	83.0	79.5	76	76.6	88.9	76.4	90	83.0
Brightness (%)											
at 570 µm (Elrepho)	94.4	92.1	92.1	96.8	95.5	94.9	93.6	83.4	96.5	96.0	96.8
at 457 µm (GE)	88.6	84.8	87.5	91.8	90.5	89.1	84.2	73.1	91.7	91.7	91.8
Viscosity											
solids content as tested (%)	59.8	57.5	65.3	70.6	62.8	62.9	56	64.2	63	67	70.6
dispersant for optimum (%) dispersion (TSPP)	0.3	0.4	0.2	0.3	0.4	0.3	0.4	0.4	0.2	0.4	0.3
Low-shear Brookfield											
100 rpm (centipoise)	284	+1 000	330	550	130	300	410	340	6 500	705	550
20 rpm (centipoise)	150	2 000	250	800	150	150	100	450	1 450	90	800
High-shear (max. rpm)	325	975	225	150	1 100	200	350	300	200	180	–

NOTE: Holmes (1993)
Dry yield is the ratio of the weight of dried refined solids to the dry weight of raw material
Undried yield is the ratio of the weight of dried refined solids to the undried weight of raw material

Table 32. Chemical analysis of sample GSWA 145107 from near Saddlers property, Tambellup

	Percentage
Al_2O_3	35.2
SiO_2	48.7
TiO_2	0.36
Fe_2O_3	0.93
MnO	<0.01
CaO	0.05
K_2O	1.44
MgO	0.23
P_2O_5	0.03
SO_3	0.05
Na_2O	0.14
LOI	13.28
Total	**100.41**

NOTE: -10 µm fraction analysed

Resources

Lipple (1977) identified three small kaolin lenses within the immediate vicinity of the mined area and estimated an inferred resource of 170 000 t, but this was apparently based on very limited data.

Goomalling

There is a kaolin deposit situated 16 km due west of Goomalling, which is 132 km northeast of Perth (Figs 12 and 37). Kaolin and ball clay were produced sporadically from this deposit from 1932 to 1995. The reported kaolin production was 4027 t (1994–95) and that of ball clay was 39 971 t (1932–86) (Tables 11–14). Currently, the deposit is within Mining Tenement 70/162 owned by Bristile Ltd.

Geology

The deposit occurs in an oval claypan, 600 m long and 400 m wide, located within a hummocky sandplain containing eolian sandridges. Basement rock consists of granite–gneiss. The kaolin is exposed below sand in small pits up to 6 m deep, situated on the northeastern edge of the claypan (Fig. 37). There are four beds of laminated kaolin within poorly consolidated quartz sand and grit. Wilde (1974) considered that these deposits had formed in a lacustrine environment, with sandy alluvium deposited in former tributaries of the Mortlock River.

Table 33. Particle-size fractionation results for sample GSWA 145107 from near Saddlers property, Tambellup

<500 µm	*<106 µm*	*<45 µm*	*H_2O*
	Percentage		
65.1	35.7	30.1	12.3

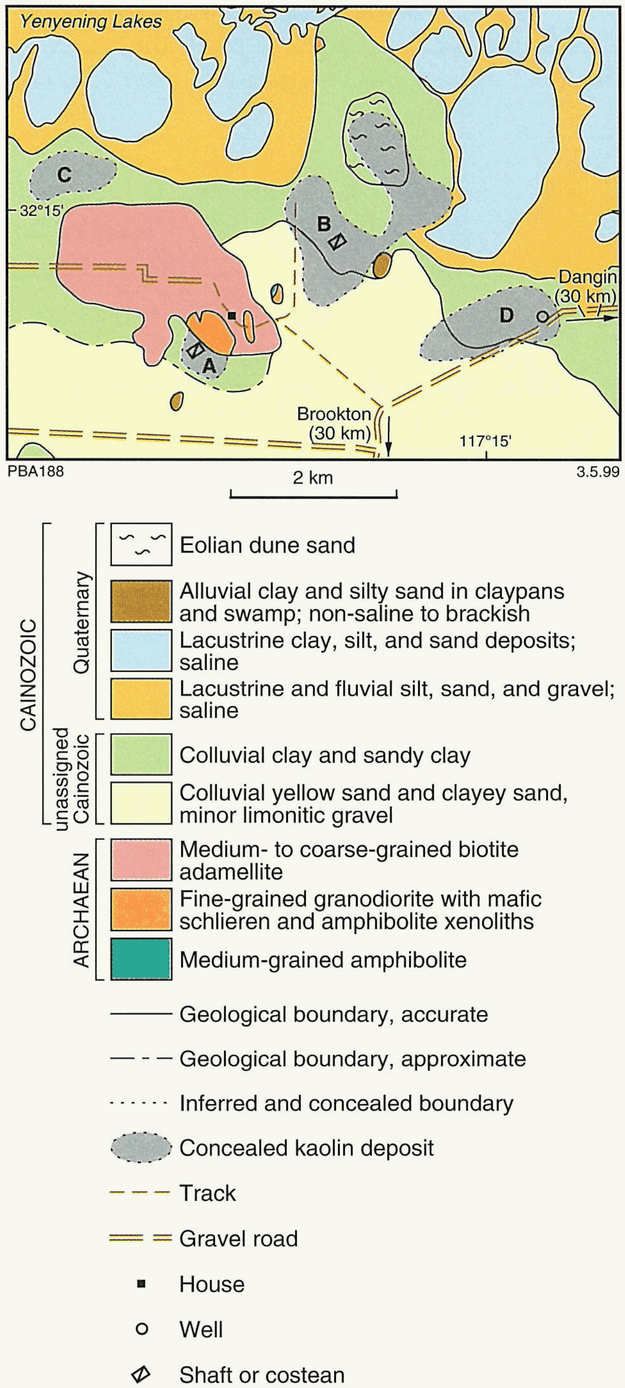


Figure 34. Geology around the Brookton deposit (after Lipple, 1977)

Matheson (1949) identified four clay beds (clay bed Nos 1–4) on a pit face (Table 38). Brisbane and Wunderlich Pty Ltd also described similar clay beds from a clay pit, and the respective thicknesses of clay beds Nos 1–4 were given as 0.79–1.83 m, 0.91–1.37 m, 0.31–0.46 m, and 0.31–0.43 m (Lipple, 1977). The clay beds are interbedded with sand beds varying in thickness from 0.10 to 0.46 m. The clay beds in this section were reported to dip at a low angle to the west-southwest, with thinning to the south. The No. 4 clay bed thins considerably, whereas the No. 3 bed lenses out completely.

Table 34. Drilling data from the Brookton deposits

Deposit	*Average depth of overburden (m)*	*Thickness of kaolin (m)*
A	4	15
B	10	16
C	10–15	18–21
D	10–20	5–13

Table 35. Particle-size fractionation results for sample GSWA 140383 from the Murray deposit

<500 μm	*<106 μm*	*<45 μm*	*H_2O*
	Percentage		
59.1	40.3	33.6	11.2

Table 36. Chemical analysis of sample GSWA 140383 from the Murray deposit

	Percentage
Al_2O_3	35.40
SiO_2	48.10
TiO_2	0.81
Fe_2O_3	0.88
MnO	<0.01
CaO	0.04
K_2O	0.26
MgO	0.21
P_2O_5	0.04
SO_3	0.06
Na_2O	0.31
LOI	14.23
Total	**100.34**

NOTE: -10 μm fraction analysed

Table 37. Chemical analysis of a kaolin sample from the Mount Kokeby opencut area

	Percentage
Al_2O_3	33.94
SiO_2	51.43
TiO_2	0.17
Fe_2O_3	0.93
CaO	0.00
K_2O	0.36
MgO	0.00
H_2O	11.32
Na_2O	0.37
Total	**98.52**

NOTE: -10 μm fraction analysed
SOURCE: Simpson (1952)

Quality

Lipple (1977) described the Goomalling clay as a semi-ball or ball clay, with 72% of the clay in the -1 μm fraction. Chemical analyses of a sample from clay bed No. 1 (dried at 100°C) and of a plastic clay from the deposit are given in Table 39. The compositions indicate that the clay in No. 1 bed is moderate quality kaolin, whereas the plastic clay (GSWA 94499) is high in SiO_2 and Fe_2O_3, possibly due to the presence of quartz and other impurities. A bulk sample (-2 μm fraction) from the stockpile of the Goomalling deposit gave a brightness of 77.3% (at 457 mμ) (Lipple, 1977).

Clays from this deposit have been used for pottery, porcelain, and sanitary ware. The low brightness value suggests that the material has low potential for paper coating or filler grades. The results for particle-size fractionation of the bulk sample are given in Table 40. These values indicate that the -2 μm fraction is 75%, and

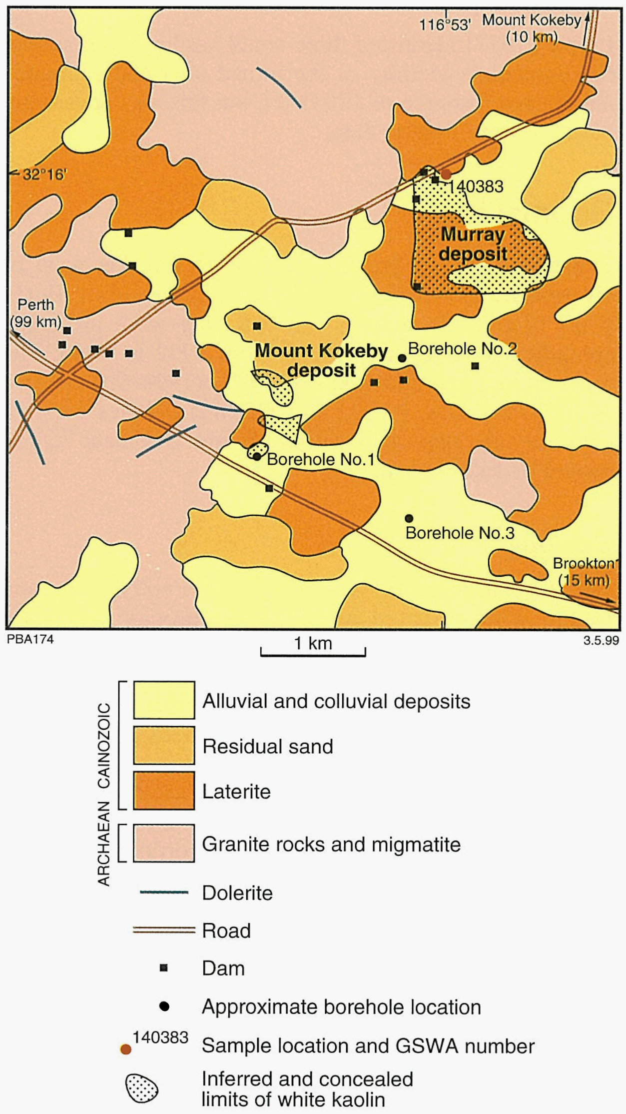


Figure 35. Regional geology around the Mount Kokeby and Murray kaolin deposits (modified from Lipple, 1977)

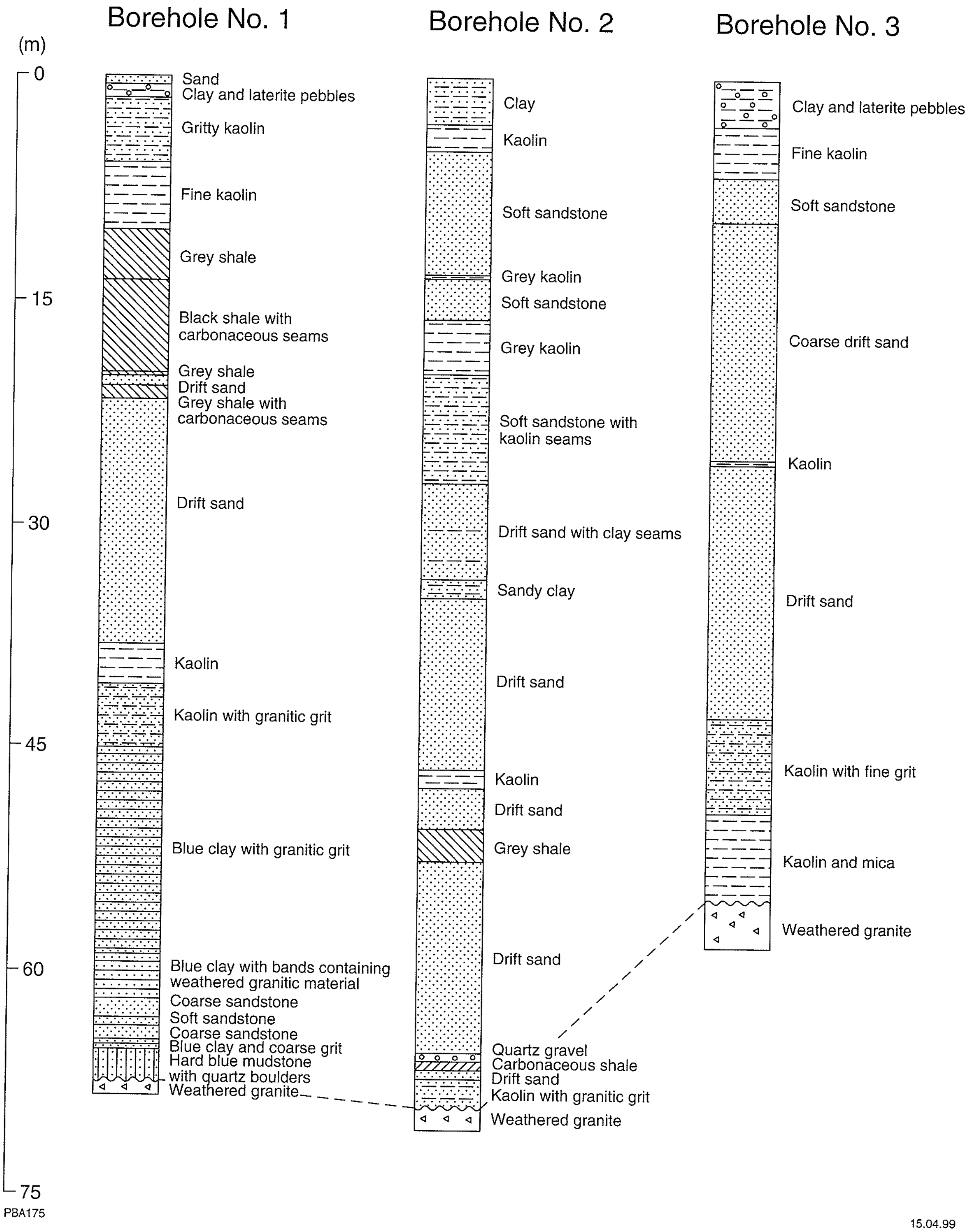


Figure 36. Borehole logs from the Mount Kokeby deposit (after Lipple, 1977)

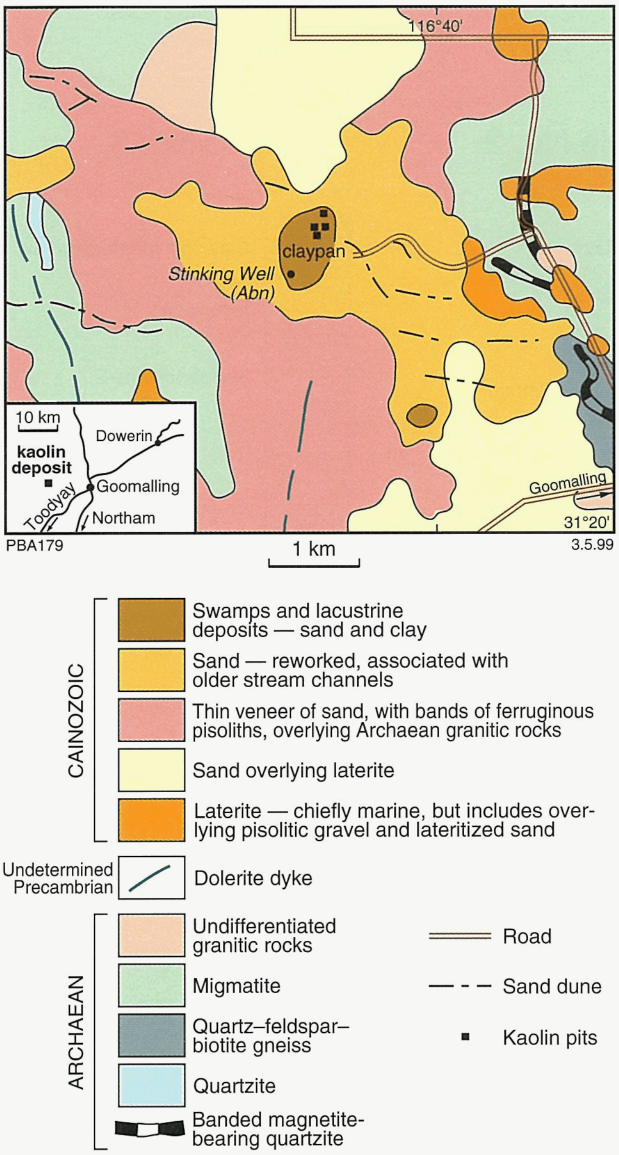


Figure 37. Geology around the Goomalling kaolin deposit (modified from Lipple, 1977)

falls within the specifications for paper filler grade. Bristile Ltd has stated that the kaolin in this deposit is suitable for the manufacture of tableware, and also as an additive for roof tiles and for use as a pottery clay.

Resources

Stacey (1994) estimated an indicated resource of 45 000 t of kaolin in the Goomalling deposit, and stated that this amount will last for many years as the current rate of consumption is only 150 tpa.

Yerecoin

The Yerecoin kaolin prospect is located approximately 6 km northeast of Yerecoin, which is about 150 km north of Perth (Fig. 12). Chester Park Pty Ltd explored the area

Table 38. Lithology of a vertical pit face in the Goomalling deposit

Depth (m)	*Description*
0–0.91	Yellow sand
0.91–2.44	Hard cemented sandstone passing into friable soft sandstone at depth
2.44–3.66	Clay bed No. 1 (varies from 1.22 to 1.83 m in thickness)
3.66–4.12	Grit
4.12–5.03	Clay bed No. 2 (varies from 0.91 to 1.37 m in thickness)
5.03–5.49	Sand
5.49–5.79	Clay bed No. 3 (varies from 0.31 to 0.46 m in thickness)
5.79–6.25	Grit
6.25–6.71	Clay bed No. 4
Below 6.71	Sand with clay seams.

SOURCE: Matheson (1949)

Table 39. Chemical analysis of kaolin from the Goomalling deposit

Sample no.	*Clay bed No. 1[(a)]*	*GSWA 94499*
	Percentage	
Al_2O_3	33.4	20.63
SiO_2	53.3	69.31
TiO_2	0.52	0.27
Fe_2O_3	0.11	2.00
MnO	–	0.01
CaO	trace	<0.01
K_2O	0.02	0.17
MgO	trace	0.13
P_2O_5	–	0.02
Na_2O	0.63	0.06
LOI	12.22	7.78
Total	**100.20**	**100.38**

NOTE: (a) Lipple (1977)

Table 40. Particle-size fractionation results for a bulk sample from the Goomalling stockpile

Particle-size range	*%*
+75 µm	2
-75 µm + 53 µm	<1
-53 µm + 2 µm	22
-2 µm	75

SOURCE: Lipple (1977)

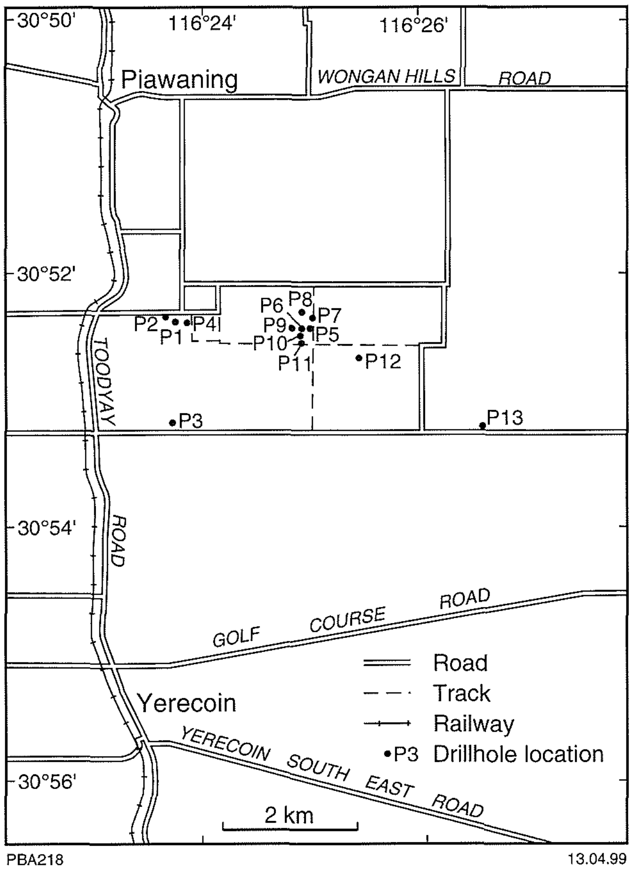


Figure 38. Drillhole location map for the Yerecoin kaolin prospect (after Thompson, 1990)

Table 41. Summary of drilling logs for Yerecoin

RAB hole	*Depth (m)*	*Comments*
P1	6	Only a thin intersection of kaolinitic clay (between 2–3 m)
P2	5	No kaolin
P3	7	About 3 m of kaolin below a hard silcrete layer
P4	4	No kaolin
P5	8	Creamy to light-pink to off-white kaolinitic clay present in most of the hole
P6	11	White kaolin with quartz from 4 to 9 m
P7	7	Kaolinitic clay from 3 m to bottom; more pinkish towards bottom
P8	9	From 4 to 7 m, kaolin and quartz, which turns to orange and pinkish clay after 7 m
P9	8	Kaolinitic clay from 3 to 7 m, turning orange at 8 m
P10	9	From 3 to 8 m, kaolin with no sample return at the last metre
P11	13	From 6 to 10 m, kaolin with pinkish clay after 10 m
P12	10	Kaolinitic clay from 3 to 9 m
P13	11	Kaolinitic clay from 3 to 10 m

SOURCE: Thompson (1990)

Table 42. Chemical analyses of kaolin samples from the Yerecoin area

Locality *Sample no.*	*Yerecoin (6 km north)* *P6*	*Yerecoin (6 km north)* *P10*	*Yerecoin (6 km north)* *P11*	*Yerecoin (7 km east)* *GSWA 94485[(a)]*	*Yerecoin (7 km east)* *GSWA 94486[(a)]*	*Yerecoin (7 km east)* *GSWA 94487[(a)]*	*Yerecoin (6 km north)* *GSWA 145117[(b)]*
				Percentage			
Al_2O_3	35.4	34.9	37.6	18.30	37.70	29.20	29.70
SiO_2	49.1	50.6	47.0	72.30	45.90	58.60	45.00
TiO_2	0.69	0.45	0.60	0.26	1.27	1.32	0.57
Fe_2O_3	0.51	0.02	0.39	0.27	0.22	0.70	0.81
MnO	0.01	<0.01	<0.01	<0.05	<0.05	<0.05	<0.01
CaO	0.02	0.03	0.01	<0.05	<0.05	<0.05	0.06
K_2O	1.77	1.95	0.86	2.13	1.30	0.45	0.44
MgO	0.18	0.17	0.15	<0.05	0.30	<0.05	0.77
P_2O_5	0.018	0.011	0.014	<0.05	<0.05	<0.05	<0.005
SO_3	–	–	–	–	–	–	0.63
S	–	–	–	0.03	0.04	0.03	–
Na_2O	–	–	–	0.40	0.79	0.20	4.20
LOI	–	–	–	6.35	13.60	10.90	18.59
Total	–	–	–	**100.04**	**101.12**	**101.40**	**100.77**

SOURCE: Thompson (1991)
NOTE: P6, P10 and P11 are partial analyses only (-38 μm fraction used)
(a) Analysed raw sample
(b) Analysed -10 μm fraction

in 1990 by drilling 13 vertical rotary airblast (RAB) holes (Fig. 38), totalling 108 m, with a maximum depth of 13 m (Thompson, 1990). Drilling was done to test for kaolin that had been encountered during the construction of dams, drainage channel excavations, and test pits. A summary of the drilling data is given in Table 41. None of these holes appear to have ended in granitic rocks, although quartz is commonly associated with the clay. In 1991, Chester Park Pty Ltd conducted a further program of drilling, which involved drilling 14 holes totalling 76 m. The deposit could possibly be of transported origin.

Quality

Particle-size fractionation studies of three samples collected from the drill cuttings of holes P6, P10, and P11 (by Chester Park Pty Ltd) indicated that the yield in the -38 µm fraction was 38.4–59.4% by weight. Another sample, GSWA 145117, collected from a location 6 km north of Yerecoin, yielded 52.1% less than 500 µm, 32.5% less than 106 µm, and 27% less than 45 µm. Chemical analyses (by Chester Park Pty Ltd) of the -38 µm fractions of three samples from drill cuttings in P6, P10, and P11 indicated average to good quality kaolinite, which approached paper coating and filler grades (Table 42). TiO_2, Fe_2O_3, and CaO values were within acceptable levels for paper coating and filler grades, and ceramic grades, but MgO and K_2O levels may be marginally high for paper grade.

Chemical analyses of three samples (GSWA 94485–87), collected from a location 7 km east of Yerecoin, and GSWA 145117 (mentioned earlier), are given in Table 42. Their compositions indicated that the samples varied from poor to high quality kaolin, with sample GSWA 94486 close to paper coating grade. However, other samples appeared to have Al_2O_3 contents that were too low for paper coating applications, but may be suitable for other uses such as for refractories and ceramics, provided that the material satisfies the physical characteristics required for such applications. XRD studies of these samples indicated dominant kaolinite, with variable proportions of quartz, mica, and feldspar (Table 43). SEM studies of these samples indicated coarse, subhexagonal, stacked platelets of kaolinite, with sample GSWA 94487 containing minor tubular halloysite.

Chester Park Pty Ltd has tested samples from the deposit at various laboratories (e. g. Australian Refractory Ceramics Pty Ltd, Commercial Minerals Ltd, and Bristile Ltd) and these results generally indicate good quality kaolin that may be suitable for a number of uses including paper coating, ceramics, and use as a rubber filler.

The above test results can only be taken as a guide to the quality of the clay in the Yerecoin area, and much more physical testing involving particle-size fractionation, viscosity, and brightness measurements would be necessary to evaluate the quality of the kaolin.

Resources

The second phase of drilling by Chester Park Pty Ltd has identified a resource of approximately 200 000 t of high-quality kaolin (Thomson, 1991). The kaolin extends over an area of 700 km^2, centred on Yerecoin, but for a meaningful evaluation of the prospect more exploratory work is required.

Minor occurrences

Cadoux

A small area, approximately 16 km south of Cadoux, has been investigated for kaolin (Figs 12 and 39). The area is generally covered with mixed sheetwash, colluvium, alluvium, and sandy deposits of Cainozoic age, but is likely to be underlain by Archaean granite, which is the dominant rock type present in the region.

During January–February 1997, Keyline Soil Conservation Services drilled 12 shallow boreholes, totalling 77 m, for Mr Duncan Avery, the owner of the property. Of these, four boreholes intersected kaolin at depths varying from 4 to 13 m, with thicknesses of kaolin ranging from 2 to 11 m.

Mineralogical analyses, ISO brightness, SEM studies, and the results of particle-size testing of five samples (GSWA 145139–43), collected from these boreholes, are summarized in Tables 44 and 45. The results indicated that kaolinite was the dominant mineral, with traces of quartz, mica, and halite. All five samples gave ISO brightness values over 80%, suggesting the possibility of a significant kaolin resource of homogeneous brightness that could meet the specifications for paper filler and possibly coating grades. The brightness values could possibly be improved by further processing of the kaolin material. The SEM studies indicated the presence of coarse, hexagonal

Table 43. Mineralogy and ISO brightness of kaolin samples from the Yerecoin area

GSWA no.	*Kaolinite*	*Quartz*	*Mica*	*Microcline*	*Halite*	*Brightness*
			Percentage			
94485	20–40	45–55	<5	5–20	<5	73.4
94486	>60	<10	5–20	–	<5	77.1
94487	40–60	25–35	<5	–	–	69.7
145117[(a)]	>50	<2	<2	–	<5	78.07

NOTE: (a) -10 µm fraction analysed

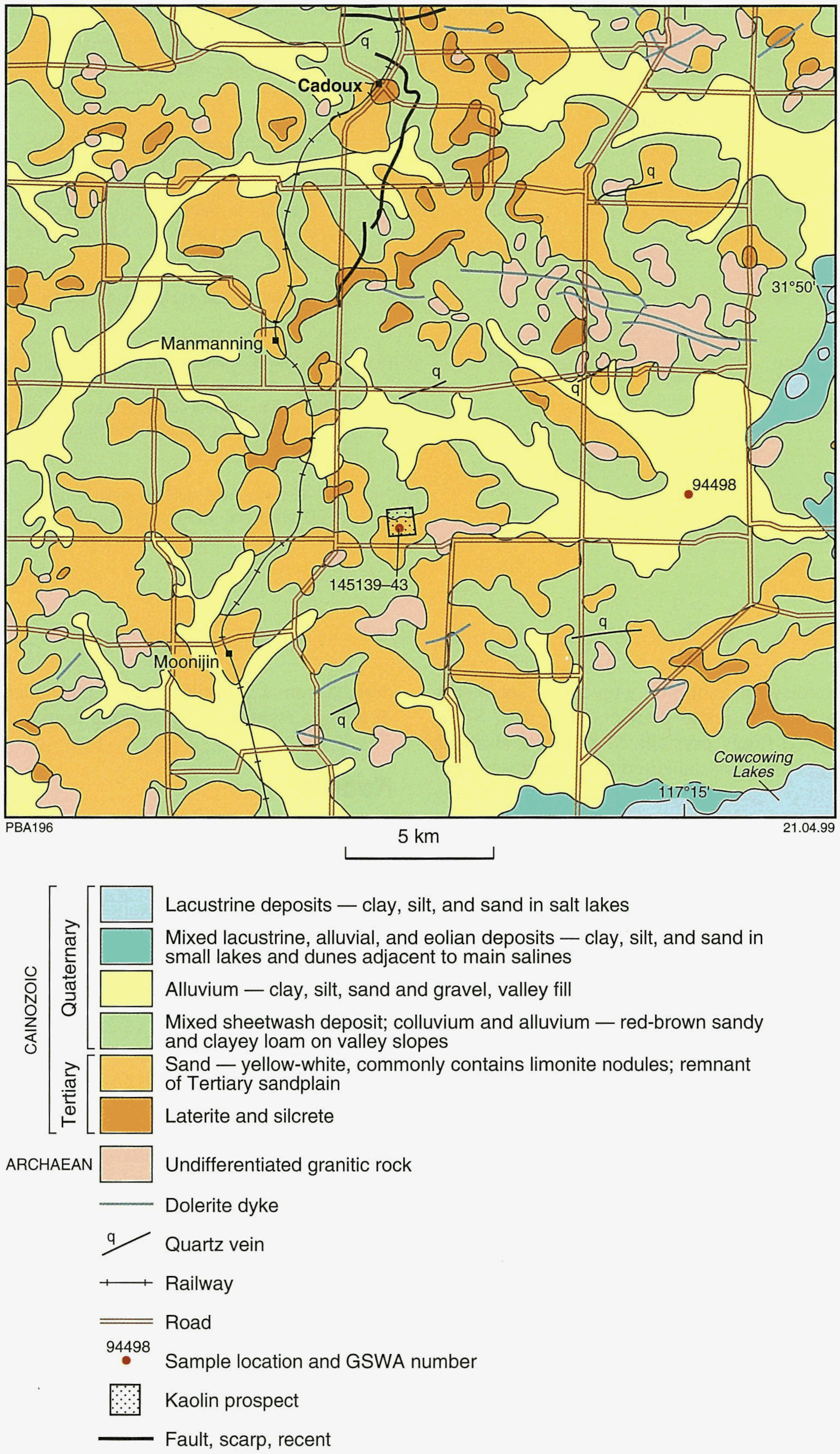


Figure 39. Regional geology around the Cadoux kaolin prospect (modified from Blight et al., 1983)

Table 44. Mineralogy, brightness, and crystallinity of kaolin samples from boreholes at the Cadoux prospect

GSWA no.	*Kaolinite*	*Quartz*	*Mica*	*Halite*	*Brightness*	*Crystallinity (using SEM)*	*Borehole no.*
		Percentage					
145139	>50	–	<2	<5	81.81	Hexagonal kaolinite platelets and flakes of ragged kaolinite (Fig. 40)	1
145140	>50	–	<2	<2	80.53	Medium- to coarse-grained, subhexagonal to hexagonal kaolin platelets and traces of tubular ?halloysite	5
145141	>50	<2	2–10	<2	80.64	Coarse-grained, subhexagonal kaolin platelets	6
145142	>50	<2	<2	<2	80.18	Finely crystallized kaolinite showing 'pseudocleavage', probably inherited from the original feldspar. Also secondary overgrowth of hexagonal kaolinite platelets (Fig. 41)	10
145143	>50	<2	<2	<2	81.71	Coarse-grained, subhexagonal kaolin platelets and traces of tubular ?halloysite	Composite

NOTE: All tests on -10 μm fractions

and ragged platelets of kaolinite, with minor secondary overgrowth of subhexagonal platelets (Fig. 40). Some samples contained finely crystallized kaolinite showing 'pseudocleavage', probably inherited from replacement of the original feldspar grains (Fig. 41). Particle-size testing of the raw samples indicated that the -45 μm fractions varied from 42.3 to 54.8%.

The chemical composition of these samples (Table 46) indicated that Al_2O_3, SiO_2, TiO_2, Fe_2O_3, MgO, CaO, and K_2O were all within acceptable levels for paper coating grades and other commercial applications such as ceramics and refractories. However, other physical characteristics such as particle-size distribution and rheological properties would need to be evaluated.

Chemical analysis of another sample (GSWA 94498), collected from approximately 10 km east of the above locations (Fig. 39), is given in Table 46. The composition of this sample was typical of kaolinite, but contained less Al_2O_3 and more SiO_2 than the other samples because the analysis was performed on the raw kaolin. The presence of a high SiO_2 value suggests that the material has been derived from a granitic source, but is not conclusive proof of either a residual or transported origin.

Table 45. Particle-size fractionation results for kaolin samples from boreholes at the Cadoux prospect

GSWA no.	*<500 μm*	*<106 μm*	*<45 μm*	*H_2O*	*Borehole no.*
		Percentage			
145139	74.3	60.5	54.8	5.7	1
145140	74.6	56.5	48.8	10.4	5
145141	72.8	59.8	53.9	11.6	6
145142	74.3	51.7	42.3	1.7	10
145143	71.3	58.0	52.6	6.3	Composite

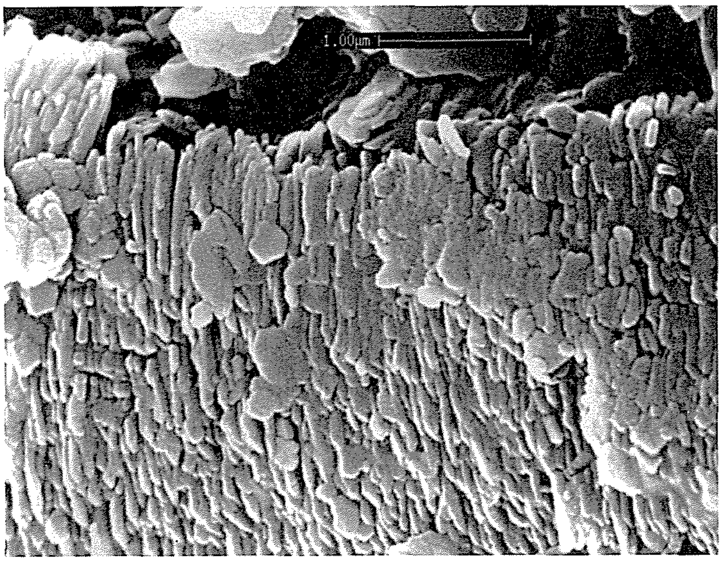
Koorda

In 1991, Reikon Mining Company drilled 17 RAB holes, totalling 160 m, at a prospect south of Lake Wallambin, approximately 25 km southeast of Koorda (Fig. 12; Koenig, 1992). The holes were drilled at latitude 31°01'25"S, longitude 117°35'00"E on the northern side of the Wallambin road. They intersected a clay bed, 1–9 m thick, at depths of 2 to 7 m from the surface. The clay bed varied in colour from white, creamy white, and off white to pale pink.

Chemical analyses of five samples (-20 μm fractions) collected by Koeing (1992) from five drillholes (Table 47) indicated average to good quality kaolin. However, the percentage of Al_2O_3 in all samples appeared to be marginally low for paper grade kaolin, although the TiO_2, Fe_2O_3, MgO, Na_2O, and CaO contents appeared to be within acceptable limits for such usage. The composition of the kaolin appeared to be suitable for some ceramic and other commercial applications. The ISO brightness of these samples ranged from 75 to 80% and could possibly be improved (by beneficiation) to acceptable levels for paper coating grades.

Noombenberry Rock

Three samples (GSWA 94488–90) were collected from a deeply weathered granite profile, 2 km northeast of Noombenberry Rock and approximately 25 km northeast of Muntadgin (Fig. 12). These were tested for mineral composition using XRD, morphology using SEM, and chemical composition using XRF (Tables 48 and 49).



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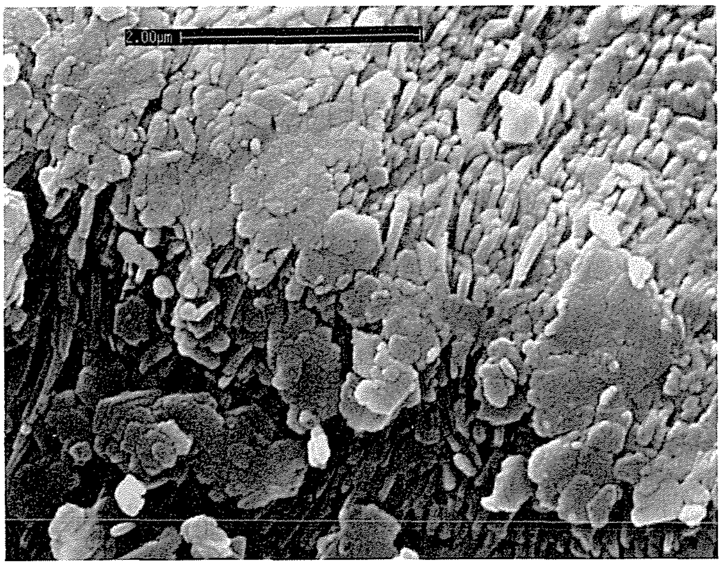

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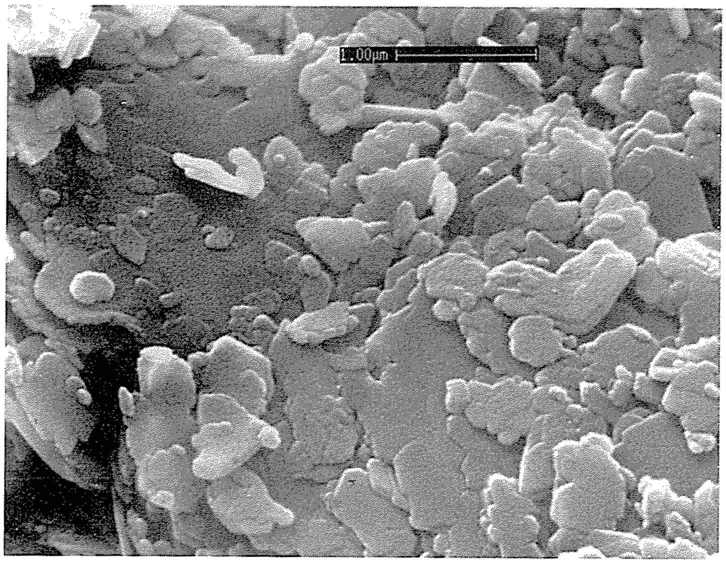
Figure 41. Scanning electron micrographs of sample GSWA 145142 from the Cadoux prospect
Top: Finely crystallized kaolinite showing pseudocleavage, probably inherited from replacement of the original feldspar
Lower: Secondary overgrowth of hexagonal kaolinite platelets in addition to pseudocleavage of the feldspar

ISO brightnesses, ranging from 70.8 to 78.7%, were measured on raw samples and could possibly be improved by separating the kaolinite from the other minerals such as quartz and mica. SEM studies indicated medium-grained kaolinite in sample GSWA 94489, with well-developed hexagonal stacked platelets (Fig. 42). Sample GSWA 94490 contained nearly equal amounts of tubular halloysite and kaolinite grains (Fig. 42), limiting its use to low-grade ceramic applications.

Chemical analyses of all three samples indicated higher SiO_2 values than is usual in typical kaolin, due to the presence of abundant quartz (25–45%) in the raw samples.

These test results can only be taken as a guide to the quality of the clay in the Noombenberry Rock area, and physical testing such as particle-size distribution, viscosity, and brightness would be necessary for further evaluation of the quality of the kaolin.



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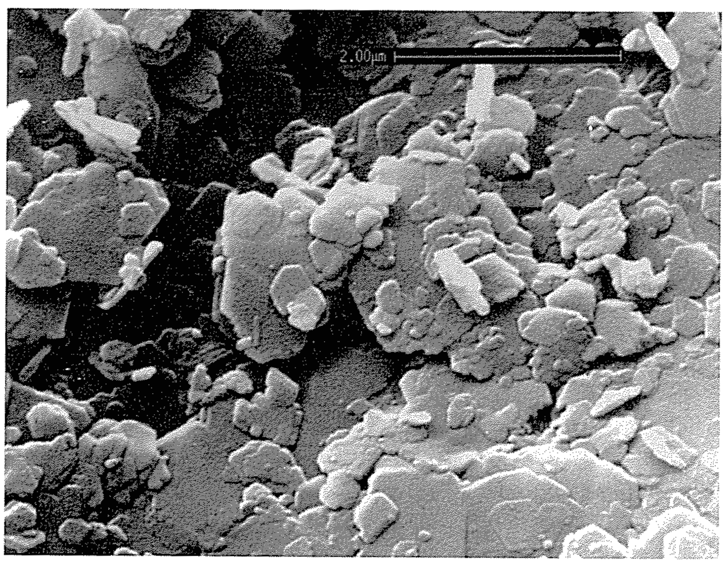

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Figure 40. Scanning electron micrographs of sample GSWA 145139 from the Cadoux prospect
Top: Hexagonal fine textured kaolinite, possibly resulting from secondary overgrowth of subhexagonal platelets
Middle: Hexagonal platelets of kaolinite probably indicating well-crystallized kaolinite
Lower: Coarse ragged flakes of kaolinite with minor secondary overgrowth of subhexagonal platelets

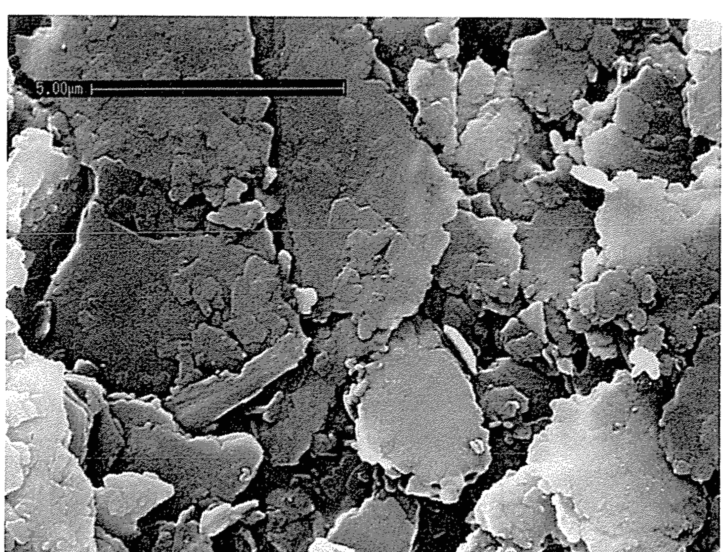

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Table 46. Chemical analyses of kaolin samples from the Cadoux prospect

Locality	*Cadoux (17 km southeast)*	*Cadoux (17 km southeast)*	*Cadoux (17 km southeast)*	*Cadoux (17 km southeast)*	*Cadoux (17 km southeast)*	*Cadoux (15 km south)*
GSWA no.	*145139*[(a)]	*145140*[(a)]	*145141*[(a)]	*145142*[(a)]	*145143*[(a)]	*94498*[(b)]
Borehole no.	*1*	*5*	*6*	*10*	*Composite*	*Grab sample*
			Percentage			
Al_2O_3	38.1	37.5	36.6	38.3	37.9	31.65
SiO_2	46.3	46.4	46.5	46.4	45.9	51.28
TiO_2	0.49	0.60	0.63	0.58	0.49	1.93
Fe_2O_3	1.05	1.13	1.27	1.02	1.05	0.85
MnO	<0.01	<0.01	<0.01	<0.01	<0.01	0.01
CaO	0.05	0.12	<0.01	0.01	0.04	0.02
K_2O	0.19	0.19	0.20	0.17	0.18	0.54
MgO	0.04	0.09	0.06	0.04	0.05	0.35
P_2O_5	<0.005	<0.005	0.012	<0.005	<0.005	0.02
SO_3	0.02	0.02	0.15	0.04	0.02	–
Na_2O	0.09	0.08	0.54	<0.05	0.07	0.50
LOI	14.20	14.24	14.46	14.18	14.13	13.37
Total	**100.53**	**100.37**	**100.42**	**100.74**	**99.83**	**100.52**

NOTE: (a) Chemical analyses on -10 µm fractions
(b) Chemical analysis of the raw sample

Table 47. Chemical analyses of kaolin samples from drillholes at Koorda

Drillhole no.	*2B2*	*B3*	*C2*	*C3*	*2C3*
Depth (m)	*4*	*3*	*5–6*	*8*	*9*
			Percentage		
Al_2O_3	35.90	35.50	33.60	37.40	32.70
SiO_2	49.20	49.70	51.80	48.00	53.20
TiO_2	0.50	0.50	1.30	0.40	0.60
Fe_2O_3	0.60	0.70	0.40	0.40	0.40
CaO	0.08	0.09	0.04	0.05	0.07
K_2O	0.50	0.50	0.05	0.40	0.50
MgO	0.08	0.06	0.04	0.04	0.06
Na_2O	0.07	0.10	0.07	0.05	0.09
LOI	13.10	12.80	12.60	13.30	12.40
Total	**100.03**	**99.95**	**99.90**	**100.04**	**100.02**

SOURCE: Koenig (1992)
NOTE: -20 µm fractions used for all analyses

Calingiri

Between Goomalling and Calingiri, granitic rocks and lateritic material with ferruginous pisoliths contain kaolin-rich horizons, which are exposed in a number of breakaways, farm dams, and outcrops (Fig. 43). The kaolin exposed at a breakaway located at latitude 31°09'10"S, longitude 116°37'55"E, on the eastern side of a gravel road, is white, rich in quartz and appears to have been derived from weathered granite. Kaolin associated with quartz, which is derived in situ from weathered granite, is present in farm dam diggings at latitude 31°06'55"S, longitude 116°31'30"E and latitude 31°07'40"S, longitude 116°29'40"E, both located on the northern side of the road. Quartz-rich kaolin, associated with laterite, is exposed at an excavation within a rubbish tip located at latitude 31°06'10"S, longitude 116°28'15"E. Samples GSWA 145113–16, collected from these

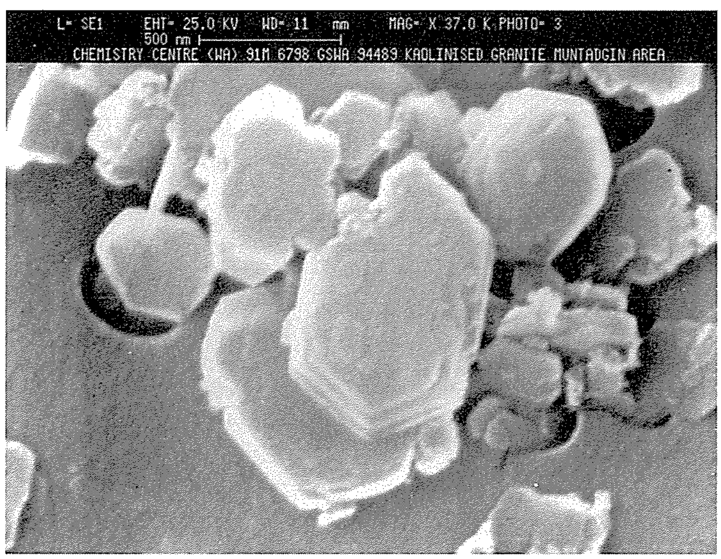
Table 48. Mineralogy, brightness, and crystallinity of kaolin samples from deeply weathered granite in the Noombenberry Rock area

GSWA no.	*Kaolinite*	*Quartz*	*Miica*	*Microcline*	*Halite*	*Brightness*[(a)]	*Crystallinity (using SEM)*
				Percentage			
94488	40–60	35–45	–	5–20	<5	77.7	Coarse-grained, subhexagonal platelets of kaolin
94489	>60	25–35	–	–	–	78.7	Medium-grained, subhexagonal to hexagonal platelets of kaolin
94490	40–60	35–45	<5	<5	<5	70.8	Medium- to coarse-grained, subhexagonal kaolin platelets and significant tubular halloysite

NOTE: (a) Brightness measured on the -0.25 mm size fraction after sieving to remove coarse- to medium-grained sand

Table 49. Chemical analyses of kaolin samples from the Noombenberry Rock area

GSWA no.	*94488*	*94489*	*94490*
		Percentage	
Al_2O_3	22.00	27.60	20.90
SiO_2	68.60	62.10	70.80
TiO_2	0.30	0.38	0.28
Fe_2O_3	0.22	0.32	0.49
MnO	<0.05	<0.05	<0.05
CaO	<0.05	<0.05	<0.05
K_2O	2.96	0.09	0.63
MgO	<0.05	<0.05	<0.05
P_2O_5	<0.05	<0.05	<0.05
S	0.02	0.02	0.03
Na_2O	0.28	0.20	0.23
LOI	7.21	10.60	8.00
Total	**101.59**	**101.31**	**101.36**



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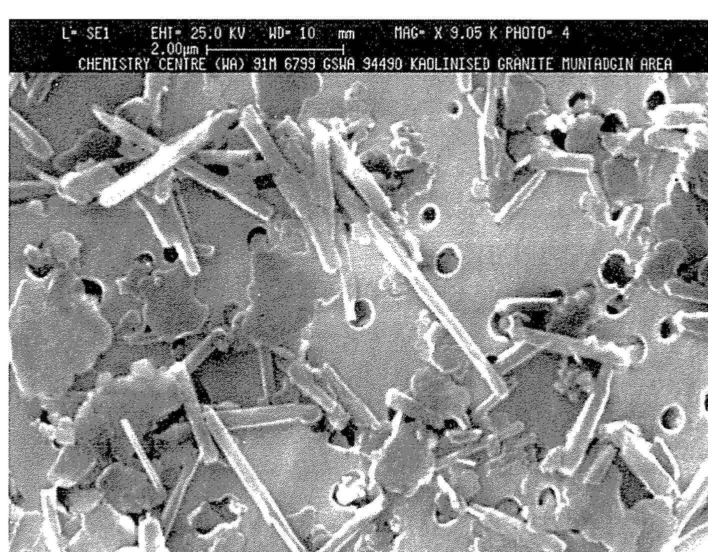

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Figure 42. Scanning electron micrographs of kaolin from Noombenberry Rock Top: Sample GSWA 94489 showing hexagonal kaolinite platelets probably indicating well-crystallized kaolin Lower: Sample GSWA 94490 showing tubular halloysite with kaolinite

Table 50. Mineralogy, ISO brightness, and crystallinity of kaolin samples from the Calingiri area

GSWA no.	*Kaolinite*	*Quartz*	*Mica*	*Microcline*	*Halite*	*Brightness*	*Crystallinity (using SEM)*
				Percentage			
145113	>50	<2	–	–	<5	77.0	Medium- to coarse-grained, subhexagonal kaolinite platelets
145114	>50	2–10	<2	–	<5	74.5	Medium-grained, subhexagonal kaolin platelets
145115	>50	10–50	–	<2	<2	68.9	Medium-grained, subhexagonal kaolin platelets
145116	>50	<2	–	<2	<5	50.2	Coarse, subhexagonal thin platelets of kaolin

NOTE: All tests on -10 µm fractions

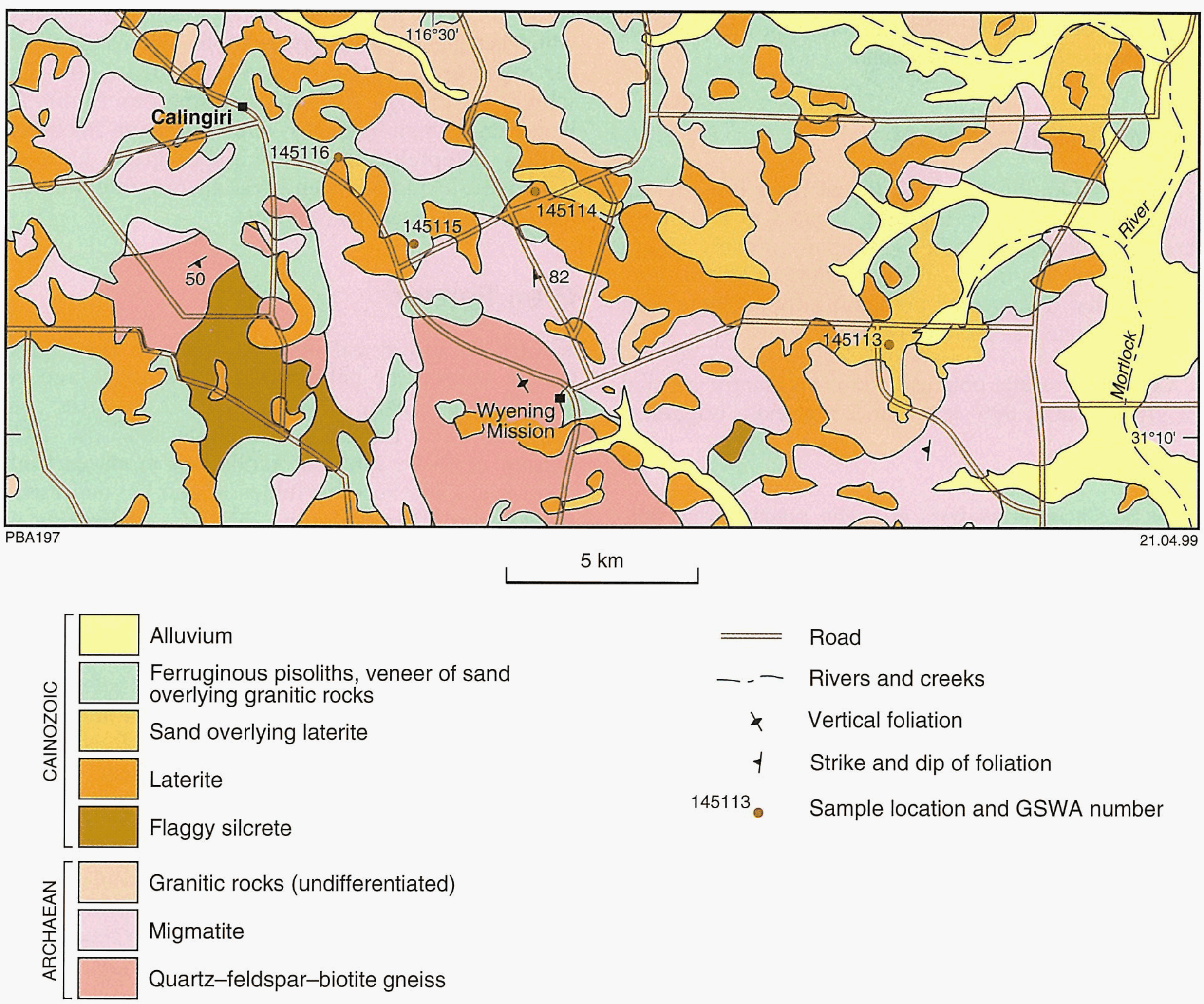

Figure 43. Regional geology east of the Calingiri area (modified from Low et al., 1978)

Table 51. Particle-size fractionation results for raw kaolin samples from the Calingiri area

GSWA no.	*<500 μm*	*<106 μm*	*<45 μm*	*H_2O*
		Percentage		
145113	52.9	33.0	27.4	17.8
145114	46.0	20.6	15.5	8.1
145115	40.9	14.5	11.2	15.2
145116	56.1	11.1	7.7	5.4

locations, showed dominant kaolinite when studied using XRD (Table 50). The ISO brightness of these samples ranged from 50 to 77% (Table 50), and was too low for high-grade applications. Particle-size fractionation tests on these samples showed that the -45 μm fraction varied from 7.7 to 27.4% (Table 51).

Chemical analyses of the -10 μm fractions (Table 52) showed typical kaolinite compositions, but the Al_2O_3 content was too low for paper coating grades. The Na_2O content in samples GSWA 145113 and 145116 appeared to be too high for many applications. However, the composition of the other samples suggested they would be suitable for ceramics, refractories, and other industrial uses, provided that the material satisfied the physical requirements for such applications.

Upper Yeriminup Pool

A sample of kaolin has been tested from Prospecting Licence P70/452 (now expired), located in the Upper Yeriminup Pool area (Fig. 12), approximately 50 km southwest of Kojonup (Wilke, 1984). XRD studies indicated that it contained predominantly kaolinite with accessory anatase and a trace of quartz.

Other test results obtained from this sample showed 1% grit (-53 μm), 89% less than 2 μm and a brightness (at 457 mμ) of 84.7%. Chemical analysis of one sample from the deposit gave 44.6% SiO_2 and 36.2% Al_2O_3, which is typical of a high-grade kaolin, but marginally low for paper grade kaolin. It also contained 2.39% TiO_2, which is too high for such applications (Table 53). However, its high brightness and high -2 μm fraction are within acceptable limits for paper grade kaolin. A systematic exploration and testing program would be required to evaluate this deposit.

Table 52. Chemical analyses of kaolin samples from the Calingiri area

GSWA no.	*145113*	*145114*	*145115*	*145116*
		Percentage		
Al_2O_3	24.80	28.00	30.50	33.40
SiO_2	39.60	56.70	49.20	42.10
TiO_2	0.27	1.59	1.76	1.42
Fe_2O_3	0.36	0.73	2.11	1.88
MnO	<0.01	<0.01	<0.01	<0.01
CaO	0.04	0.04	0.05	0.04
K_2O	0.21	0.07	0.08	0.15
MgO	1.77	0.19	0.43	0.44
P_2O_5	0.02	<0.005	0.01	0.01
SO_3	1.57	0.12	0.08	0.35
Na_2O	6.96	0.60	0.57	3.40
LOI	25.30	12.44	15.18	17.25
Total	**100.90**	**100.48**	**99.97**	**100.44**

NOTE: All analyses on -10 μm fractions

Table 53. Chemical analysis of a sample from the Upper Yeriminup Pool area

	Percentage
SiO_2	44.60
Al_2O_3	36.20
Fe_2O_3	1.47
CaO	0.02
MgO	0.15
Na_2O	0.12
K_2O	<0.01
TiO_2	2.39
MnO	0.01
SO_3	<0.01
P_2O_5	0.01
BaO	0.02
SrO	0.01
H_2O	1.10
LOI	14.70
Total	**100.79**

SOURCE: Wilke (1984)

Glen Forrest

Kaolin occurs at various localities in the Darling Range, within the pallid zone of a laterite and clay weathering profile developed over granitic rocks (Archer, 1975; Lipple, 1977; Wilde and Low, 1978). During 1939–41, 2762 t of kaolin was produced from a deposit at Glen Forrest (Tables 11 and 12) and used as filler material. In addition, 236 046 t of fireclay was produced from a number of deposits in the Glen Forrest area (Tables 15 and 16).

A brief survey in the area around Glen Forrest, carried out by the authors in 1997, found that the area is now subject to significant urban development. There are some small pits with kaolin dumps on the southern side of Thomas Street (between Hardy and Craven Roads) but the area is covered by real estate development. It is now inevitable that competing landuses are likely to hinder the development of clay resources in this area.

White kaolinitic clay also occurs as alluvial clay in the Guildford Formation, and outcrops in flat-lying areas of the Darling Range south and north of Glen Forrest. Fireclay has been produced from a number of these localities, including Byford and Bedfordale (south of Glen Forrest) and Bullsbrook (north of Glen Forrest) (Table 15). The 'white clay' from these localities has been used in the

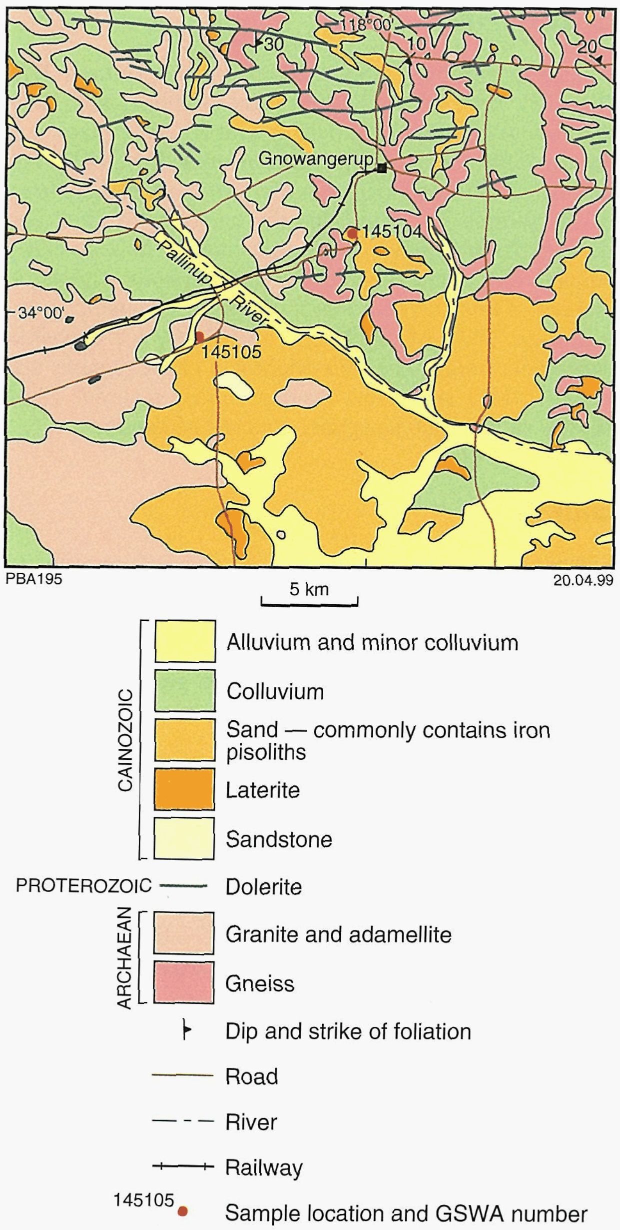

Figure 44. Regional geology around the Gnowangerup area (modified from Muhling et al., 1984 and Brakel et al., 1985)

brick, pipe, and tile industries as a colour controller. Ball clay has been produced from Jarrahdale, south of Byford (Table 13).

Gnowangerup

Thick weathering profiles containing kaolinitic clay are found in the area south-southwest of Gnowangerup (Fig. 44) and may be seen in numerous farm dam diggings. The region contains numerous reasonably high-grade deposits, a good example of which is Tambellup, located approximately 30 km west-southwest of Gnowangerup (Fig. 12). Many of these occurrences are residual kaolin derived from weathered granite, adamellite, and gneiss. Samples GSWA 145104–05, collected from southwest of Gnowangerup, showed kaolinite as their dominant mineral, with minor quartz and feldspar, when their -10 µm fractions were studied using XRD (Table 54).

Table 54. Mineralogy of kaolin samples from the Gnowangerup area

GSWA no.	*Kaolinite*	*Quartz*	*Mica*	*Halite*
			Percentage	
145104	Dominant (>50)	<2	2–10	<2
145105	Dominant (>50)	–	–	–

NOTE: All tests on -10 µm fractions

The ISO brightnesses of these samples were 82.1 and 64.6% respectively. SEM studies indicated that both samples contained coarse subhexagonal platelets of kaolinite. Particle-size testing of these samples gave yields of 55.9–60.4% in the -45 µm fraction (Table 55).

Table 55. Particle-size fractionation results on raw samples from the Gnowangerup area

GSWA no.	*<500 µm*	*<106 µm*	*<45 µm*	H_2O
			Percentage	
145104	74.6	59.4	55.9	10.3
145105	88.1	69.2	60.4	15.0

The chemical composition of these samples (Table 56) indicated that they both consisted of typical kaolin. Sample GSWA 145104 had a composition characteristic of paper coating grade kaolin with 38.1% Al_2O_3, 45.8%

Table 56. Chemical analyses of kaolin samples from the Gnowangerup area

GSWA. no.	*145104*	*145105*
	Percentage	
Al_2O_3	38.10	33.70
SiO_2	45.80	44.50
TiO_2	0.46	1.77
Fe_2O_3	0.58	1.40
MnO	<0.01	<0.01
CaO	0.01	0.07
K_2O	0.53	0.16
MgO	0.12	0.26
P_2O_5	<0.005	0.41
SO_3	0.12	0.27
Na_2O	0.53	1.24
LOI	14.45	15.78
Total	**100.70**	**99.56**

NOTE: All analyses on -10 µm fractions

SiO_2, and acceptable levels of TiO_2 and Fe_2O_3. The composition of sample GSWA 145105 was of lower grade, but appeared to be suitable for ceramic and other commercial applications, provided other physical specifications were satisfactory.

Boxwood Hill

Numerous road cuttings, approximately 8 km west of Boxwood Hill along the Borden Road (latitude 34°20'10"S, longitude 118°41'30"E), exhibit kaolin development within laterite (Fig. 45). Such kaolin appears to be widespread in the area and generally occurs as subhorizontal to horizontal horizons below laterite. Three samples (GSWA 145101–03) from the road cuttings were collected for testing (Fig. 46). All three samples were from well-exposed white, relatively hard, compact kaolin layers forming part of a laterite profile. Rocks associated with the laterite and kaolin horizons are dominantly yellow to grey siltstone, silty sandstone, and spongolite of the Upper Eocene Pallinup Siltstone. Granitic and gneissic rocks are also found adjacent to some of these kaolin occurrences, and it is possible that the kaolin has formed as transported deposits derived from these granites, but there is no firm evidence to confirm this view.

Samples GSWA 145101–03, collected from these locations, showed dominant kaolinite with minor quartz, feldspar, and halite when the -10 µm fractions were studied using XRD (Table 57). Particle-size fractionation results showed that 26.6–41.5% of the material was in the -45 µm fraction (Table 58).

The ISO brightness of these samples ranged from 57.7 to 62.8%, which is too low for paper grade material. SEM studies indicated that the material was platy, coarse grained and subhexagonal. Chemical analyses of the -10 µm fractions (Table 59) gave poor to average kaolin compositions, which suggested that they were unsuitable for paper grade material. They contained low Al_2O_3 and high SiO_2, as well as unacceptably high percentages of Na_2O, Fe_2O_3, and TiO_2. Further testing of the material would be required to check its suitability for other industrial applications.

Collie

Good quality clays have been produced from the Collie Coal Measures, particularly in the vicinity of Shotts (Lord, 1952). Simpson (1952) stated that clays from these coal measures could be used in the manufacture of a wide range of ceramic products. Two chemical analyses of this material indicated medium grade kaolin (Table 60). Lipple (1977) reported a brightness (at 467 mµ) of 82% for two samples in the Collie Coal Measures and particle-size fractionation tests on these samples showed yields of 24 and 17% for the -2 µm fraction. Kaolinitic clay, with some fine-grained quartz and illite, also occurs at the Premier coal mine, approximately 4 km east of Shotts. During 1994–97, 154 074 t of kaolinitic clay was produced as a byproduct from this mine and has been used in the cement industry.

Bakers Hill

A kaolin sample (GSWA 94456) from Bakers Hill (Fig. 12), near Coates Siding, showed greater than 60% kaolinite (with minor halloysite) with 25–35% quartz and less than 5% mica or illite when examined by XRD. The chemical composition (Table 60) and mineralogy of the sample suggested that the kaolin is residual and derived from granite or granitic gneiss. It is possibly suitable for ceramic or refractory applications. The Al_2O_3 content of this clay was low for paper grade applications, although TiO_2, MgO, Na_2O, and Fe_2O_3 were within acceptable limits. The ISO brightness of the sample was 71.0%, which is too low for paper grade material. SEM studies showed subhexagonal platelets of kaolin.

Balkuling

Simpson (1952) recorded the presence of completely kaolinized dykes, as well as kaolinized granite, at Location 11008 near Balkuling (Fig. 12). The clay which has been derived from the dykes burns to a good white colour up to 1350°C. The clay derived from the granite is said to be highly refractory.

Bruce Rock

Lipple (1977) reported test results on a kaolin sample (Govt Chem. Lab. No. 16159/73) from this location (Location 16289; Fig. 12) as having a brightness (at 457 mµ) of 81% and a size grading of 5% finer than 2 µm, 25% in the range 2–20 µm, and 70% coarser than 20 µm.

Corrigin

Clay has been obtained from pits in this area (Fig. 12) for the manufacture of bricks (Chin, 1986a). However, there has been no reported production to the Department of Minerals and Energy from this locality. Lipple (1977) reported a brightness (at 457 mµ) of 80% from a -2 µm sample (Govt Chem. Lab. No. 8150/72) from Corrigin, but the exact location was not given.

Cunderdin

Simpson (1952) recorded the occurrence of a highly refractory white clay at a location 14 km southeast of Cunderdin (Fig. 12). This clay burnt to a pure white colour at all temperatures up to 1350°C.

Dale River

Kaolin with 2% quartz and minor iron oxide staining occurs at this location (Fig. 12), 17.6 km southwest of Beverley (Lipple, 1977).

Darling Range

During 1996–97, CRA Exploration Pty Ltd carried out regional exploration for high-quality kaolin in localities

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Figure 45. Development of kaolin in road cuttings along the Boxwood Hill – Borden road
Top: Development of kaolin during lateritization (Lat. 34°20'10"S, Long. 118°41'30"E)
Lower: Development of kaolin during lateritization (Lat. 34°19'55"S, Long. 118°39'50"E)

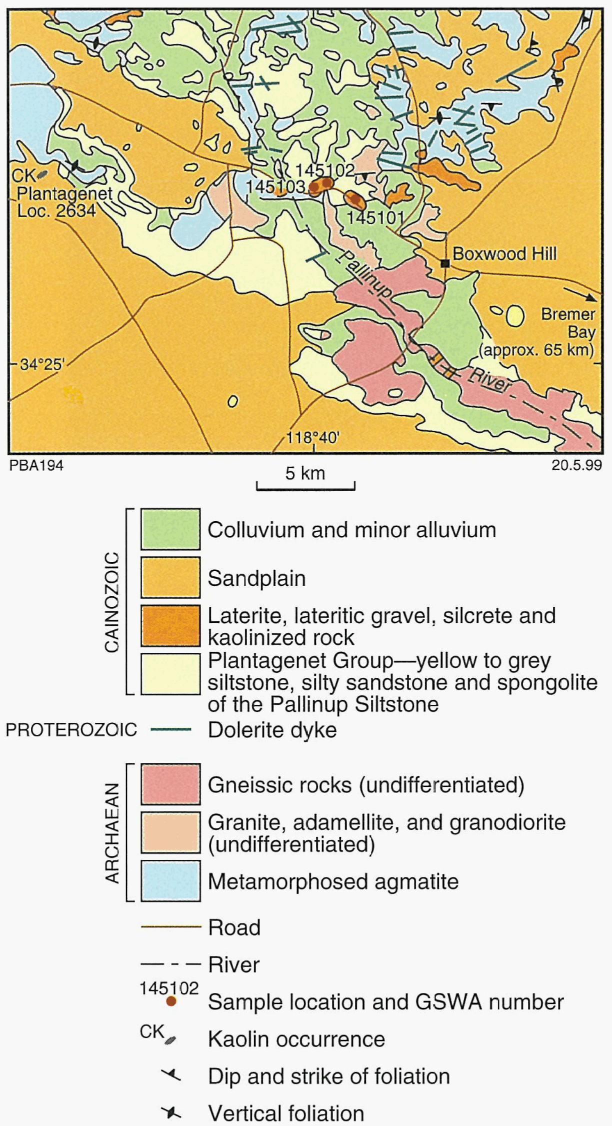

Figure 46. Regional geology around Boxwood Hill and the Pallinup River (modified from Thom and Chin, 1984)

around the Darling Range (Fig. 12), within Exploration Licences E70/1583–1585, E70/1589, and E70/1625. The localities explored were approximately 8 km east of Upper Swan, Smiths Mill Hill, Berry Brow Hill, approximately 5 km west of Gidgegannup Hill, and approximately 2 km northwest Nunamullen Lake. However, results of these investigations remain confidential.

Dowerin

Gritty clay, derived from granite and containing 57% kaolin, occurs at this location (Fig. 12), and is apparently suitable for use as ball clay (Chin, 1986b).

Gairdner South

Lipple (1977) reported that a kaolin sample (Govt Chem. Lab. No. 5793/72) from this location (Fig. 12) had a brightness (at 467 mμ) of 88% and size fractions of 35% less than 2 μm, 30% in the 2–20 μm range, and 35% greater than 20 μm.

Table 57. Mineralogy of kaolin samples from the Boxwood Hill area

GSWA no.	*Kaolinite*	*Quartz*	*Mica*	*Halite*
		Percentage		
145101	>50	<2	<2	<5
145102	>50	2–10	–	<5
145103	>50	2–10	<2	<2

NOTE: All tests on -10 μm fractions

Table 58. Particle-size fractionation results for kaolin samples from the Boxwood Hill area

GSWA no.	*<500 μm*	*<106 μm*	*<45 μm*	*H_2O*
		Percentage		
145101	77.7	45.0	26.6	15.1
145102	80.7	45.8	35.1	12.6
145103	59.3	47.7	41.5	19.9

Hillman

During 1996, CRA Exploration Pty Ltd conducted regional exploration for high-grade kaolin in the area around Hillman (Fig. 12), but the results remain confidential. During this program, CRA explored in a number of areas outside this region. Of these, the more important localities included Jacobs Well (latitude 32°02'S, longitude 117°13'E) approximately 150 km north of

Table 59. Chemical analyses of kaolin samples from the Boxwood Hill area

GSWA no.	*145101*	*145102*	*145103*
		Percentage	
Al_2O_3	28.30	27.70	19.90
SiO_2	48.10	49.30	48.20
TiO_2	1.22	3.15	1.06
Fe_2O_3	1.96	1.37	1.52
MnO	<0.01	0.02	<0.01
CaO	0.02	0.03	0.08
K_2O	0.67	0.29	0.73
MgO	0.97	0.47	1.38
P_2O_5	0.04	0.02	0.03
SO_3	0.83	0.45	1.11
Na_2O	2.38	2.71	6.73
LOI	16.64	15.31	19.56
Total	**101.13**	**100.82**	**100.30**

NOTE: All analyses on -10 μm fractions

Table 60. Chemical analyses of kaolin samples from minor occurrences in the South-West terranes, Yilgarn Craton

Locality	*Bakers Hill*	*Collie*	*Collie*	*Kalannie*	*Karlgarin*	*Kulja*	*Kweda*	*Kweda*	*Lake Magenta*	*Mount Mallet*	*Ongerup*	*Ongerup*	*Pingaring*	*Wagin*	*West Morawa Hill*	*West River (Location 3533)*
GSWA no.	*94456*[a]	*13*[c]	*14*[c]	*132214*[b]	*140391*[b]	*145124*[b]	*140384*[b]	*140385*[b]	*94460*[a]	*140393*[b]	*94473*[a]	*94474*[a]	*140397*[b]	*29*[b]	*94462*	*140400*[b]
								Percentage								
Al_2O_3	25.70	29.58	28.32	23.81	34.00	28.8	32.2	34.2	33.80	31.60	27.90	34.60	33.50	38.28	35.20	34.50
SiO_2	61.00	51.59	54.31	65.51	47.40	53.9	50.9	48.7	45.90	50.30	59.00	44.90	48.10	45.57	47.90	46.40
TiO_2	0.66	nd	0.56	0.08	0.33	0.61	0.83	0.84	0.37	0.27	0.30	1.25	0.53	0.30	0.52	0.82
Fe_2O_3	1.56	3.40	1.23	0.36	2.83	1.19	0.84	0.81	0.44	1.94	0.76	0.70	1.19	0.70	1.09	0.43
MnO	<0.05	tr	0.58	<0.01	<0.01	<0.01	<0.01	<0.01	<0.05	<0.01	<0.05	<0.05	<0.01	–	<0.05	<0.01
CaO	<0.05	tr	–	0.08	0.02	0.05	0.06	0.05	<0.05	0.16	<0.05	<0.05	0.07	–	0.12	<0.01
K_2O	0.22	0.63	0.39	0.07	0.25	0.11	0.28	0.32	0.12	0.50	0.25	0.22	0.27	0.91	1.99	0.27
MgO	<0.05	1.01	0.33	0.06	0.47	0.21	0.29	0.17	0.53	0.42	0.07	0.42	0.21	0.14	0.60	0.35
P_2O_5	<0.05	nd	nd	<0.01	<0.005	0.007	0.03	0.13	<0.05	0.10	<0.05	<0.05	0.04	0.14	<0.05	0.01
SO_3	0.05	nd	–	nd	0.09	0.65	0.22	0.07	0.23	0.10	0.05	0.20	0.21	0.01	nd	0.37
S	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.04	–
Na_2O	<0.05	1.09	0.11	0.33	0.40	0.38	0.96	0.33	2.84	0.28	0.59	1.70	0.78	0.20	0.19	1.51
LOI	11.10	[d]11.77	[d]12.51	9.51	14.55	12.98	13.81	13.94	16.40	14.31	9.53	16.20	15.00	[d]13.67	12.70	15.57
Total	**100.29**	**99.07**	**98.34**	**99.81**	**100.34**	**98.89**	**100.42**	**99.56**	**100.63**	**99.98**	**98.45**	**100.19**	**99.90**	**99.92**	**100.35**	**100.23**

NOTES:
(a) Raw sample was used for analysis
(b) -10 µm fractions were used
(c) Simpson, (1952)
(d) H_2O^+ and H_2O^-
nd not determined

Hillman and Spring Hill (latitude 31°43'S, longitude 116°39'E) approximately 175 km north of Hillman.

Jacup Creek

Approximately 35 km northeast of Jerramungup (Fig. 12), at Location 1609 (within MC 3942), Hawkstone Minerals Ltd carried out a drilling program and showed that kaolin is present to a depth of 12–18 m over a large area. The average yield of the -2 µm fraction was 11–16%, with brightnesses (at 457 mµ) of 85–86% (Lipple, 1977).

Kalannie

A kaolin sample (GSWA 132214) from this location (Fig 12) contained 64% kaolinite and 36% quartz when examined by XRD. The ISO brightness of the sample was 74.9% and could possibly be increased to greater than 80% if the quartz were removed before measurement. The chemical composition (Table 60) indicated that the material may be suitable for some ceramic applications. However, other physical tests, such as particle-size distribution and viscosity, would have to be carried out for a meaningful assessment of the material.

Karlgarin

A quartz-rich kaolin sample (GSWA 140391), collected from diggings around a farm dam at this location (Figs 12 and 29), contained kaolinite as the dominant (>50%) mineral with traces (<2%) of quartz and feldspar, and less than 5% halite, when the -10 µm fraction was examined by XRD. The sample had an ISO brightness of 78.8%, which would appear to be too low for paper grade applications. Particle-size distribution studies of the raw sample showed a relatively small proportion (25.5%) in the -45 µm fraction (Table 61). SEM studies identified the presence of subhexagonal, coarse to medium platelets of kaolinite. The chemical composition (Table 60) indicated that the kaolin had a moderately high Fe_2O_3 content (2.83%), rendering it unsuitable for high-grade uses such as paper and ceramics, but the material may be suitable for use in the brick, tile, clay pipe, or pottery industries.

Katanning

Clay deposits have been worked in quarries in this area (Fig. 12) for the manufacture of bricks (Chin and Brakel, 1986).

Table 61. Particle-size fractionation results for kaolin samples from minor occurrences in the South-West terranes

Locality	*GSWA no.*	*<500 µm*	*<106 µm*	*<45 µm*	*H_2O*
			Percentage		
Karlgarin	140391	50.9	29.9	25.5	9.8
Mount Mallet	140393	54.2	40.5	35.8	5.0
Pingaring	140397	63.7	40.5	34.2	6.8
Kulja	145124	50.5	18.9	12.7	5.0
West River	140400	77.7	57.3	51.7	18.6

Kellerberrin

Lipple (1977) reported the test results of a kaolin sample (Govt Chem. Lab. No. 7842/72) from this location (Fig. 12), which had a brightness (at 467 mµ) of 81% and contained 19% in the -2 µm fraction.

Kirup

Limited drilling programs, carried out during 1979–80 on MC 17109 and 17110 in the area around Kirup (Fig. 12), located kaolin of poor quality (Australis Mining NL, 1981).

Kulja

A quarry at this location (Fig. 12) exposes kaolin below a gravel layer of about 2 m thickness. The kaolin appears to have been derived from weathering in situ of a granite. A -10 µm fraction of sample GSWA 145124, when examined using XRD, showed dominant kaolinite and less than 10% quartz. The ISO brightness of the sample was 74.5%. Particle-size test results of this sample are given in Table 61. The chemical composition (Table 60) and mineralogy of the sample suggest that the kaolin has probably been derived from granite. The Al_2O_3 content is too low for high-grade uses such as paper coating and ceramics, but the kaolin may have an application in the brick, tile, clay pipe, or pottery industries.

Kweda

Two kaolin-rich samples (GSWA 140384–85), collected from farm dam diggings in the Kweda area (Figs 12 and 22), were found to contain a high proportion of quartz, feldspar, and mica, suggesting that the kaolin is residual in origin and has been derived from granite or granitic gneiss. XRD studies of the -10 µm fractions of these samples showed that kaolinite was the dominant mineral (>50%), with minor quartz (2–10%) and less than 2% mica present. The ISO brightnesses of these samples were 75.9 and 77.9%. Particle-size fractionation tests showed that the samples contained 25.1 and 24.6% in their -45 µm fractions, respectively. SEM studies showed that sample GSWA 140384 contained coarse, ragged flakes with secondary overgrowths of finer subhexagonal platelets of kaolinite (Fig. 47). The chemical analyses (Table 60) of these samples indicated typical kaolin compositions. A low Al_2O_3 content and low brightness values make the material unsuitable for paper grade applications. However, their chemical compositions appear to be acceptable for porcelain and earthenware applications.

Lake Magenta

Sample GSWA 94460, collected from Location 2293 north of Lake Magenta (Fig. 12), was found to contain greater than 60% kaolinite, less than 10% quartz, and less than 5% halite, when studied using XRD. This suggests that the kaolin formed in situ and was derived from granite

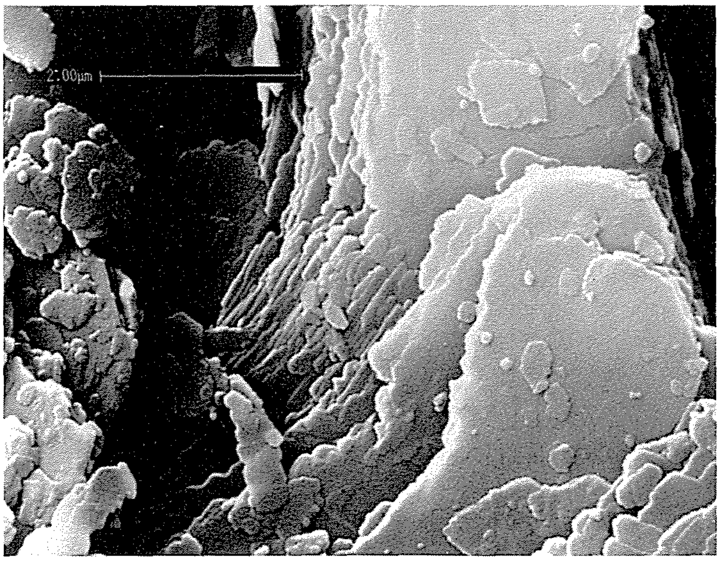

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Figure 47. Scanning electron micrograph of kaolin from Kweda, showing coarse ragged flakes with secondary overgrowth of finer subhexagonal platelets of kaolinite (sample GSWA 140384)

or granitic gneiss. Chemical analysis (Table 60) indicated that TiO_2, Fe_2O_3, CaO, and K_2O were within acceptable limits for paper coating grades, but Al_2O_3 was slightly low and Na_2O and MgO levels appeared to be high for such uses. The ISO brightness was 80% and was within specifications for some paper filler grades. SEM studies showed coarse platelets of kaolin.

Lomos

During 1994–97, CRA Exploration Pty Ltd carried out regional exploration in this area (Fig. 12) using aerial photographs, road traverses, and visual observations from aircraft to identify potential areas for kaolin. They also drilled two aircore drillholes (Williams, 1997b). One hole intersected moderately bright kaolin (ISO brightness 77–83%). However, tenure to the area (Exploration Licences E70/1441, 1444, and 1447) was subsequently relinquished.

Manjimup

Lipple (1977) reported two samples (Govt Chem. Lab. Nos 20352/73 and 20353/73) with brightnesses (at 467 mµ) of 85 and 86.5% from a location near Manjimup (Fig. 12).

Meckering

Simpson (1952) described the occurrence of a fine-grained refractory ball clay, possibly derived from a kaolinized dolerite dyke, at Location 22233, 14 km northeast of Meckering (Fig. 12). The clay burnt to a pure white colour at temperatures up to 1250°C, at which point incipient vitrification set in.

Mount Mallet

A quartz-rich kaolin sample (GSWA 140393), collected from this location (Figs 12 and 29), was found to contain kaolinite as the dominant (>50%) mineral, with traces (<2%) of quartz, feldspar, and halite, when the -10 µm fraction was studied using XRD. The sample had an ISO brightness of 77%, which would be too low for paper grade applications. SEM studies showed subhexagonal to hexagonal, coarse- to medium-grained platelets of kaolin with possible minor tubular halloysite. Particle-size fractionation studies of the raw sample showed a relatively small proportion (35.8%) in the -45 µm fraction (Table 61). The chemical composition (Table 60) indicated that it had a marginally low Al_2O_3 content for high-grade uses such as ceramics and paper, but would be suitable for use in the brick, tile, clay pipe, or pottery industries.

Narrogin

Clay was excavated from a deeply weathered lateritic zone overlying a large Proterozoic mafic dyke (Chin, 1986a) in this area (Fig. 12).

Newlands

Kaolin suitable for tile and stoneware manufacture has been reported in a railway cutting 1.5 km north of Newlands (Fig. 12). This has been documented by Woodward (1917), Simpson (1952), and Wilde and Walker (1982).

Ongerup

Two samples (GSWA 94473–74) were collected from pits located at Kent Location 1083, situated 25 km north-

northeast of Ongerup (Fig. 12). XRD studies of these samples showed greater than 60% kaolinite, with some associated halloysite, 10–30% quartz, less than 5% mica or illite, and less than 5% undifferentiated clay. Sample 94474 also contained less than 5% halite. This suggests that the kaolin is residual material derived from granite or granitic gneiss. Chemical analyses (Table 60) showed that the Al_2O_3 content of these clays was low for paper grade applications, although the TiO_2 and Fe_2O_3 were within acceptable limits for such applications. Na_2O and MgO were also high for paper grade kaolin. The ISO brightnesses of the two samples were 79.2 and 69.2%, and were too low for high-grade applications. SEM studies showed the presence of fine to coarse platy kaolin with some tubular halloysite.

Pallinup River

There has been some exploration for kaolin at Plantagenet Location 2634, close to the Pallinup River (Fig. 46), and also subsequent work involving drilling and laboratory testing (Lipple, 1977). At this location, clay overlies coarse sandstone and conglomerate, which in turn overlies granite containing dolerite dykes.

Piawaning

Kaolin occurs at a location 2 km southwest of Piawaning (Fig. 12), where it overlies weathered porphyritic granite. Recorded production was 406 t of kaolin in 1943 (Tables 11 and 12) when the kaolin was used as a filler. In 1985–89, 4294 t of fireclay was produced from M70/240 in this area (Tables 15 and 16).

Pingaring

A quartz-rich kaolin sample (GSWA 140397), collected from a small outcrop of kaolin near the railway line in this area (Figs 12 and 29), showed kaolinite as the dominant mineral with 2–10% quartz, less than 2% mica and less than 2% halite, when the -10 µm fraction was studied using XRD. The sample had a low ISO brightness of 67%, which is too low for high-grade applications. The chemical composition (Table 60) indicated that it was suitable for brick, tile, and clay pipe production, or for use in the pottery industry. Particle-size fractionation studies of a raw sample indicated a relatively small proportion (34.2%) in the -45 µm fraction (Table 61).

Quairading

Refractory clay, derived from deeply weathered granitic gneiss, outcrops at this location (Fig. 12; Chin, 1986a). Lipple (1977) reported six brightness (at 457 mµ) measurements, ranging from 80 to 89.5%. Particle-size fractionation tests of these samples showed 21.7% finer than 2 µm and 58% finer than 76 µm.

Roelands

Kaolin has been reported (Wilde and Walker, 1982) in a pallid zone of the weathering profile developed on gneissic rocks east of Roelands (Fig. 12).

Skeleton Rocks

The Skeleton Rocks kaolin occurrence is situated approximately 80 km southeast of Southern Cross and 80 km northeast of Hyden (Fig. 12). Most of the exploration in the area has been for gold by Aztec Mining Company Ltd on the expired Exploration Licence 77/465. Testing of lithological, structural, and geophysical targets returned subeconomic gold intersections. However, intervals of up to 15 m of kaolinitic clay were intersected during exploration drilling for gold.

A composite sample of kaolin from aircore spoils was tested to determine the amount of material less than 10 µm, the total silicate content of the -45 µm fraction and the fired brightness (at 457 mµ) (Stallman, 1996). The sample was found to be coarse grained with only 30% less than 10 µm. Total silicate analysis of the -45 µm fraction (degritted) showed a clay suitable for sanitary ware applications. The brightness (at 457 mµ) of the sample was 86%.

Wagin

Kaolin has formed beneath a thin capping of laterite at Location 3533, near Wagin (Fig. 12), and is associated with a weathered portion of a dolerite dyke within Archaean granite. Simpson (1952) stated that the clay burnt pure white at 1150°C. Chemical analysis of this kaolin gave 45.57% SiO_2 and 38.28% Al_2O_3 (Table 60).

Wandering South

Kaolin, with traces of feldspar, occurs at Location 28199 near Wandering South (Fig. 12). Lipple (1977) stated that a sample from this location had a brightness (at 457 mµ) of 84% and a particle-size fractionation test indicated 18% finer than 2 µm.

West Morawa Hill

A sample (GSWA 94462) from this location contained greater than 60% kaolinite, less than 10% quartz, and 5–20% mica/illite when studied using XRD. The ISO brightness of the sample was 63.8%, which was too low for high-grade applications such as paper coating. SEM studies showed coarse and partly hexagonal platelets of kaolinite. The chemical composition (Table 60) and mineralogy of the sample suggested that the kaolin had formed in situ from granite or granitic gneiss. The Al_2O_3 was slightly low and the MgO too high for paper coating grades, but the kaolin appeared to be suitable for ceramic applications.

West River

White fine-grained kaolin with significant quartz, which is associated with lateritic material, is exposed in a road cutting at West River (Fig. 12). A sample (GSWA 140400) of quartz-rich kaolin was found to contain greater than 50% kaolinite, 2–10% quartz, less than 2% mica, and less than 5% halite when the -10 µm fraction was studied using XRD. This sample had an ISO brightness of 82.2%, which is within specifications for some high-grade uses such as paper filler. SEM studies showed relatively medium to coarse, subhexagonal stacked platelets of kaolinite. The chemical composition (Table 60) indicated a relatively high-grade kaolin, but there was also relatively high Na_2O (1.51%). Particle-size fractionation studies of the raw sample showed 51.7% in the -45 µm fraction (Table 61).

Murchison terranes, Yilgarn Craton

The presence of extensive areas of granitoid and gneiss in the Murchison terranes suggests a strong potential for large kaolin deposits. Significant residual deposits are known at Gabbin, Mullewa, Mount Gibson, and Carlinga Well. However, in this area, kaolin deposits of transported origin are unknown. The distribution of known deposits in the Murchison terranes is shown in Figure 12.

Residual deposits

Gabbin

The Gabbin kaolin deposit (Figs 12 and 48) is located approximately 140 km northeast of Perth, in a valley 22.5 km north of Gabbin Siding. A farmer, Mr Whitsed, discovered the deposit in 1970 when drilling waterbores. In 1972, the Whitsed syndicate, along with a neighbouring farmer Mr Ottey, entered into a joint-venture agreement with Winjallock Resources Pty Ltd, and carried out fairly detailed exploration programs on a number of claims in the area. In 1976, Consolidated Goldfields Australia Ltd (CGFA) took up a 50% interest in the project with Western Titanium Ltd (WTL). West Australian Kaolin Company Pty Ltd (WAKCO) held the other 50% share. Soon afterwards, Renison Goldfields Consolidated Ltd (RGC) acquired a 50% share in the venture through CGFA. In 1990, Falcona Exploration and Mining NL secured an option over WAKCO's interest in the project, but financial problems left the company unable to exercise its option. The deposit is at present held by RGC (50%) and WAKCO (50%), but both companies have decided to sell the project (Industrial Minerals, 1995).

Geology

The main rock types in the Gabbin area consist primarily of Archaean granite, gneiss, and migmatite (Fig. 48). These rocks are mostly overlain by Tertiary sand, commonly containing limonite nodules, and Quaternary sheetwash deposits, colluvium, and alluvium. A porphyritic granite with prominent feldspar phenocrysts, considered to be the parent rock of the kaolin, is exposed just southeast of the Gabbin kaolin deposit. A typical cross section through the Gabbin kaolin deposit is shown in Figure 49.

The weathering profile in the Gabbin area is very deep, and contains thick kaolin horizons capped by mottled and/or laterite zones. The overburden depths vary from about 4.5 to 18 m, but are mostly within the range 9 to 13.5 m. Exploration drilling and testing of samples were carried out in a number of areas, with most of the work being concentrated on the Castlemain claim (Fig. 48). Other localities of significant exploration are the Watts, Ottey, and Whitsed claims.

Castlemain claim

In 1973, 19 holes were drilled on the Castlemain claim, with many of these holes intersecting appreciable amounts of kaolin (Fig. 50; Table 62). The average overburden depth was 12.5 m, consisting of mainly sandstone, sand, and lateritic material, with minor kaolin horizons.

The clay content, on a dry basis, ranged from 35 to 80% with an average of around 57%. The remaining 43% was grit. The moisture content of the clay in situ was around 16%.

The fractionation results are summarized in Table 63. Sodium hexametaphosphate (calgon) was used as the dispersant. Disaggregation was enhanced considerably by a rise in temperature of the deflocculated liquid system. Moisture content was determined on a separate sample in order that the data could be converted to an oven-dried (110°C) basis.

Since the yield of clay (-5 µm) for samples from drillholes 34 and 43 (Table 63) was much higher than samples from other drillholes that are typically derived from a granite–gneiss parent, the existence of two types of parent material was suggested. The first sample from drillhole 38 also had a high yield, possibly reflecting a different source from the rest of the samples.

All samples showed uniformly high brightness values (Table 64). The average brightness of the natural material was 79.7% measured at 350 mµ, 88.5% at 460 mµ, and 91.7% at 700 mµ. Because of the high brightness of the natural material, there was very little improvement obtained by bleaching the kaolin. Debney (1977) gave an average brightness (at 457 mµ) of 87.7%.

Natural and bleached clay fractions (-5µm) were tested for rheological properties in a Contraves viscometer. The results indicated that in terms of percent solids loading, samples from eight boreholes (34, 37, 38, 41, 43, 44, 44A, 44B; Fig. 64) produced excellent material that approached stringent coating grade standards, but samples from the remaining holes produced poorer results. Low-shear viscosity appeared to be unaffected by the level of salts present and little affected by variations in the percentage of -2 µm material in the coating clay. Testing of low-shear viscosity generally gave comparable values to other commercial coating clays (BHP Engineering Pty Ltd., 1991). Debney (1977) reported an average low-shear viscosity of 70.4% solids loading at a slurry viscosity of 500 centipoise measured at 100 rpm (Brookfield ECC test method).

The chemical compositions of two kaolin samples (GSWA 145118 and 145120), collected from the area around the Castlemain deposit, are given in Table 65.

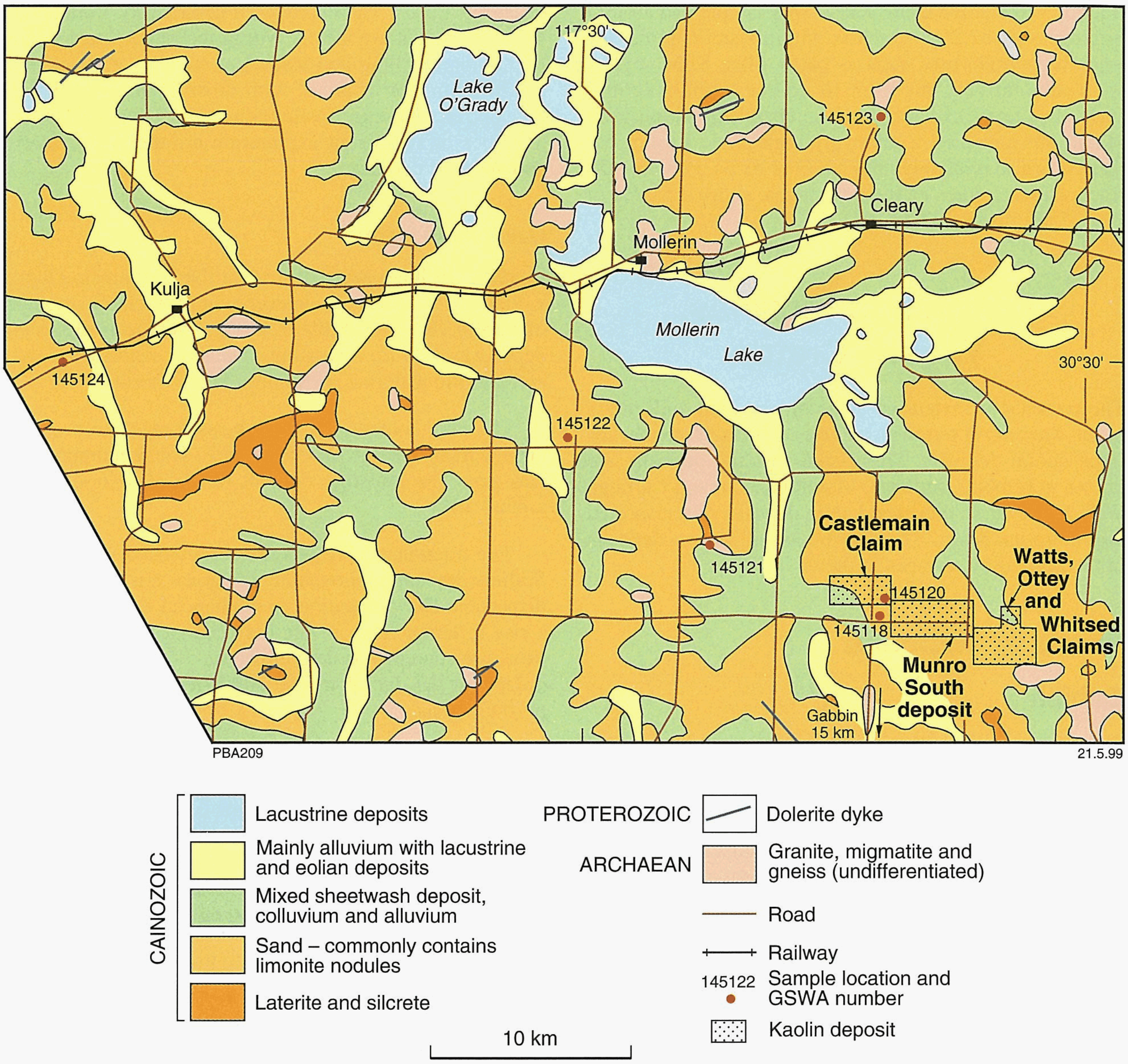


Figure 48. Regional geology around the Gabbin kaolin deposit (modified from Blight et al., 1983)

Sample GSWA 145118 was taken from a highly quartz-rich kaolin horizon overlain by lateritic material and exposed in a shallow excavation, whereas GSWA 145120 was taken from a stockpile of white kaolin ore, approximately 300 m east of the road. The composition of the sample from the kaolin stockpile indicated that it was of high grade and approached paper coating quality, with an ISO brightness of 84.1%. However, the Al_2O_3 content of 36.40% was marginal for a high-grade kaolin, but this sample may not have been representative of the ore from the Castlemain deposit. The other sample (GSWA 145118) had a composition typical of poorer quality kaolin and an ISO brightness of 78.2%. The -10 µm fractions of both these samples, when examined by XRD, were found to contain greater than 50% kaolinite, with traces (<2%) of quartz and mica. SEM studies of both samples showed subhexagonal, coarse, relatively thick platelets of kaolinite. Particle-size fractionation tests on the raw samples showed a low proportion of fines with 16.0 and 32.7% less than 45 µm (Table 66).

Watts, Ottey, and Whitsed claims

Three percussion holes and 20 reverse-circulation (RC) holes were drilled on the Watts, Ottey, and Whitsed claims during 1973. A line of percussion holes across the valley was drilled to gain a broader picture. Kaolin of variable quality was intersected at depths of 12–15 m, below a sandstone layer, and continued to a depth of around 30 m. Sampling of the drill chips was generally done at 3 m intervals. The follow-up drilling of 20 RC holes was carried out on a grid of approximately 400 m × 400 m, and each drilled metre was sampled.

Tests on 22 kaolin samples, collected from 14 holes, yielded an average of 16.7% for the 44–5 µm fraction and

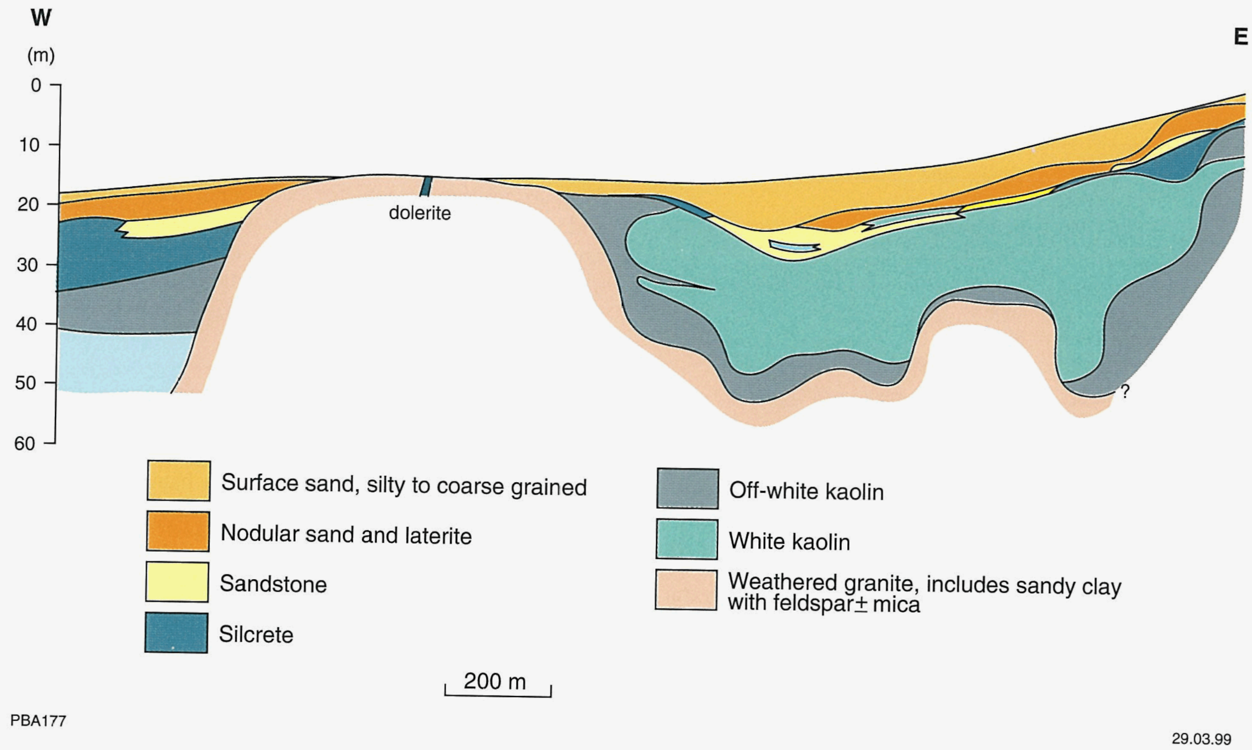


Figure 49. Typical section through the Gabbin kaolin deposit (after Lipple, 1977)

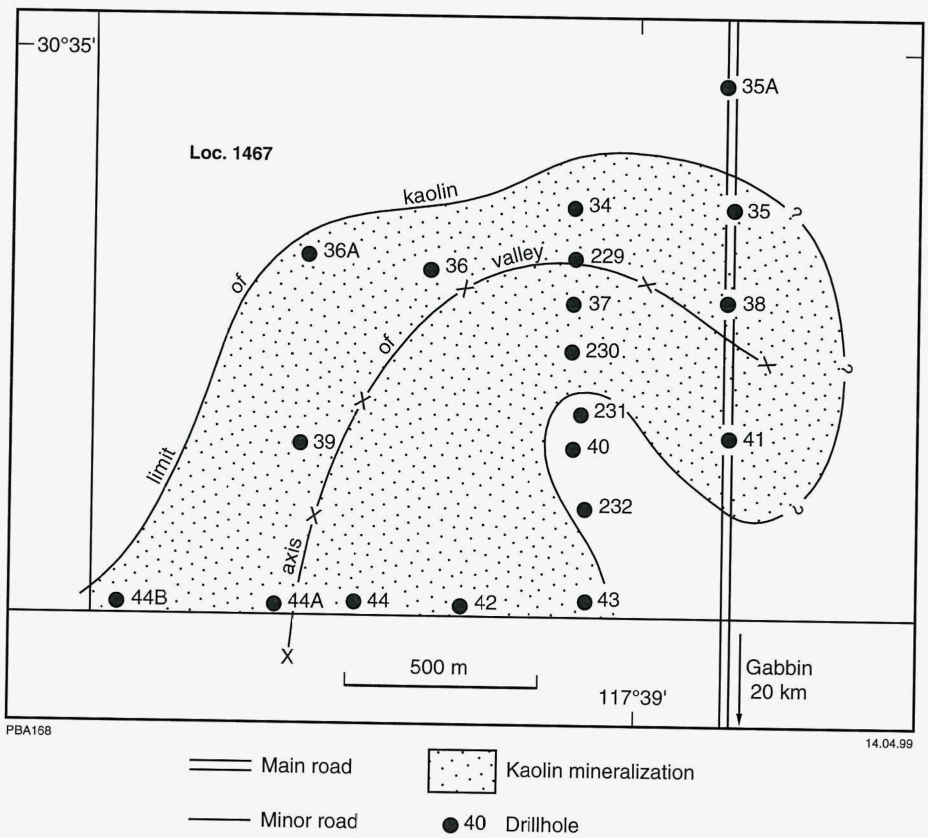


Figure 50. Map of drillhole locations on the Castlemain claim (after McCall, 1974)

Table 62. Summary of drillholes on the Castlemain claim

Drillhole no.	*Depth (m)*	*Lithology*
34	0–9	Yellow sand, gravel, sandstone, sandy clay
	9–14.6	Kaolin
	14.6–19.5	Buff kaolin, feldspar remnants weathering to brown clay
35	0–10.5	Yellow and brown sand, sandstone, minor kaolin
	10.5–14.0	Kaolin
	14.0–17.7	Yellow clay
35A	0–8.5	Yellow and brown sand, laterite
	8.5–10.4	Granite
36	0–6.7	Yellow and red sand, orange clay, minor kaolin
	6.7–28.7	Kaolin
36A	0–6.7	Brown and yellow sand, sandstone
	6.7–28.7	Kaolin
37	0–10.5	Clay, laterite, sandstone, sand, sandy clay
	10.5–11.6	Good kaolin
	11.6–12.5	Kaolin and brown clay
	12.5–15.8	Good kaolin
38	0–13.4	Yellow sand, laterite, sandstone
	13.4–19.5	Kaolin
39	0–12.2	Brown sand, sandstone, grey clay
	12.2–28.7	Kaolin
40	0–7.6	Yellow sand, sandstone (abandoned)
41	0–10.4	Yellow and red sand, sandstone, minor pink kaolin
	10.4–17.7	Kaolin, minor staining after 15.8 m
	17.7–19.5	Yellow kaolin
42	0–4.9	Pisolitic sand, ferruginous sandstone, soft brown clay
	4.9–6.7	Kaolin
	6.7–8.5	Alternating kaolin and brown clay
	8.5–14	Good kaolin with buff kaolin zones
43	0–6.7	Yellow and brown sand, sandstone, brown clay, minor kaolin
	6.7–11.9	Good kaolin with minor buff kaolin zone
	>11.9	Brown clay and kaolin
44	0–7.62	Red sand, grey clay, sandstone
	7.64–10.4	Kaolin
	10.4–12.2	Stained kaolin
	12.2–29.8	Kaolin
44A	0–7.9	Red sand, grey clay, sandstone
	7.9–34.1	Kaolin
44B	0–12.2	Red sand, sandstone
229	11–17.7	High-grade kaolin
	17.7–19.5	High-grade kaolin with minor feldspar
230	11.6–23.2	High-grade kaolin
231	10.4–17.7	High-grade kaolin
232	9.1–12.2	High-grade kaolin

SOURCE: McCall (1974)

35.3% for the -5 µm fraction. Further sizing tests indicated, in general, values of less than 35% for the -5 µm fraction. The results suggested that the clay yield was generally lower in the uppermost and some deeper horizons. The moisture content indicated by these tests also raised concerns on transport costs of the wet material, and appropriate methods for disaggregating the wet clay.

XRD studies indicated that the coarse fraction of the samples consisted of mainly subangular quartz of variable size, with some kaolinized feldspar closer to the surface. Mica, mainly sericite, was present in the finer of the three coarse fractions but was absent below 44 µm. XRD studies of the -5 µm fraction revealed that it was commonly free from impurities, except for occasional traces of feldspar and rare traces of mica. There was a wide variation in crystallinity of the kaolin samples, and also a slight degree of lattice disorder. However, studies showed excellent development of 001 and hkl crystal faces in 14 out of 22 samples.

The average brightness of the natural material from the RC drill chips was 73.9% measured at 350 mµ, 82.8% at 460 mµ, and 85.1% at 700 mµ. The bleached material showed a significant improvement in brightness with an average of 77.6% at 350 mµ, 87.5% at 460 mµ, and 89.2% at 700 mµ.

The average viscosity of 22 samples tested was 65% solids loading for natural clay and 65.6% solids loading for bleached clay. Of these, 14 of the better quality samples had an average of 67.4% solids loading for natural material and 68.4% solids for bleached clay. The best grade occurs in the middle horizons of the kaolin deposit. McCall (1974) considered that about two-thirds of all the kaolin in the prospect was of high quality and suitable for paper coating applications.

Resources

On the Castlemain claim, Debney (1977) estimated inferred resources of 27.6 Mt of material, containing 10.7 Mt of coating clay and 6.2 Mt of filler clay. Coating clay content was calculated on the basis of 61% kaolin in the resource, with the ratio of coating clay to filler clay estimated at 1.75:1.00. However, not all the resources could be beneficiated and only 55% of the in situ material was considered capable of yielding coating clay of satisfactory high-shear viscosity. On that basis, the recoverable resources were estimated as 5.9 Mt of coating clay and 3.4 Mt of filler clay (Debney, 1977). The above estimates were considered preliminary, with further drilling and testing of material for brightness and viscosity still being required.

On the Ottey and Whitsed claims, McCall (1974) estimated an inferred resource of 15.1 Mt of raw clay, containing 4.3 Mt of minus 5 µm clay material. The northern portion of the deposit contained kaolin with an average low-shear viscosity of 72.5% solids loading (Debney, 1977). McCall (1974) considered that large tonnages could be produced by selective mining, producing coating clay having a brightness greater than or equal to 88% (measured at 460 mµ) and 35% less than 5 µm. Debney (1977) stated that the potential for coating clay in these leases is around 3.5 Mt

Processing

The Gabbin clay contains about 43% grit, of which 80% is +0.25 mm (+60 mesh BSS) material. This fraction is

Table 63. Particle-size fractionation and moisture content for kaolin samples from the Castlemain claim

Drillhole no.	Depth (m)	Fraction +600 μm	600–150 μm	150–44 μm	44–5 μm	-5 μm	Total	Moisture
				Percentage				
30	12.2–14.0	29.7	21.9	14.4	8.1	25.9	100.0	8.5
34	9.1–10.4	14.9	2.8	6.5	8.8	64.4	97.4	16.4
36	17.7–19.5	33.6	6.3	2.9	25.0	30.1	97.9	18.1
	21.3–23.2	32.7	7.6	8.8	23.4	24.2	96.7	18.0
	25.0–26.8	35.1	7.6	6.6	23.1	24.5	96.9	24.2
	bulked	27.8	6.0	12.1	24.9	28.3	99.1	–
36A	17.7–19.5	16.9	13.8	28.2	18.4	21.0	98.3	17.3
	21.3–23.2	28.2	9.6	27.1	15.8	17.0	97.7	17.6
	25.0–26.8	32.1	9.0	8.4	26.5	23.8	99.8	22.4
	bulked	26.5	9.3	4.8	28.7	27.6	96.9	17.8
37	14.0–15.8	33.9	6.0	3.4	25.2	28.8	97.3	20.5
	19.5–21.3	35.8	6.6	5.2	21.7	28.8	98.1	19.0
	23.2–25.0	34.8	7.0	8.6	23.0	25.7	99.1	25.0
38	13.4–15.8	6.4	8.4	8.8	12.1	62.5	98.2	20.5
	15.8–17.7	37.4	16.9	16.2	9.9	19.5	99.9	15.9
	17.7–19.5	35.9	16.6	16.4	8.5	21.4	98.8	11.1
	19.5–21.3	41.8	22.7	12.7	8.6	12.5	98.3	10.1
39	15.8–17.7	34.4	7.1	7.2	26.5	23.2	98.4	25.7
	21.3–23.2	33.8	5.3	10.6	29.7	20.2	99.6	16.1
	25.0–26.8	27.0	6.3	9.3	29.8	25.1	97.5	22.6
	14.0–28.7 (bulk)	30.8	6.3	7.4	33.7	21.9	100.1	24.6
41	12.2–15.8	30.5	6.8	8.0	15.2	39.6	100.1	15.1
43	6.7– 8.5	22.5	8.6	9.3	10.3	48.1	98.8	22.2
44	15.8–17.7	35.7	5.9	13.1	22.1	21.2	98.0	25.7
	21.3–23.2	31.3	9.8	18.9	17.4	21.1	98.5	22.6
	26.8–28.7	35.0	13.8	14.7	15.6	20.3	99.4	19.7
	28.7–30.5	38.8	14.5	14.1	15.1	15.9	98.2	16.3
	14.0–29.9 (bulk)	34.8	8.7	12.7	21.6	19.4	97.2	21.3
44A	15.8–17.7	30.5	9.1	6.7	16.8	35.3	98.4	21.3
	19.5–21.3	32.5	5.3	6.9	21.8	30.4	96.9	28.0
	25.0–26.8	36.5	6.4	4.3	14.8	36.4	98.4	24.9
	30.5–32.3	42.7	5.4	4.7	21.7	25.3	99.8	22.2
	32.3–34.1	40.1	4.6	11.4	20.9	22.3	99.3	21.7
	15.8–34.1 (bulk)	38.3	5.4	6.2	19.0	31.3	100.2	25.0
44B	15.8–17.7	27.4	7.0	11.7	23.8	26.4	96.3	16.3
	17.7–19.5	30.7	9.9	13.4	19.1	24.6	97.7	20.9
	19.5–21.3	28.7	10.8	9.4	21.4	30.1	100.4	21.4
	21.3–23.2	38.4	13.5	10.4	18.0	19.0	99.3	21.7
	23.2–25.6	39.5	12.3	11.2	15.3	21.1	99.4	20.2

SOURCE: McCall (1974)

almost entirely made up of angular to subrounded quartz and less than 1% by weight of heavy minerals. The clay fraction of the Gabbin clay is 57%, on a dry basis, and consists predominantly of kaolinite, which ranges in size from large books to stacks of kaolinite (10 μm or more in diameter) to fine kaolinite (a fraction of a micron in diameter). Preliminary tests need to be carried out using wet and dry processes to identify the best processing option, but the following general comments can be made.

Since the kaolin as mined would have a moisture content of 16%, the most satisfactory method of beneficiating this material would be via the wet process. A critical factor would be the sourcing of large quantities of suitable water. Unfortunately, the groundwater in the area is likely to be too saline to be used in a processing plant. Transportation of the ore over large distances, to a readily available water supply, may be uneconomical as it involves the haulage of low-value material containing a large proportion of quartz as an impurity.

The main problem in using a dry process for the Gabbin clay is the presence of 16% moisture in the material as mined, which would make it difficult to efficiently separate the kaolin from the grit material. Therefore, an economically viable method of drying the ore to reduce the moisture content would need to be identified.

Table 64. Brightness measurements for samples from the Castlemain claim

Drillhole no.	*Depth (m)*	*Natural/bleached*	*Reflectivity at 350 mμ*	*460 mμ*	*700 mμ*
			Percentage		
30	12.19 – 14.02	natural	75.0	86.0	88.5
	12.19 – 14.02	bleached	75.0	87.0	89.5
34	9.14 – 10.36	natural	84.0	89.0	90.5
	9.14 – 10.36	bleached	84.0	90.0	91.5
36	17.68 – 19.51	natural	82.0	89.5	92.0
	17.68 – 19.51	bleached	82.5	90.0	92.5
	21.34 – 23.16	natural	82.5	90.0	92.5
	21.34 – 23.16	bleached	82.0	90.0	92.5
	24.99 – 26.82	natural	80.0	87.5	91.0
	24.99 – 26.82	bleached	82.5	90.0	92.0
36A	17.68 – 19.51	natural	80.5	89.0	92.5
	17.68 – 19.51	bleached	81.0	89.0	90.5
	21.34 – 23.16	natural	79.0	90.0	93.0
	21.34 – 23.16	bleached	78.0	90.5	92.5
	24.99 – 26.82	natural	79.0	90.0	92.5
	24.99 – 26.82	bleached	79.0	90.0	92.5
37	14.02 – 15.85	natural	75.0	88.0	92.0
	14.02 – 15.85	bleached	75.5	87.5	92.0
	19.51 – 21.34	natural	81.5	89.5	93.0
	19.51 – 21.34	bleached	82.5	89.0	91.5
	23.16 – 24.99	natural	80.0	88.5	92.5
	23.16 – 24.99	bleached	81.0	89.0	92.0
39	15.85 – 17.68	natural	78.0	87.5	92.0
	15.85 – 17.68	bleached	79.0	87.5	91.0
	21.34 – 23.16	natural	78.5	88.5	92.0
	21.34 – 23.16	bleached	80.0	89.0	91.5
	24.99 – 26.82	natural	78.0	88.0	92.0
	24.99 – 26.82	bleached	79.5	88.5	91.0
41	12.19 – 15.85	natural	81.0	88.5	92.0
	12.19 – 15.85	bleached	80.5	87.5	91.0
43	6.71 – 8.53	natural	80.5	88.5	91.5
	6.71 – 8.53	bleached	80.0	87.5	91.0
44	15.85 – 17.68	natural	78.0	89.0	93.0
	15.85 – 17.68	bleached	79.0	88.0	92.0
	21.34 – 23.16	natural	79.5	88.5	91.5
	21.34 – 23.16	bleached	78.0	87.5	91.0
	26.82 – 28.65	natural	76.0	86.5	90.5
	26.82 – 28.65	bleached	75.5	86.5	90.0
	28.65 – 30.48	natural	74.5	86.5	92.0
	28.65 – 30.48	bleached	76.0	86.5	91.5
44A	15.85 – 17.68	natural	81.5	88.5	91.5
	15.85 – 17.68	bleached	81.5	88.5	92.0
	19.51 – 21.34	natural	80.0	88.5	92.5
	19.51 – 21.34	bleached	80.0	88.5	92.0
	24.99 – 26.82	natural	82.5	88.5	91.5
	24.99 – 26.82	bleached	83.5	89.5	92.0
	30.48 – 32.31	natural	84.5	90.0	92.5
	30.48 – 32.31	bleached	85.0	90.0	92.5
	32.31 – 34.14	natural	81.5	88.5	91.5
	32.31 – 34.14	bleached	82.5	89.5	92.5
44B	15.85 – 17.68	natural	80.0	88.0	90.5
	15.85 – 17.68	bleached	82.0	90.0	92.0
	17.68 – 19.51	natural	76.5	86.5	90.5
	17.68 – 19.51	bleached	79.5	89.5	92.0
	19.51 – 21.34	natural	79.0	88.0	90.5
	19.51 – 21.34	bleached	79.5	89.0	91.5
	21.34 – 23.16	natural	80.5	89.5	91.5
	21.34 – 23.16	bleached	82.0	89.5	91.5
	23.16 – 25.60	natural	81.5	89.0	91.0
	23.16 – 25.60	bleached	81.0	89.5	91.5
Average		**natural**	**79.7**	**88.5**	**91.7**
		bleached	**80.3**	**88.9**	**91.7**

SOURCE: McCall (1974)

Table 65. Chemical analyses of kaolin samples around the Castlemain deposit, Gabbin

GSWA no.	*145118 Quartz-rich kaolin horizon*	*145120 Kaolin stockpile*
	Percentage	
Al_2O_3	28.90	36.40
SiO_2	56.50	48.90
TiO_2	0.28	0.47
Fe_2O_3	0.59	0.16
MnO	<0.01	<0.01
CaO	0.05	0.02
K_2O	0.02	0.43
MgO	0.07	0.05
P_2O_5	<0.005	<0.005
SO_3	0.26	0.06
Na_2O	0.34	0.29
LOI	13.06	13.78
Total	**100.07**	**100.56**

NOTE: All analyses on -10 µm fractions

Mullewa

In 1992, Auralia Resources NL explored an area immediately northeast of Mullewa townsite for kaolin (Fisher, 1994). Tenure of the deposits in the area subsequently changed to Sunray Nominees Ltd, who holds the ground at present.

Geology

A large kaolin resource straddles Wenmillia Creek, and immediately underlies 5–6 m of laterite and recent creek sediments. This is a basin-shaped zone that thins to the east (Fisher, 1995). Two promising kaolin deposits occur at Wenmillia Dam and Woolshed (Fig. 51). The Wenmillia Dam deposit is the larger and here the kaolin horizon extends to a depth of over 30 m, below 5–6 m of overburden (Fig. 52). Drilling indicated that the kaolin was derived as residual material from weathered granite (Kwiecien, 1991). There are also indications that kaolin occurs to the south, between Mining Lease M70/861 and the Mullewa – Mount Magnet road.

The bedrock, where exposed, is dominantly granite, gneiss, and migmatite (Fig. 51). Pegmatite, dolerite, and vein quartz occur locally. The granitic rock in the area is medium- to coarse-grained granite to granodiorite with scattered phenocrysts. These rocks contain few mafic minerals. For example, granitic outcrops at Wooderarung Gully, in the vicinity of Mullewa cemetery, are leucocratic, conspicuously creamy white, and contain only trace ferromagnesian minerals (Fig. 53). Laterite, containing massive pisolitic material rich in goethite, and quartz, generally overlie weathered granitic rocks (Muhling and Low, 1977). Laterite also outcrops on the edges of breakaways and sandplains.

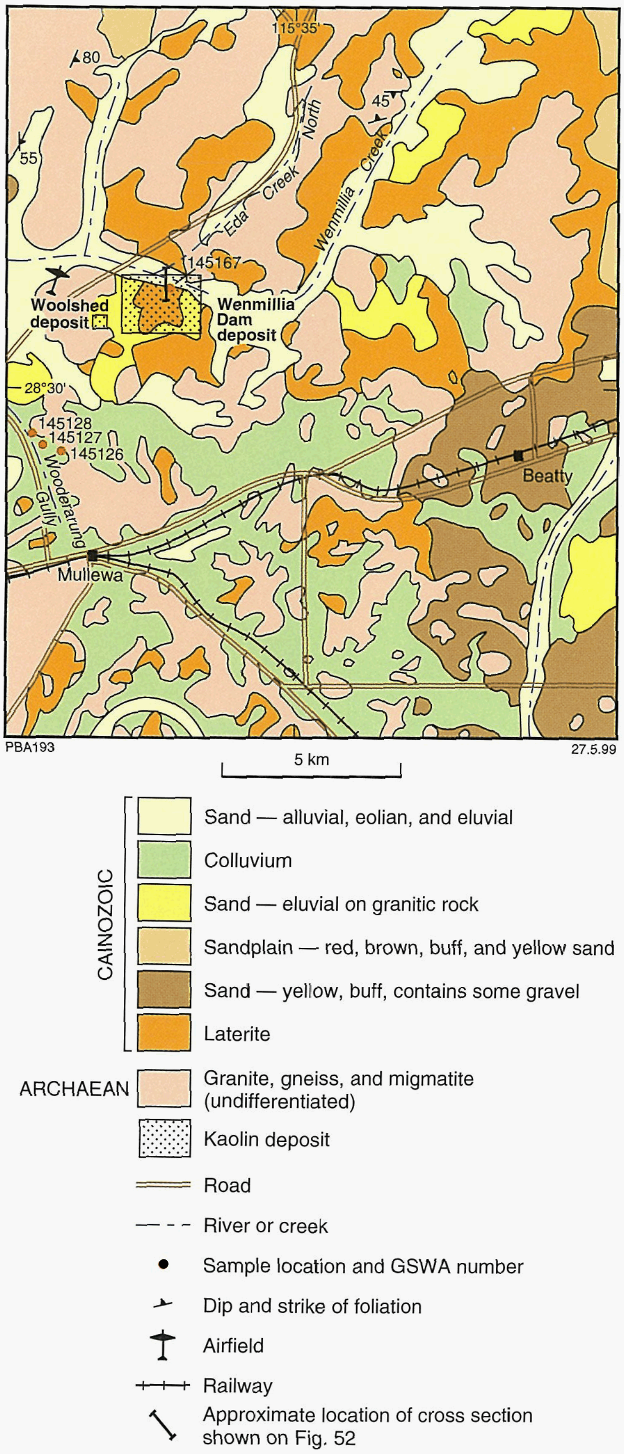


Figure 51. Regional geology around the Mullewa kaolin deposit (modified from Muhling et al., 1975)

Table 66. Particle-size fractionation results for kaolin samples around the Castlemain deposit, Gabbin

GSWA no.	*<500 µm*	*<106 µm*	*<45 µm*	H_2O
		Percentage		
145118	38.9	19.7	16.0	16.4
145120	57.3	39.6	32.7	15.6

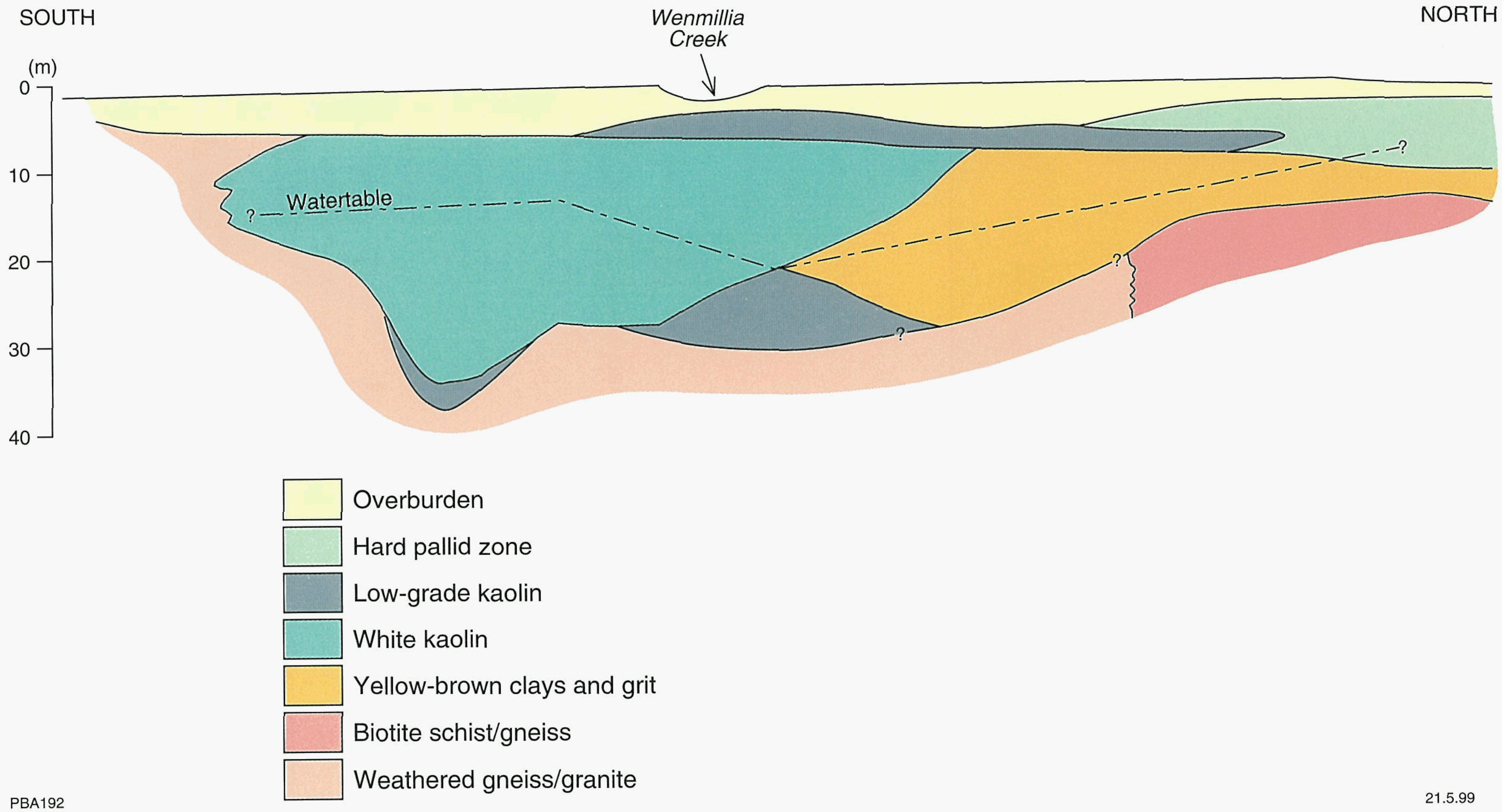


Figure 52. North–south cross section of the Wenmillia Dam kaolin deposit at Mullewa (after Kwiecien, 1991)

Figure 53. Weathered leucocratic, white, medium- to coarse-grained granite exposed at Wooderarung Gully, Mullewa (Lat. 28°31'12"S, Long. 115°30'30"E)

Quality

Test results for XRD, SEM, and ISO brightness of samples GSWA 94457–59, 145126–28, and 145166–68 are given in Table 67. Particle-size fractionation results for GSWA 145126–28 and 145166–68 are given in Table 68. Samples GSWA 94457–59 and 145167 were from the Wenmillia Dam kaolin deposit. Samples GSWA 145166 and 145168 were from drillhole M134 at Eda Creek North (exact location is unknown), and the other samples were taken from nearby weathered leucocratic granite outcrops along the Wooderarung Gully. All samples contained varying proportions of kaolinite, quartz, and feldspar, suggesting that the kaolin is residual material derived from granite. The XRD scans of the kaolinite basal reflections of most of these samples were very sharp, suggesting a high degree of crystallinity. Particle-size fractionation tests showed that drillhole samples (GSWA 145166–68) contained 42.5–78.6% in their -45 μm fractions, whereas outcrop samples (GSWA 145126–28) contained 33.4–46.3% in their -45 μm fractions. SEM studies showed coarse flakes of kaolinite, some of which were corroded (Fig. 54). The ISO brightnesses of two raw kaolin samples (GSWA 94457–58) were 67 and 84.5%, whereas the ISO brightness of the -10 μm fractions of the other samples ranged from 73.8 to 91.2%, suggesting the presence of kaolin of acceptable brightness for paper coating and filler grades.

Chemical analyses (Table 69) of the raw samples and the -10 μm fractions showed that they consisted of average to good quality kaolin. The higher SiO_2 content in the raw samples was due to the presence of appreciable quartz derived from weathered granite. The Al_2O_3 content of many of the samples appeared to be too low for paper grade kaolin, but samples GSWA 94442 and 145168 contained in excess of 37% Al_2O_3, indicating the possibility of suitable paper grade material. Furthermore, TiO_2 and Fe_2O_3 levels were generally within acceptable limits.

The yield of -2 μm material in samples GSWA 145126–28 ranged from 28.2 to 52.2%, and appeared to be low for paper coating clays. Therefore, further drilling and testing of samples is required. However, the material may be useful in relatively low-grade applications such as the brick, tile, clay pipe, or pottery industries, but this would also require further testing.

Resources

At the Wenmillia Dam deposit, the total measured and indicated resources of high-grade kaolin are estimated at 2.04 Mt, with an additional 0.52 Mt of lower grade kaolin (Minerals Gazette, 1991).

Carlinga Well

The Carlinga Well kaolin prospect is located 75 km north of Mullewa and 150 km east of Geraldton (Fig. 12). Mr B. I. Smith and Great Eastern Mines explored for kaolin in this locality during 1971–72, with exploration work aimed at locating kaolin suitable for paper coating (Lipple, 1977; Attwell, 1995). Although the area was

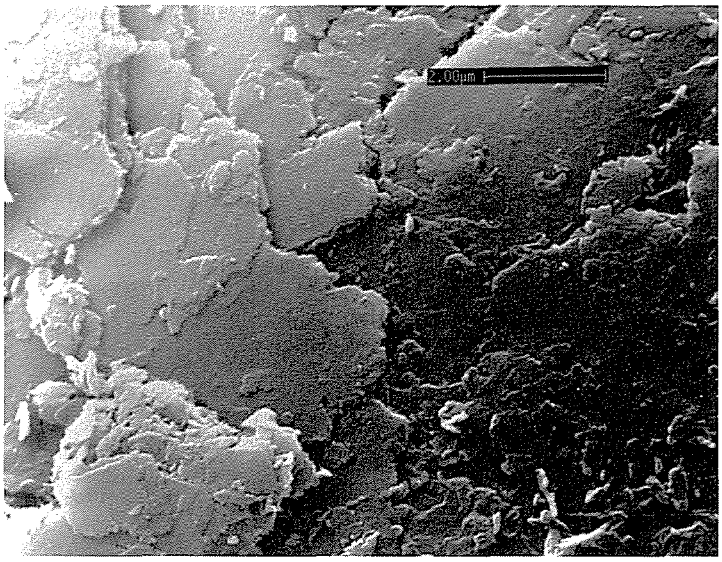
Table 67. Mineralogy, brightness, and crystallinity of kaolin samples from the Mullewa area

GSWA no.	*Kaolinite*	*Quartz*	*Mica*	*Microcline*	*Halite*	*Brightness*	*Crystallinity (under SEM)*	*Drillhole*	*Locality*
			Percentage						
94457[a]	>60	25–30	–	–	–	67.0	Coarse, subhexagonal to hexagonal, stacked platelets of kaolinite	M121 (18–21 m)	Wenmillia Dam deposit
94458[a]	>60	10–20	–	–	–	80.5	Medium, thin to thick, stacked platelets of kaolinite and tubular ?halloysite	M118 (12–15 m)	Wenmillia Dam deposit
94459[a]	>60	20–30	–	–	–	84.5	Medium, subhexagonal, stacked platelets of kaolin	M112 (12–15 m)	Wenmillia Dam deposit
145126	>50	<2	2–10	<2	<5	73.8	Medium to coarse, subhexagonal, thin platelets of kaolinite		Wooderarung Gully
145127	>50	<2	2–10	<2	<5	91.2	Contains coarse flakes and coarse, corroded flakes of kaolinite (Fig. 54)		Wooderarung Gully
145128[b]	>50	<2	2–10	<2	<5	74.4	Coarse, subhexagonal thin platelets of kaolinite		Wooderarung Gully
145166	>50	<2	10–50	–	–	83.2	Coarse, subhexagonal, thin and stacked kaolinite platelets	M134 (6–9 m)	Eda Creek North
145167	>50	<2	2–10	<2	<5	75.4	Coarse, subhexagonal, thin platelets of kaolinite	M115 (9–12 m)	Wenmillia Dam deposit
145168	>50	<2	2–10	<2	<2	82.3	Coarse, subhexagonal, thin platelets of kaolinite with traces of tubular ?halloysite	M134 (12–15 m)	Eda Creek North

NOTE: Samples GSWA 145126–28 and 145166–68 were tested using -10 µm fractions
(a) Testing of raw samples
(b) Significant smectite present

Table 68. Particle-size fractionation results for raw kaolin samples from the Mullewa area

GSWA no.	*<500 µm*	*<106 µm*	*<45 µm*	H_2O	*Drillhole*	*Locality*
		Percentage				
145126	93.5	59.7	46.3	14.3	–	Wooderarung Gully
145127	86.9	45.9	35.9	10.8	–	Wooderarung Gully
145128	79.5	44.9	33.4	14.2	–	Wooderarung Gully
145166	95.8	86.6	78.6	16.4	M134 (6–9 m)	Eda Creek North
145167	95.5	58.0	42.5	22.0	M115 (9–12 m)	Wenmillia Dam deposit
145168	81.2	61.0	50.6	11.8	M134 (12–15 m)	Eda Creek North



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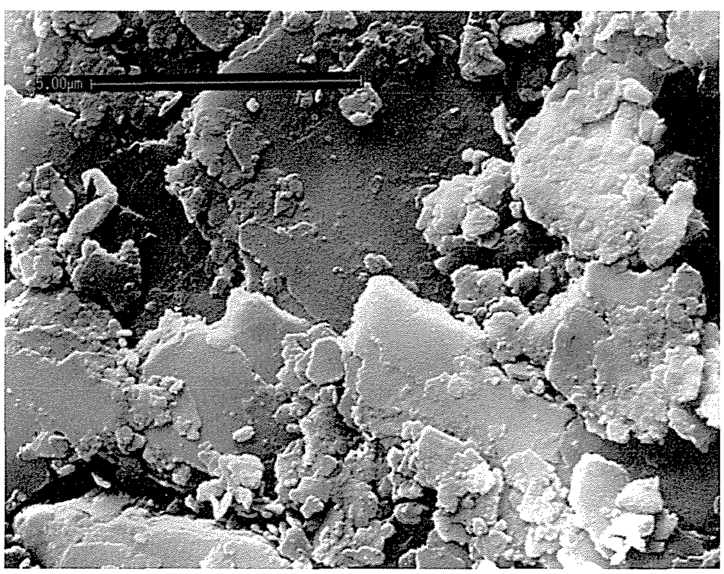

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Figure 54. Scanning electron micrographs of kaolin from Mullewa (sample GSWA 145127)
Top: Coarse flakes of kaolinite
Lower: Coarse corroded flakes of kaolinite

Table 69. Chemical analyses of kaolin samples from the Mullewa area

GSWA no.	*94442*[a]	*94457*[a]	*94458*[a]	*94459*[a]	*145126*[b]	*145127*[b]	*145128*[b]	*145166*[b]	*145167*[b]	*145168*[b]
						Percentage				
Al_2O_3	37.30	26.10	30.90	28.60	30.50	31.50	23.10	36.80	33.60	37.50
SiO_2	46.50	61.50	56.30	60.60	43.70	45.10	45.50	47.10	44.00	46.80
TiO_2	0.38	1.50	0.10	0.07	0.42	0.56	0.32	0.66	2.64	0.89
Fe_2O_3	0.14	0.56	0.38	0.15	1.09	1.04	1.78	0.58	1.98	0.51
MnO	<0.01	<0.05	<0.05	<0.05	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CaO	0.03	<0.05	<0.05	<0.05	0.12	0.07	4.56	0.05	0.07	0.04
K_2O	0.16	0.09	0.09	0.10	1.47	0.77	1.66	2.32	1.22	0.94
MgO	0.17	<0.05	<0.05	<0.05	2.07	1.10	3.61	0.51	0.35	0.10
P_2O_5	0.01	0.08	0.08	0.09	0.07	0.02	0.02	0.07	0.12	0.07
SO_3	–	–	–	–	0.44	0.34	0.14	<0.01	0.19	0.01
S	0.02	0.04	0.04	0.04	–	–	–	–	–	–
Na_2O	0.12	0.08	0.12	0.12	4.12	3.44	1.52	0.09	2.07	0.18
LOI	14.50	9.82	11.70	10.80	16.01	16.28	17.73	11.94	13.73	13.26
Total	**99.33**	**99.77**	**99.71**	**100.57**	**100.01**	**100.22**	**99.94**	**100.12**	**99.97**	**100.30**

NOTE: (a) Raw kaolin
(b) -10 μm fraction analysed

extensively drilled with more than 133 holes, very little drilling information is available. Subsequent work in the area included limited sampling by the Geological Survey of Western Australia (Lipple, 1977). In 1995, Sunray Nominees Pty Ltd drilled 46 aircore holes totalling 994 m.

Geology

The area forms a part of the narrow east–west striking Tallering greenstone belt, which is bordered by granitic batholiths. Over the project area, the weathered lateritic profile is variably developed, obscuring much of the original rock fabrics. Schistose rocks consisting of kaolin, sericite, and quartz (with variable proportions of chlorite and mica) have been identified in the area. These rocks are derived from felsic tuffs and clastic sedimentary rocks.

Drilling by Sunray Nominees has indicated the following suite of rocks in the area: sericitic schist, massive granitoid, foliated granitoid, undifferentiated sedimentary rocks, ultramafic rocks, mafic volcanic rocks, and quartz veins.

Kaolin of potential economic interest is apparently restricted to the upper pallid zone of the weathering profile, to a depth of around 20 m from the surface. The distribution of white and light-cream clays, based on drilling, is broadly indicated in Figure 55. The main area of interest forms a zone approximately 500 m wide and extending 1000 m to the north of Carlinga Well. This area coincides with the best area outlined by Great Eastern Mines.

Quartz–muscovite schists, derived from felsic tuffs and clastic sedimentary rocks, are deeply weathered, giving rise to thick kaolin horizons formed in situ. Schistose foliation is often preserved in the kaolin. The main white kaolin bodies occur beneath 3–5 m of colluvium consisting of soil, clay, and quartz, and a lateritic or ferruginous layer caps some kaolin horizons.

Quality

There is considerable variation in the quality of the clay within the Carlinga Well area, especially due to iron oxide staining, but possibly also due to the presence of fine-grained opaques and tourmaline.

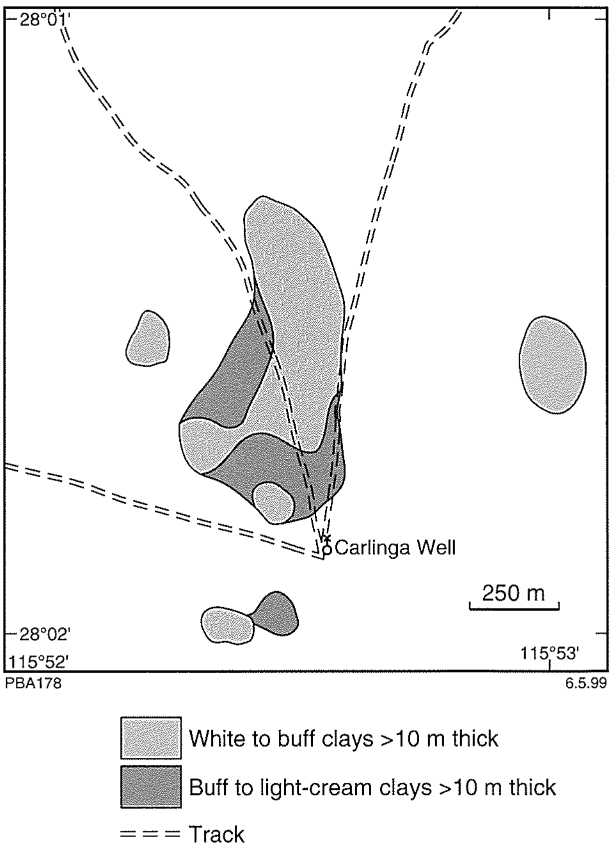

Figure 55. Distribution of clays in the Carlinga Well area, based on drilling (after Atwell, 1995)

Typical test results for clay from the Carlinga Well area (Attwell, 1995), obtained during investigations by Great Eastern Mines, are as follows:

- Brightness (at 570 mμ) of 61.3–93.1%
- Viscosity (solids loading) of 44.3–69.2%
- Fe_2O_3 of 0.29–0.51%
- Loss on ignition of 11.1–13.8%
- Crystallinity is moderate to poor
- Particle size (-2 μm) of 24–92%

Only 13 samples out of 133 tested returned viscosity measurements of greater than 65% solids loading, and most of these samples were from a depth of less than 12 m. This value is less than the desired minimum value of 70% for coating clay, but the brightness of some samples was within acceptable limits for paper coating uses.

Lipple (1977) reported results for three samples collected from Carlinga Well. These had a brightness (at 457 mμ) of less than 84% and a yield of less than 17% for the -2 μm fraction, both of which are outside the specifications for paper coating grade. However, these samples appear to have been collected further north of the main prospect and correspond to locations where Great Eastern Mines also recorded poor results.

Resources

Although Lipple (1976b) estimated an inferred resource of 130 Mt in this locality, his later publication does not quote any resource and suggests that the material has low commercial potential (Lipple, 1977).

Mount Gibson

This deposit is located 8 km northwest of Mount Gibson, 30 km east of the Great Northern Highway, and 70 km northeast of the township of Wubin (Figs 12 and 56). Kaolin was discovered in the area in the early 1990s by ES Minerals Pty Ltd and a syndicate comprising Nanne Sjerp, James Kenneth Williams, and Malcolm Anthony Carson. Exploration included photogeological interpretation of the kaolinized granite, drilling of four target areas (Table 70), and testing of drillhole samples for -2 μm fraction yield and brightness (Sjerp, 1992, 1993). The results were considered encouraging, and Australian Resources Pty Ltd now holds the area under tenement E59/615.

Geology

The kaolin deposits are located in fault-controlled portions of deeply weathered granitic intrusions. Kaolin occurs in

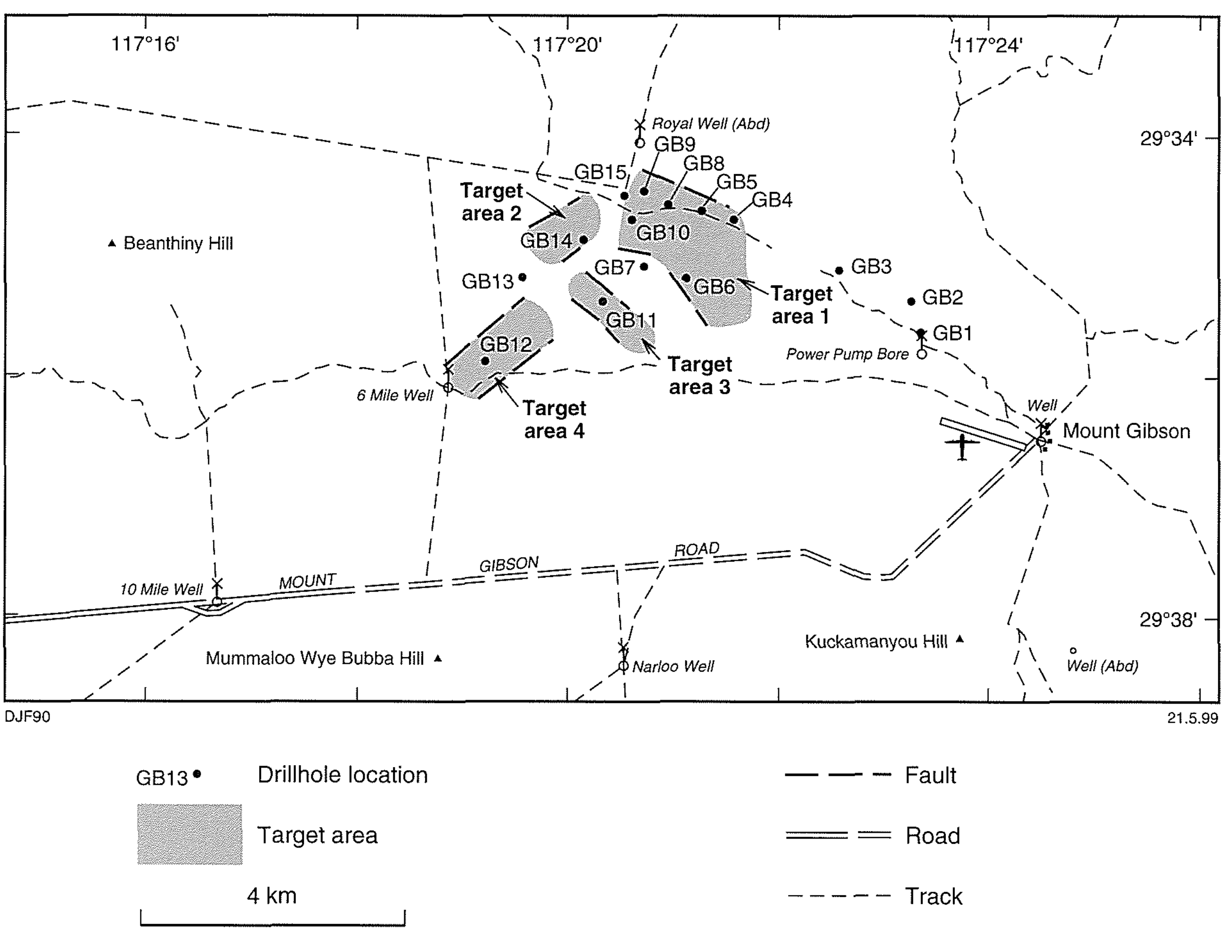

Figure 56. Drillhole locations and target areas 1–4 of the Mount Gibson kaolin deposit (modified from Sjerp, 1992, 1993)

Table 70. Drilling results from Mount Gibson

Target area	*Drillhole*	*Intersection (m)*	*Interval sampled (m)*	*Colour*	*Remarks*
1	GB 5	4–18	5–10	White	Terminated at 18 m in damp kaolin
			10–14	White	
			14–18	White	
1	GB 6	3.5–17.5	6–9	White	Some creamy intercalations
			9–12	White	
			13–15	Creamy	
1	GB 8	3–18	3–7	White	Terminated at 18 m in creamy kaolin
			7–10	White	
			10–13	White	
1	GB 9	7–20	7–11	White	Terminated at 20 m in damp kaolin. Creamy between 11–12 m
			12–16	White	
			16–20	White	
1	GB 10	5–18	6–11	White	Terminated at 18 m in white damp kaolin
			11–15	White	
			15–18	White	
2	GB 14	9–16	10–13	White	Terminated at 18 m in damp grey-pink kaolin
			13–16	White	
3	GB 11	7–19	7–11	White	Terminated at 21 m in damp creamy kaolin
			11–15	White	
			15–19	White	
4	GB 12	3–24	3–5	White	Terminated at 27 m in damp greyish-yellow kaolin
			5–9	White	
			9–14	White	
			14–19	White	
			19–24	White	

SOURCE: Sjerp (1992)

the top 25 m of the weathering profile and is covered by a 1–3 m layer of sand, pebbly laterite, and silcrete.

Quality

More than 20 composite aircore samples were metallurgically tested by ECC Pacific in their UK and Australian laboratories to obtain information on size distribution (including -2 µm yield), brightness, viscosity, mineralogy, and chemical composition.

The average yield of kaolin in the -5 µm fraction was rather low, ranging from 9.9 to 30.6%, with an average of 21.5% (Table 71). In such cases, the yield can often be improved by applying more energy into the kaolin dispersion, although one drawback would be the possibility of introducing additional colour. Another possible reason for the low yield value is that sample processing may have resulted in high losses of the -2 µm fraction.

The average -2 µm content of the -5 µm fraction was 68% (Table 71), which is rather low in comparison with values of around 90 required for paper coating clay. A sample (GSWA 145144) from a drillhole (hole number unknown) was found to contain 57.5% material less than 45 µm (Table 72). Since the -2 µm yield is an important component of many kaolin specifications, it is imperative that appropriate tests be selected to determine this value. Furthermore, the particle-size distribution of the product is partially dependent upon the processing method utilized, and therefore it may be possible to adjust the processing techniques to produce a final product of slightly better grade.

The average brightness of 86% is good and is within the specifications for normal paper coating clay.

Table 71. Test results for clay from Mount Gibson

Parameters	*Range*	*Average*
	Percentage	
Kaolin in -5 µm fraction	9.9–30.6	21.5
-2 µm content of -5 µm fraction	41–80	68
Brightness	77–90	86
Viscosity (solids loading)	57–72	68
XRD silica	traces –2	trace
XRF Fe_2O_3	0.18–1.80	0.78
TiO_2	0.11–0.88	0.78

NOTE: *after* Sjerp (1992)
-5 µm fraction tested

Table 72. Particle-size fractionation results for kaolin sample GSWA 145144 from Mount Gibson

<500 µm	*<106 µm*	*<45 µm*	*H_2O*
	Percentage		
95.9	71.1	57.5	8.2

Table 73. XRD analyses of drillhole samples from Mount Gibson

Borehole	*Depth (m)*	*Kaolin*	*Mica*	*Quartz*	*Feldspar*	*Montmorillonite*
				Percentage		
GB 5	5–10	90	3	trace	–	7
	10–14	93	4	trace	2	1
	14–18	81	6	1	6	6
GB 6	6–9	80	4	1	15	trace
	9–12	80	5	2	11	2
GB 8	3–7	97	2	1	–	–
	7–13	97	2	trace	1	–
GB 9	7–11	96	3	trace	–	1
	12–16	94	3	trace	2	1
	16–20	86	9	trace	1	4
GB 10	6–18	99	1	trace	–	–
GB 11	7–11	95	3	trace	–	2
	11–15	96	4	trace	–	–
	15–19	92	6	–	–	2
GB 12	3–19	99	trace	trace	–	trace
	19–24	97	3	trace	–	–
GB14	10–13	99	1	trace	–	–
	13–16	99	trace	–	–	1

NOTE: after Sjerp (1992)
-2 µm fractions tested

In order to measure the viscosity, the kaolin product was dispersed into a slurry using the standard ECC technique, and the percentage solids required to give a slurry viscosity of 500 centipoise was determined. The average solids-loading value obtained was 68%, although the desired loading of 70–73% could possibly be achieved by optimization of slurry conditions.

XRD studies indicated that the products were generally high in kaolin with minor amounts of mica, feldspar, and montmorillonite. Although mica can have an unfavourable effect on brightness, the values obtained suggest that there was no significant adverse effect in this case. XRD analyses of the -2 µm fractions of the samples showed 80–99% kaolinite, up to 9% mica (generally less than 5%), up to 2% quartz, up to 15% feldspar (generally 0–2%), and up to 7% montmorillonite (generally less than 2%) (Table 73).

The partial chemical analyses (using XRF) of the drillhole samples indicated that they are generally within acceptable limits for paper grade kaolin (Table 74). Table 75 shows an analysis of the -10 µm fraction of a sample of kaolin from a drillhole (hole number unknown) in the Mount Gibson deposit.

Further testing by ES Minerals of 24 composite samples gave brightness values up to 89.7%, viscosities up to 72.2% solids loading, and low quartz contents (i.e. low abrasion), suggesting the possibility of the presence of paper coating clay.

Resources

Within the area under investigation, kaolin occurs in four fault-bounded blocks. Based on RAB drilling and follow-up aircore RC drilling, Sjerp (1993) estimated an indicated resource of 30.5 Mt in target area 1, with an additional inferred resource of 27.3 Mt of crude kaolin in target areas 2–4 (Fig. 56). Kaolin also occurs to the southeast of target area 1, and in areas 12 km south of the resource, as indicated by consistent intersections in RAB holes.

Table 74. Partial chemical analyses of drillhole samples from Mount Gibson

Borehole	*Depth (m)*	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	K_2O
				Percentage		
GB 5	5–10	48	36	1.07	0.23	0.77
	10–14	47	38	0.71	0.16	1.09
	14–18	49	36	1.10	0.29	1.17
GB 6	6–9	50	34	1.59	0.16	2.66
	9–12	52	32	1.80	0.32	2.13
GB 8	3–7	47	38	0.41	0.43	0.51
	7–10	47	38	0.31	0.31	0.58
	10–13	47	38	0.42	0.32	0.86
GB 9	7–11	47	38	0.78	0.40	0.55
	12–16	47	38	1.02	0.30	0.96
	16–20	48	36	1.75	0.31	1.37
GB 10	6–11	46	39	0.47	0.42	0.26
	11–15	46	39	0.25	0.27	0.29
	15–18	46	39	0.18	0.28	0.26
GB 11	7–11	47	38	0.76	0.21	0.61
	11–15	48	37	0.80	0.19	0.51
	15–19	47	38	0.66	0.22	0.73
GB 12	3–5	47	38	0.75	0.38	0.20
	5–9	48	37	0.77	0.88	0.32
	14–19	47	38	0.45	0.11	0.46
	19–24	47	38	0.43	0.26	0.39
GB14	10–13	46	38	0.66	0.35	0.25
	13–16	46	39	0.73	0.50	0.27

NOTE: after Sjerp (1992)
-2 µm fractions analysed

Table 75. Analysis of a kaolin sample from the Mount Gibson deposit

GSWA no.	*145144*
	Percentage
Al_2O_3	38.30
SiO_2	46.70
TiO_2	0.35
Fe_2O_3	0.63
MnO	<0.01
CaO	0.03
K_2O	0.33
MgO	0.07
P_2O_5	<0.005
SO_3	0.03
Na_2O	0.12
LOI	14.09
Total	**100.65**

NOTE: -10 µm fraction analysed

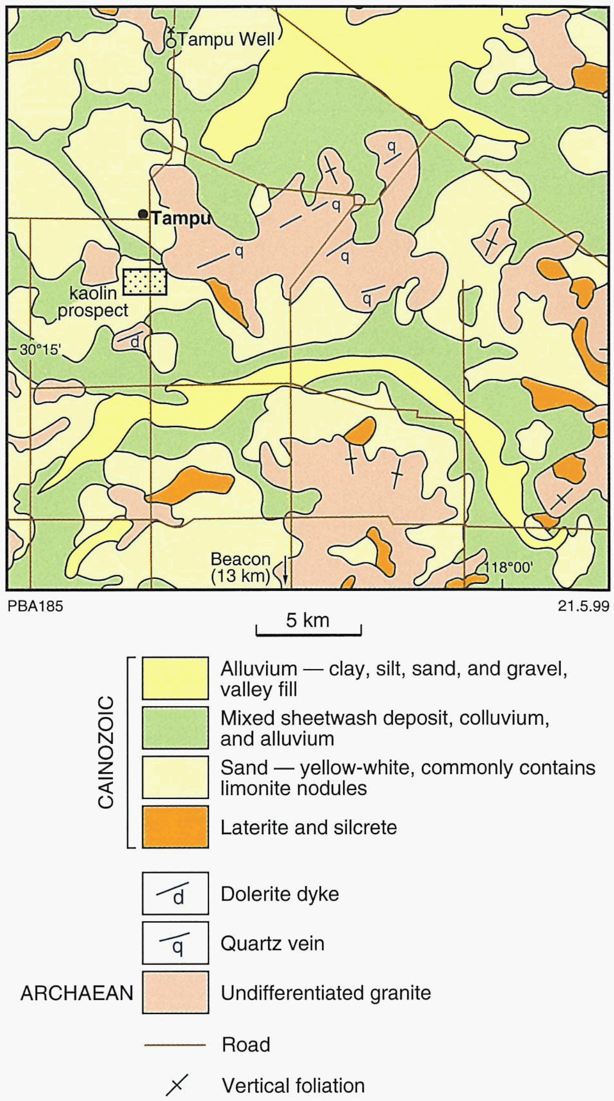

Figure 57. Regional geology around the Tampu kaolin prospect (modified from Blight et al., 1983)

Tampu

In early 1991, Mr Whitsed submitted six samples of kaolin to the Geological Survey of Western Australia in order to obtain geological advice. The samples were from a drilling program that he had carried out on a kaolin prospect at Tampu, but precise drillhole locations are unknown (Figs 12 and 57).

The main rock type found in the area is Archaean granite, which is generally covered to varying depths with Tertiary sand, laterite, and silcrete.

Six samples (GSWA 94476–78 and 94482–84) were shown by XRD to contain kaolinite as their main mineral, with a high proportion of quartz and minor mica (Table 76). This suggests that the kaolin is derived from a granite source and is a residual deposit. The SEM studies showed partly hexagonal to hexagonal kaolin platelets, with minor amounts of tubular halloysite.

The ISO brightness of the samples ranged from 74 to 81% (Table 76). This was measured on raw samples without significant processing, and could possibly be improved by separating the kaolin from the other minerals such as quartz and mica. Chemical analyses of six raw kaolin samples (Table 77) indicated kaolin of only average grade. The high SiO_2 contents (66.4–70.5%) were due to the presence of 30–55% free quartz in the samples. The Al_2O_3 contents (20.7–24.3%) were low for paper grade applications, but may be significantly improved by the separation of impurities from the raw kaolin. The raw material appears to be of acceptable chemical composition for ceramic and refractory grades. However, further testing would be required to determine the kaolin's physical characteristics in order to evaluate the material fully.

Mount Magnet

Approximately 7 km north of Mount Magnet (Fig. 12), on the eastern side of the main road, there are extensive breakaway ridges (approximately 25 m high) showing outcrops of weathered granite, which contain kaolin-rich horizons (Fig. 58). The breakaway ridges extend for a few kilometres towards the east, and it appears that the kaolin unit extends northwards at shallow depths below the soil cover of these ridges. Some spectacular caves have developed within the kaolin horizons due to weathering (Fig. 59). The presence of extensive beds of kaolin in the area is also indicated by the abundant kaolin within the dump at the Hill 50 gold mine, located on the western side of the main road. Although the main rock type within the ridges is granite, mafic and ultramafic rocks are also common in adjacent areas (Fig. 60).

The kaolin is white, rich in quartz and has been derived from the weathering of medium- to coarse-grained leucocratic granite containing predominantly quartz and feldspar, with traces of mica.

Five samples (GSWA 145134–38) were collected from kaolinized outcrops extending a distance of about 1.5 km

Table 76. Mineralogy, brightness, and crystallinity of kaolin samples from the Tampu prospect

GSWA no.	*Borehole*	*Depth (m)*	*Kaolinite*	*Quartz*	*Mica*	*Brightness[a]*	*Crystallinity (using SEM)*
				Percentage			
94476	7	13–15	40–60	30–40	<5	78.7	Coarse subhexagonal kaolin platelets
94477	9	11	40–60	30–40	–	76.4	Coarse to fine, subhexagonal to hexagonal kaolin platelets
94478	10	13	40–60	40–50	<5	74.5	Coarse to medium, subhexagonal kaolin platelets
94482	7	unknown	40–60	35–45	<5	80.8	Coarse to medium, subhexagonal kaolin platelets
94483	9	unknown	40–60	40–50	<5	76.3	Coarse to medium, subhexagonal kaolin platelets
94484	10	unknown	40–60	45–55	<5	75.9	Coarse to medium, subhexagonal kaolin platelets

NOTE: (a) Measured on the -0.25 mm size fraction

from the eastern side of the main road. The samples were from kaolinized material present near the caves, as well as from talus slopes off the ridges. The test results for these samples are summarized in Tables 78–80. XRD studies on the -10 μm fractions of these samples showed that kaolinite was the dominant mineral with only traces of quartz, and minor amounts of mica and halite. The ISO brightness of the samples ranged from 68 to 82%. The highest value was from sample GSWA 145138, which was coarse grained, rich in quartz, and friable, and was collected at the bottom of a cliff. Particle-size fractionation tests showed that the -45 μm fraction of these samples varied from 11.7 to 28.8%. Chemical analyses showed that samples GSWA 145137–38 were typical of high-grade kaolin, having compositions within acceptable limits for ceramic applications. However, samples GSWA 145134–36 contained low silica, high Na_2O, and had a high ignition loss, and appeared to be of relatively low-grade material.

Minor occurrences

Samples of kaolin were collected from road cuttings, old workings, breakaways, and other exposed kaolin horizons in a number of localities in the Murchison terranes. Information on these occurrences, which are currently considered to be of minor importance, is summarized in the following section.

Cleary

A sample (GSWA 145123) of quartz-rich kaolin with iron oxide staining was collected from a farm dam at this location (Figs 12 and 48). It contained dominant kaolinite, traces of quartz and mica, and minor halite, when examined using XRD (-10 μm fraction). The ISO brightness of the sample was 64.6%, and SEM

Table 77. Chemical analyses of kaolin samples from the Tampu prospect

GSWA no.	*94476*	*94477*	*94478*	*94482*	*94483*	*94484*
			Percentage			
Al_2O_3	23.80	23.50	20.70	24.30	24.00	21.60
SiO_2	66.40	66.70	70.10	67.60	67.80	70.50
TiO_2	0.45	0.40	0.36	0.48	0.42	0.37
Fe_2O_3	0.19	0.29	0.50	0.16	0.29	0.51
MnO	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
CaO	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
K_2O	0.30	0.07	0.22	0.27	0.07	0.23
MgO	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
P_2O_5	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
S	<0.01	<0.01	0.02	0.01	0.02	0.02
Na_2O	<0.05	<0.05	<0.05	<0.05	<0.05	0.12
LOI	8.77	8.87	8.06	8.65	8.86	8.19
Total	**99.91**	**99.83**	**99.96**	**101.47**	**101.46**	**101.54**

NOTE: Raw kaolin samples were analysed

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Figure 58. Photograph showing kaolinized horizons at a breakaway ridge 7 km north of Mount Magnet

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Figure 59. Caves formed within kaolinitic horizons of weathered leucocratic granite along a breakaway ridge 7 km north of Mount Magnet

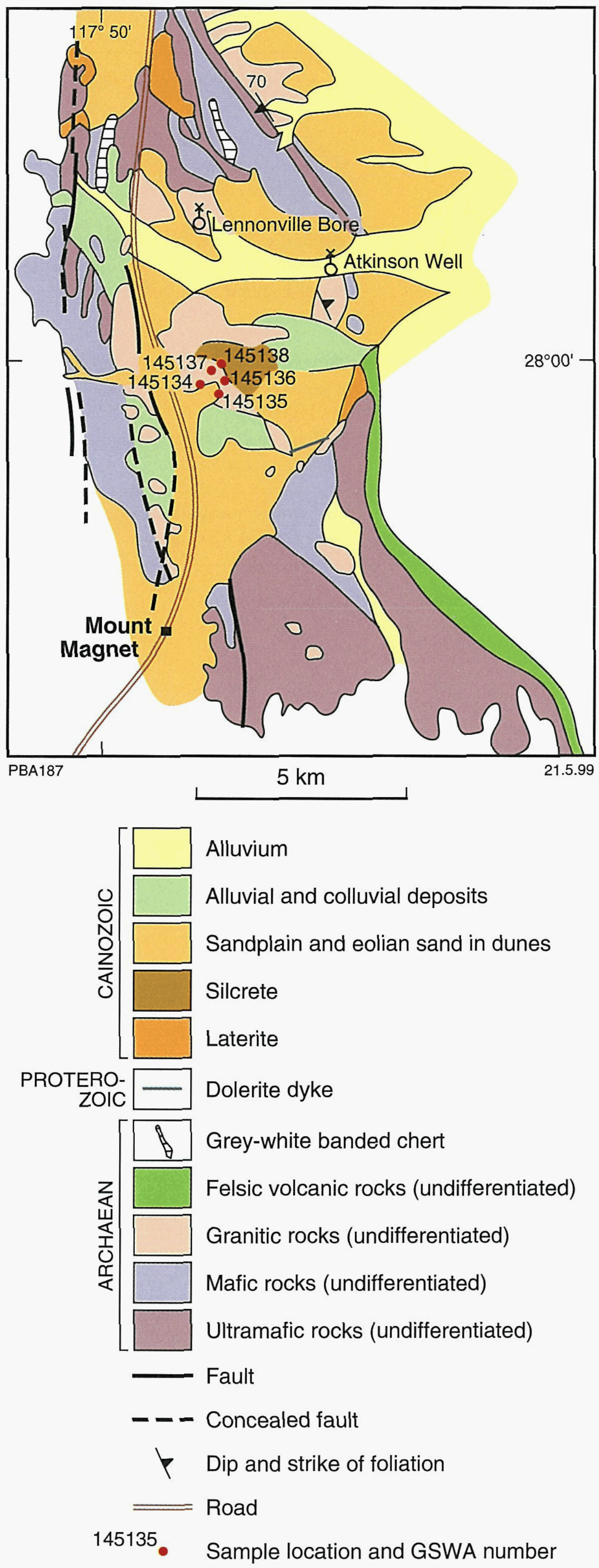

Figure 60. Regional geology north of Mount Magnet (modified from Baxter et al., 1982)

studies showed aggregates of relatively fine and coarse, subhexagonal platelets of kaolinite. Particle-size fractionation results for the raw sample indicated a relatively small percentage (29%) in the -45 µm fraction (Table 82). The chemical composition (Table 81) indicated that it was a typical kaolin. The material appeared to contain insufficient Al_2O_3 for paper and ceramic grade kaolin, but may have an application in the brick, tile, clay pipe, or pottery industries.

Cue

A total of 42 t of kaolin for filler applications has been obtained from this location (Fig. 12; Lipple, 1977).

Jibberding

Kaolin outcrops 17 km northwest of Jibberding (Fig. 12) in a 'rest area' on the western side of the Great Northern Highway. When examined in a pit, the kaolin layer was about 30 cm thick and appeared to have been derived from weathered granite. The chemical composition of a sample (GSWA 145125) from this location (Table 81) suggested that the Al_2O_3 was slightly low for paper coating grades, but appeared to be within acceptable limits for use in the brick, tile, clay pipe, or pottery industries. The sample had an ISO brightness of 69.3%. Examination of the -10 µm fraction using XRD showed dominant kaolinite and less than 10% quartz. SEM studies indicated that the material was coarse and platy. Particle-size fractionation tests showed that the -45 µm fraction was 42.0% (Table 82).

Lake Brown

Chemical analyses of two samples (GSWA 145169 and 95161) from this location (Fig. 12) are given in Table 81. The raw sample (GSWA 95161) contained 70% kaolinite, 25% quartz, and 5% iron and titanium oxides when studied by XRD. The -10 µm fraction of the other sample (GSWA 145169) contained dominant kaolinite with traces of quartz and mica, and minor halite. These mineral compositions suggest that the kaolin formed in situ from granite or granitic gneiss. The ISO brightness of sample GSWA 145169 was 72.7% (-10 µm fraction). Particle-size fractionation studies of the raw sample (GSWA 145169) showed that it contained a relatively high proportion (65.2%) of -45 µm material (Table 82). The samples appeared to contain excessive SiO_2, TiO_2, and Fe_2O_3, and insufficient Al_2O_3 for paper coating grades, but the material may have an application in the brick, tile, clay pipe, or pottery industries.

Mollerin Lake

A sample (GSWA 145121) of kaolin was collected from a weathered outcrop of granite at a location 7 km south of Mollerin Lake (Figs 12 and 48). When examined by XRD, the -10 µm fraction of the sample was found to contain kaolinite as its main mineral, with minor mica and halite. The ISO brightness of the sample was 64%, and SEM studies indicated that the kaolinite was coarse to medium grained, platy, subhexagonal, and contained possible traces of tubular halloysite. Particle-size fractionation studies of the raw sample showed a

Table 78. Mineralogy, ISO brightness, and crystallinity of kaolin samples from the Mount Magnet area

GSWA no.	*Kaolinite*	*Quartz*	*Mica*	*Calcite*	*Halite*	*Brightness*	*Crystallinity from SEM*
					Percentage		
145134	>50	–	2–10	–	<5	71.2	Medium to coarse, subhexagonal platelets of kaolinite
145135	>50	–	2–10	–	<5	72.8	Medium to coarse, subhexagonal to hexagonal, thin to relatively thick platelets of kaolinite, and minor tubular ?halloysite
145136	>50	–	–	–	<5	78.5	Medium to coarse, subhexagonal to hexagonal, thin platelets of kaolinite
145137	>50	<2	2–10	–	<5	68.9	Medium to coarse, subhexagonal, stacked platelets of kaolinite
145138	>50	<2	2–10	?traces	<5	82.2	Medium to coarse, subhexagonal aggregates of kaolinite

NOTE: All tests on -10 µm fractions

Table 79. Particle-size fractionation results for kaolin samples from the Mount Magnet area

GSWA no.	*<500 µm*	*<106 µm*	*<45 µm*	*H_2O*
		Percentage		
145134	51.3	18.7	11.7	8.3
145135	51.5	36.6	28.5	14.1
145136	55.3	36.6	28.9	7.4
145137	37.7	20.4	16.1	5.8
145138	60.5	29.1	21.8	7.8

NOTE: Raw samples tested

Table 80. Chemical analyses of kaolin from the Mount Magnet area

GSWA. no.	*145134*	*145135*	*145136*	*145137*	*145138*
			Percentage		
Al_2O_3	25.00	25.70	28.50	34.10	33.40
SiO_2	35.70	34.10	36.60	45.20	52.40
TiO_2	0.28	0.37	0.33	0.33	0.34
Fe_2O_3	0.40	0.32	0.39	0.54	0.41
MnO	<0.01	<0.01	<0.01	<0.01	<0.01
CaO	1.33	0.23	1.01	0.41	0.03
K_2O	0.81	0.59	0.76	0.86	0.82
MgO	1.78	0.93	2.07	0.39	0.15
P_2O_5	0.02	0.01	0.03	0.11	0.01
SO_3	0.83	1.25	0.88	0.29	0.07
Na_2O	7.27	7.93	4.79	1.31	0.31
LOI	26.78	29.37	24.83	17.01	12.62
Total	**100.20**	**100.80**	**100.19**	**100.55**	**100.56**

NOTE: All analyses on -10 µm fractions

Table 81. Chemical analyses of kaolin samples from minor occurrences in the Murchison terranes

Locality	*Jibberding*	*Perangery*	*Cleary*	*Lake Brown*	*Lake Brown*	*Mollerin Lake*	*Mollerin Lake*
GSWA no.	*145125*[(a)]	*94475*	*145123*[(a)]	*145169*[(a)]	*95161*[(b)]	*145121*[(a)]	*145122*[(a)]
				Percentage			
Al_2O_3	34.6	33.70	33.00	32.40	27.90	29.60	32.30
SiO_2	49.0	48.00	47.10	45.60	55.70	53.10	49.80
TiO_2	0.24	0.57	0.38	2.38	1.39	0.09	1.13
Fe_2O_3	0.57	0.47	0.81	0.62	1.87	1.64	0.54
MnO	<0.01	<0.05	<0.01	<0.01	<0.01	<0.01	<0.01
CaO	0.08	0.05	1.38	0.10	0.02	0.25	0.11
K_2O	0.43	3.83	0.15	0.23	0.12	0.84	0.57
MgO	0.20	0.39	0.34	0.43	0.10	0.32	0.27
P_2O_5	0.008	<0.05	<0.005	0.14	0.03	<0.005	<0.005
SO_3	0.14	nd	–	–	–	–	–
S	nd	0.08	0.18	0.58	0.10	0.09	0.13
Na_2O	0.57	0.70	1.17	2.31	0.13	0.55	1.21
LOI	14.24	11.70	16.01	15.01	11.86	13.97	14.22
Total	**100.08**	**99.49**	**100.52**	**99.80**	**99.22**	**00.45**	**100.28**

NOTES: (a) -10 µm fraction analysed
(b) raw sample analysed
nd not determined

relatively small proportion (23.7%) present in the -45 µm fraction (Table 82). The chemical composition (Table 81) indicated that it was a typical kaolin. The material is possibly suitable for porcelain and earthenware applications. Brightness and Al_2O_3 values were too low for paper grade applications.

Another sample (GSWA 145122) was collected from a small gravel quarry located 5 km south of Mollerin Lake, close to the road intersection (Fig. 48). Kaolin at this location occurs at the bottom of the quarry, and is apparently derived from weathered granite. The sample showed dominant kaolinite and minor mica and halite when the -10 µm fraction was studied under XRD. The ISO brightness of the sample was 76.6%, and SEM studies indicated that the material consisted of coarse to medium, platy, subhexagonal kaolin. Particle-size fractionation studies of the raw sample indicated that it contained a relatively small proportion (26.6%) of -45 µm material (Table 82). The chemical composition (Table 81) indicated that it is a typical kaolin. The material is probably suitable for ceramic usage, but the brightness and Al_2O_3 are too low for paper grade material.

Table 82. Particle-size fractionation results for kaolin samples from minor occurrences in the Murchison terranes

Locality	*GSWA no.*	*<500 µm*	*<106 µm*	*<45 µm*	*H_2O*
			Percentage		
Mollerin Lake	145121	49.0	28.8	23.7	11.7
Mollerin Lake	145122	66.9	34.8	26.6	18.4
Cleary	145123	66.3	37.9	29.0	10.9
Jibberding	145125	79.7	51.0	42.0	6.2
Lake Brown	145169	96.6	79.5	65.2	9.3

Mukinbudin

During 1975–78, 244 t of kaolin was produced in this area from weathered zones of quartz–feldspar pegmatite (Table 11; Fig. 12).

Perangery

A sample (GSWA 94475) from Location 10578, near Perangery (approximately 15 km northeast of Perenjori; Fig. 12), contained greater than 60% kaolinite, 10–20% quartz, less than 5% halite, 5–20% mica/illite, and had a low ISO brightness of 69.7%. SEM studies showed coarse, partly hexagonal platelets of kaolinite. Chemical analyses (Table 81) and mineralogical studies of the sample suggested that the kaolin was residual and derived from granite or granitic gneiss. The Al_2O_3 was slightly low for paper coating and ceramic grades, but the kaolin may have an application in the brick, tile, clay pipe, or pottery industries.

Another sample (GSWA 94479), from Location 7670 (approximately 17 km northeast of Perenjori), had an ISO brightness of 89.4% and was within the specifications for paper coating material. The fired shrinkage at 950°C was 7.3% and at 1250°C was 13.7%, while the fired adsorption at 950°C was 14.8% and at 1250°C it was 15.2%.

Southern Cross terranes, Yilgarn Craton

The presence of extensive granite, gneiss, and deep weathering profiles in the Southern Cross terranes suggests that there is a significant potential for the discovery of large kaolin deposits. However, large deposits have not yet been discovered in this region and the known prospects are restricted to the southern parts of the region, which are relatively closer to port facilities and population centres. The lack of large kaolin deposits or prospects in the northern part of the region may be attributed to the absence of exploration for this commodity due to the remoteness of the areas from transport facilities and population centres.

Residual deposit

Lort River

The Lort River kaolin prospect is located approximately 5 kilometres northeast of Lake Mends, about 130 km northwest of Esperance (Fig. 12), and adjoins the southern boundary of the Peak Charles National Park (Fig. 61). The area was explored by Summit Gold (Aust) Pty Ltd during 1988–89 for base and precious metals associated with rocks of ultramafic and/or alkaline affinity (Eggers, 1989).

Geology

The area is transected by a regional northeasterly trending lineament (referred to as the North Fraser Lineament) and is underlain by Archaean adamellite, banded and migmatitic granitic rocks, and intrusive quartz–amphibole syenite and pyroxene-bearing syenitic rocks of probable Proterozoic age (Fig. 61). Eggers (1989) stated that regional airborne magnetic data suggested the presence of a subsurface, east–west trending dolerite dyke approximately 8 km south of the tenement area. In addition, a crescent-shaped series of positive magnetic anomalies was interpreted to be a subsurface ultramafic suite of rocks or, possibly, an intrusive suite of alkaline affinity.

Reconnaissance fieldwork by Summit Gold (Aust) Pty Ltd confirmed the presence of Archaean granitic rocks, ultramafic amphibolitic rocks, and Proterozoic syenite intrusives within the area. Three open-hole percussion holes were drilled in an area northeast of Lake Mends (Fig. 61). However, since the exploration was for base and precious metals, sampling and testing of kaolin were given low priority.

Quality

Five percussion chip samples and one surface sample were analysed for CaO, Na_2O, K_2O, P_2O_5, Mo, Ba, and Y contents (Table 83). One sample (81-003) that contained quartz and clay, when studied by XRD and XRF, was found to contain 45–55% kaolinite and 45–55% quartz. Results for three samples tested in the CSIRO Laboratory in Western Australia are given in Table 84.

These tests showed that the -2 µm yield was satisfactory. Brightness at 570 mµ of the -2 µm fraction was 80.9–82.6%, which is satisfactory for some paper grade uses. However, at a wavelength of 457 mµ the brightness was 65.4–71.8%, which is not satisfactory for such applications. The effect of bleaching on brightness values has not been investigated. The viscosity was not satisfactory for paper grade applications, and this was considered to be partly due to the soluble salts associated with the clay that may have affected dispersion. The removal of these salts was found to be difficult even on a laboratory scale, and was considered to be even more difficult on a commercial scale. Particle sizing may be affected to some extent by the soluble salts. XRD studies generally showed kaolinite of poor crystallinity. The characteristic X-ray spectra collected and visually displayed on the multichannel analyser of the SEM indicated the presence of Fe, Ti, and K peaks, but the particle shape was unable to be resolved.

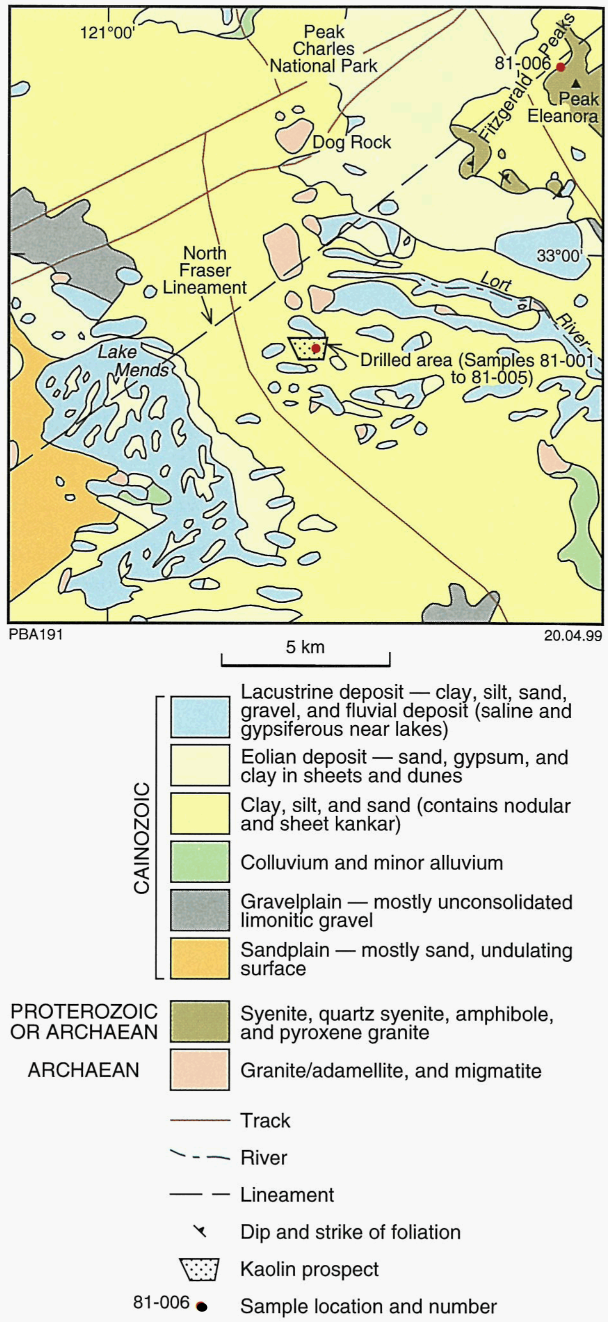

Figure 61. Regional geology around the Lort River kaolin deposit (modified from Gower and Bunting, 1974; Thom and Lipple, 1974; Eggers, 1989)

Table 83. Partial chemical analyses of drill chip samples from the Lort River prospect

Sample no.	*81-001*	*81-002*	*81-003*	*81-004*	*81-005*	*81-006*
CaO (%)	4.53	3.41	0.05	0.46	0.42	1.41
Na_2O (%)	1.40	2.13	1.28	3.32	3.40	4.99
K_2O (%)	0.62	0.65	0.45	5.38	5.44	4.90
P_2O_5 (%)	0.05	0.04	<0.02	<0.02	<0.02	0.09
Y (ppm)	11	15	4	3	4	8
Mo (ppm)	<20	<20	<20	<20	<20	<20
Ba (ppm)	259	219	168	417	372	1 460

SOURCE: Eggers, (1989)

Further tests were carried out on one of the above samples after removal of the soluble salts by washing and filtration. The tests showed that the amount of tetrasodium pyrophosphate required to obtain optimum dispersion was reduced from 0.4 to 0.25% (by weight) after washing. Viscosity solids loading (both high- and low-shear viscosity) of the washed sample was increased from 62.57 to 66.78%. A further improvement in high- and low-shear viscosity and percentage solids was achieved when the clay was macerated in a high-speed blender for 10 minutes. Brightness was unchanged for the washed sample of the -2 µm fraction. For the unwashed sample, an improvement of 3.7% reflectance at 475 mµ was achieved by using 1 ml of domestic bleach. Firing of the unwashed sample at 1000°C for 1 hour resulted in pink coloration of the clay.

These results indicate that more work is required to test the suitability of this clay for paper grade material. The lack of sufficient chemical analytical data makes it difficult to comment on the suitability of the material for other uses.

Table 84. Results of physical tests on clay samples from the Lort River prospect

Sample no.	*81-002*	*81-003*	*81-004*
Yield			
Weight of raw clay (kg)	2	2	1.5
Moisture (raw clay)	2.4	3.8	2.4
+150 µm	32.3	36.3	37.8
-150 + 53 µm	6.5	7.7	6.8
-53+2 µm	14.8	15.3	21.6
-2 µm	46.4	40.7	33.8
Brightness (-2 µm)			
Wavelength 570 mµ	80.9	81.35	82.6
Wavelength 457 mµ	70.75	71.75	65.4
Moisture (-2 µm)	1.1	1.4	1.1
Deflocculant required for optimum dispersion (-2 µm)	0.4	0.7	0.4
Viscosity (-2 µm; centipoise)			
Low shear (20 rpm)	5 000+	5 000+	4 150
Low shear (100 rpm)	1 000+	1 000+	1 000+

NOTE: after Eggers (1989)
All units percentage unless otherwise indicated

Minor occurrence

Ryans Find

White clay, containing halloysite horizons, occurs around lakes 32 km north-northwest of Boorabbin, at a locality known as Ryans Find, located east of Mount Walter. The halloysite forms a layer up to 2.1 m thick, which is exposed along the western side of a lake. A thin veneer of saline alluvium partly conceals the clay (Kriewaldt, 1968; Sofoulis, 1963; Fetherston and Brown, 1990).

Eastern Goldfields terranes, Yilgarn Craton

Exploration activities in the Eastern Goldfields terranes have not yet focused on low-priced commodities such as kaolin, due to a combination of factors such as distance to markets, high transport costs, and the non-availability of freshwater and cheap energy sources. However, the presence of large deposits of kaolin and other commercial clays within the region cannot be ruled out. For example, exploration drilling for gold, nickel, and base metals in the region has revealed the presence of considerable thicknesses of Tertiary clays that are very plastic, but appropriate testing for their suitability as industrial minerals has not been conducted. Deep weathering profiles on granitoids, in many instances exceeding 60–70 m, can give rise to large deposits of kaolin or other commercial clays. Hydrogeological drilling by the GSWA in many palaeochannels in the area has revealed the presence of thick accumulations of transported clay. Some of these palaeochannels are discussed in the section on transported deposits.

Recent developments in the Eastern Goldfields terranes, such as the extension of natural gas pipelines to the key mining centres and the upgrading of road networks, are important incentives for industrial mineral developers to explore more vigorously.

However, at present, as will be evident from the following descriptions, the available information on quality and quantity of commercial clays, including kaolin, from the Eastern Goldfields terranes is scarce. Much more exploration work is required to search for high-quality kaolin and other commercial clays.

Residual deposit

Bromus

The Bromus kaolin deposit is located near the railway line to Esperance, 5 km south-southwest from Bromus Siding (Figs 12 and 62). Esperance port is 165 km south of the deposit and Norseman is 40 km by road to the northeast.

In 1970, Petromin NL discovered a kaolin deposit in the area when exploring for base metals in areas of magnetic anomalies (Petromin NL, 1974; Lipple, 1977). Kaolin was intersected in one drillhole at a location approximately 5 km south of Bromus, and testing of a sample proved that the material was of good quality. A second drilling program, involving 120 percussion holes, was carried out in 1971 to assess the kaolin mineralization. Three 15 m shafts were sunk adjacent to drillholes to check the kaolin profile and to collect bulk samples for testing (Fig. 62). Erdel Research & Development Ltd and Raldrew Pty Ltd carried out further bulk sampling during 1993–94 from locations adjacent to the three shafts and also from material adjacent to percussion drillholes and lateritized gravel (Roberts, 1994).

Geology

The area contains sporadic outcrops of migmatite, and granitoid consisting of fine-grained equigranular adamellite. Coarse irregular pegmatite and medium- to coarse-grained foliated adamellite intrude the migmatite. Deposits of residual and reworked silcrete, ferricrete, yellow to buff sand, limonitic nodules, and ferruginous sandstone are widespread. The area also contains partly reworked Quaternary eolian deposits of clay, silt, and sand with locally derived calcareous nodules. There are also extensive alluvial and colluvial deposits derived from sheetwash. Kaolin occurs beneath various surficial deposits. The drilling indicated that white and coloured clays, consisting of kaolinite with up to 40% quartz grit, have developed mainly due to weathering in situ of fine-grained adamellite. The approximate boundary of the white kaolin is shown in Figure 62.

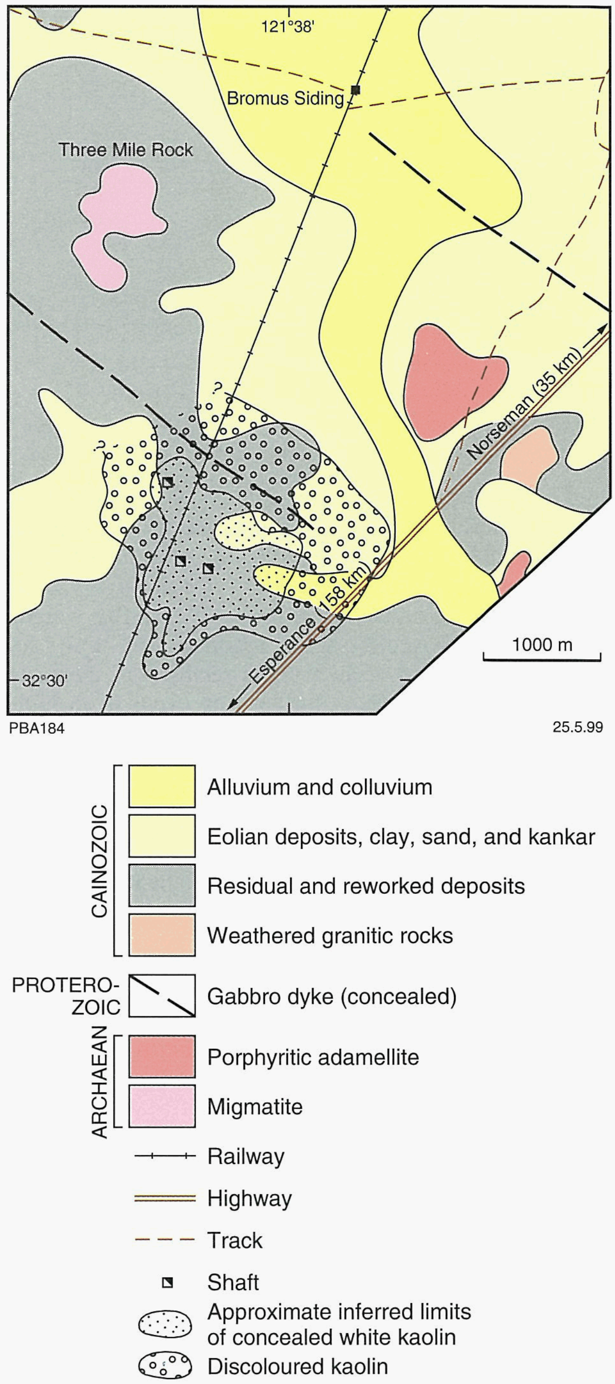

Figure 62. Geology around the Bromus kaolin deposit (after Lipple, 1977)

Quality

Testing of 13 drillhole samples was mainly performed on the -54 µm fractions, unless otherwise specified. The samples consisted of 44.4–54.8% (average 48.7%) -54 µm material, which contained 0.04–0.8% (average 0.4%) soluble salts and had an unbleached brightness of 84–93% (average 90.7%). The viscosity of this size fraction was equivalent to 52–59% solids loading at 500 centipoise. The -2 µm fractions had solids loadings of 51 and 52%. The -2 µm fraction of one sample was 15% of the sample.

There was no evidence to suggest that the high viscosities were due to the presence of soluble salts, montmorillonite, or halloysite (Petromin NL, 1974). XRD studies showed kaolinite and quartz as the main minerals present, with traces of mica in four samples.

The results of the testing of bulk samples from the shafts (Roberts, 1994) indicated that:

1. The kaolin had an average clay content of 62%;
2. The -20 µm fraction was virtually free of quartz and had an average yield of 43%. There was no increase

in kaolinite content in the -2 µm fraction, which constituted 15–20% of the material;

3. The viscosity of both the -20 µm and -2 µm fractions of the clay was too high for paper coating purposes;

4. The unbleached brightness was 83.9%;

5. The material had an abrasive index of 24 mg, which is comparable with other filler grade clays.

Ten samples collected from shafts and tested at the Government Chemical Laboratories had 12% or less in their -2 µm fraction (Lipple, 1977). It was concluded that material close to coating grade could be produced if the problems associated with viscosity could be overcome.

During 1993–94, Erdel Research & Development Ltd and Raldrew Pty Ltd carried out further studies, using samples collected from the west shaft. These samples showed that the material consisted almost entirely of kaolinite (60–65%) and quartz (35–40%) (Roberts, 1994). Studies using electron microscopy showed that the kaolinite occurred in clusters, replacing feldspar, and appeared to have three size groupings: 5–2 µm, 2–1 µm and less than 1 µm. Such groupings suggest that size separation of the material could improve the viscosity, probably to coating clay specifications. XRD studies indicated that kaolinite was the dominant clay mineral, with only trace amounts of illite. Studies of the different size fractions showed that the finer fractions had a higher degree of crystallinity. Chemical analyses of the -10 µm fractions of five samples showed that SiO_2 (45.6–47.2%) and Al_2O_3 (36.1–39.0%) were within the specifications for high-grade uses such as in the paper industry (Odom Holdings Pty Ltd, 1998).

Resources

Petromin NL (1974) estimated a resource of 30 Mt of kaolinitic clay containing 13.5 Mt of kaolin less than 44 µm. Lipple (1977) modified the resource figure to an indicated resource of 13.5 Mt of kaolinitic clay containing 2.5 Mt of -2 µm kaolin. Odom Holdings (1998) estimated a tonnage of 21 Mt of kaolinitic clay excluding the material sterilized by the railway line. Of this amount, the tonnage of the -20 µm fraction of kaolin has been estimated at 9 Mt (possibly in the inferred category). These latter estimations are also based on the earlier drilling programs carried out by Petromin NL (1974).

Transported deposits

Kaolin in palaeochannels

In the area 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. 11). Drilling carried out for hydrogeological investigations in these regions has indicated that some of these palaeochannels contain kaolin horizons (Commander et al., 1992). However, since the purpose of the drilling was for hydrogeological investigations, the information on kaolin horizons intersected in these drillholes is scarce.

Drilling information, in general, indicates that the kaolin horizons are mainly confined to the Perkolilli Shale. This shale is conformably underlain by the Wollubar Sandstone, usually with a sharp contact indicating a rapid change of facies, and is unconformably overlain by Quaternary deposits. The top of the formation is usually weathered and the contact between the Perkolilli Shale and clayey Quaternary sediments is often difficult to distinguish due to reworked underlying material present in the latter and also due to ferruginization that obscures the relationship. Lithologically the Perkolilli Shale correlates with the Eocene Pallinup Siltstone of the Plantagenet Group and the lower lacustrine facies containing clay and siltstone in the Eocene Eundynie Group (Griffin, 1989). The Perkolilli Shale is equivalent in age to the Eocene Princess Royal Spongolite in the Lefroy Palaeodrainage (Jones, 1990). The Perkolilli Shale is up to 39 m thick and kaolin horizons occur at various depths. In the Kalgoorlie region, the Perkolilli Shale occurs only in palaeochannels and does not outcrop.

Black Flag and Yindarlgooda

Hydrogeological drilling carried out by GSWA in 1988 in the Black Flag and Yindarlgooda palaeochannels showed kaolin-rich horizons (Figs 11 and 12). These palaeochannels are located 30 km northwest and 40 km east of Kalgoorlie, respectively. A cross section through the Yindarlgooda South palaeochannel, which contains Perkolilli Shale, is shown in Figure 63.

Eleven samples of kaolinitic material obtained from this drilling program were tested for their mineral constituents using XRD (Tables 85 and 86) and were analysed for major-element oxides (Table 87). All analyses were carried out on raw samples. The variable quartz content of the clay samples, which ranged from less than 1 to 60%, indicated deposition of the clay from transported material, as would be expected in a palaeochannel deposit. The samples generally contained appreciable amounts of goethite and hematite and, consistent with this, chemical analyses indicated high Fe_2O_3 contents (3.46–12.8%). Such high levels of iron make the material unsuitable for high-grade applications such as the paper industry. However, the material may be useful in relatively low-grade applications such as in the brick, tile, clay pipe, or pottery industries, but further testing would be required.

Minor occurrences

Kunanalling and Kintore

This is an area where there has been intense exploration and mining for gold, but there is no record of any exploration activities for kaolin. Near Kunanalling and Kintore, located approximately 30–40 km north of Coolgardie, dump material and walls of abandoned gold mines and old shafts in the area show evidence of

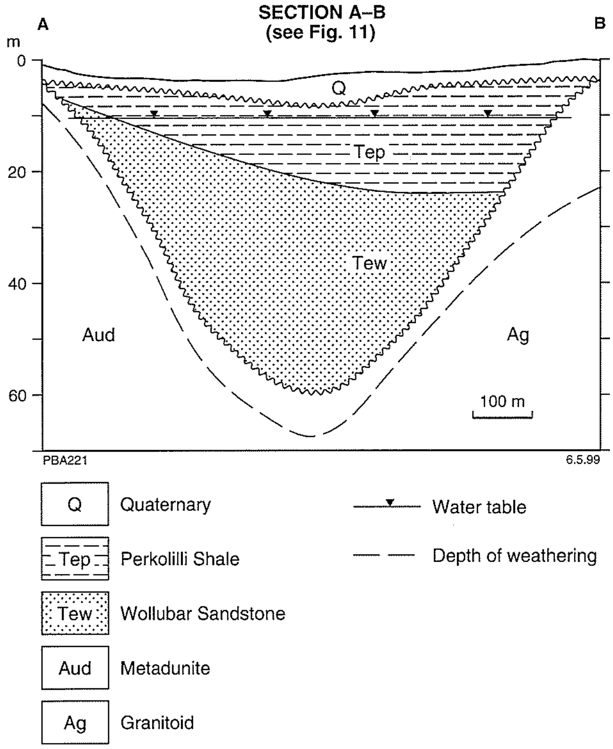

Figure 63. Cross section of the Yindarlgooda South palaeochannel (after Commander et al., 1992)

abundant kaolinitic material. Kaolin has formed as thick bands within mafic to ultramafic rocks, probably after weathered pegmatitic or granitoid dykes, and also as residual material derived from weathered granitic rocks. The rock types distinguished in the area include mafic and ultramafic rocks, and granites of Archaean age that are often covered with Cainozoic alluvial, colluvial, or lateritic material (Fig. 64).

Two samples (GSWA 145145–46) of kaolin, considered to be representative of kaolin bands in the wall of the openpit, were collected from mine dumps of an abandoned gold mine at Kunanalling. Both samples consisted of creamy brown kaolin containing quartz and feldspar, probably derived from granite. The pit walls of the mine contained 1.5–2.0 m bands of kaolin horizons, probably after weathered pegmatitic or granitoid dykes, within weathered mafic rocks containing lateritic horizons.

Kaolin, containing quartz and feldspar and commonly overlain by lateritic material, also occurs in the dump material of shallow shafts found in the Kunanalling area. A sample (GSWA 145147) of creamy white, soft, quartz-rich kaolin was collected from dumps of a small shaft about 15 m deep, located approximately 30 m west of the Coolgardie–Kintore road. The kaolin is possibly derived from weathered granite, and lateritic material overlies the kaolin horizon. The thickness of the kaolin bed is not visible in the shaft due to timber covering. Similar shallow shafts containing kaolin dump material are common at Kintore, approximately 10 km north of Kunanalling, suggesting that kaolin is widespread in the general region. Two samples (GSWA 145148–49) of coarse, quartz-rich, creamy white kaolin from the shaft dumps at Kintore were collected for testing.

The results of particle-size fractionation studies, XRD and SEM studies, ISO brightness measurements, and chemical analyses of the samples collected from the above locations are given in Tables 88–90. The -45 µm fractions of the Kunanalling samples ranged from 52.0 to 62.3%. However, sample GSWA 145149 from Kintore contained only 33.2% in the -45 µm fraction, indicating a relatively low percentage of fines. XRD studies of the -10 µm fractions indicated that the samples contained greater than 50% kaolinite with varying amounts of quartz, mica, and feldspar. The ISO brightness of the samples varied from 68 to 82%, with two samples having values above 80%. These values could possibly be further improved by separating out the quartz and mica before brightness testing. SEM studies indicated that the material consisted of partly hexagonal, thin to thick platelets. The chemical composition of the five samples indicated reasonably high-grade kaolin with 30.7–37.0% Al_2O_3, 44.8–51.0% SiO_2, and low values for TiO_2, Fe_2O_3, K_2O, CaO, and MgO. Sample GSWA 145148 had a composition suitable for paper grade, whereas the other samples (except GSWA 145145) appeared to contain excessive Na_2O and be unsuitable for ceramic purposes.

Table 85. Description of samples from the Black Flag and Yindarlgooda palaeochannels in the Kalgoorlie area

GSWA no.	*Locality*	*Latitude (S)*	*Longitude (E)*	*Comments*
103901–103903	Approximately 35 km northwest of Kalgoorlie	30°33'10"	121°09'50"	Black Flag palaeochannel. Respective sample depths are 6–10 m, 10–14.2 m and 14.2–18 m
103904–103908	Approximately 24 km north of Kalgoorlie	30°32'07"	121°26'34"	Black Flag palaeochannel. Samples 103904–907 are 3 m composites from 9.04–21.04 m depth, and 103908 is a 2.6 m composite from 21.04– 23.6 m depth
103909–103911	Approximately 31 km northeast of Kalgoorlie	30°32'28"	121°42'52"	Yindarlgooda palaeochannel. Samples 103909–910 are 3 m composites from 24.03–30.03 m depth, and 103911 is a 6 m composite from 33.03–39.03 m depth

Table 86. Mineralogy of samples from the Black Flag and Yindarlgooda palaeochannels in the Kalgoorlie area

GSWA no.	*103901*	*103902*	*103903*	*103904*	*103905*	*103906*	*103907*	*103908*	*103909*	*103910*	*103911*
						Percentage					
Kaolin	51–65	41–50	21–30	51–65	41–50	51–65	51–65	51–65	51–65	66–80	66–80
Quartz	6–10	20–30	51–60	11–20	31–40	6–10	6–10	11–20	21–30	<1	1–5
K-feldspar	nd	nd	nd	1–5	1–5	<1	<1	<1	1–5	<1	<1
Smectite	nd	6–10	11–20	nd	nd	6–10	nd	nd	nd	nd	nd
Mica/illite	1–5	nd	nd	1–5	1–5	1–5	1–5	11–20	1–5	nd	1–5
Interstratified clay	6–10	nd	nd	nd	nd	nd	6–10	nd	nd	6–10	1–5
Chlorite	nd	nd	nd	<1	nd	nd	nd	nd	nd	nd	nd
Goethite/hematite	11–20	6–10	6–10	nd	1–5	1–5	6–10	1–5	6–10	1–5	1–5
Anatase	1–5	1–5	1–5	1–5	1–5	1–5	<1	<1	<1	nd	<1
Gypsum	nd	nd	<1	nd	nd	nd	nd	<1	nd	nd	1–5
Halite	nd	nd	nd	1–5	<1	1–5	1–5	1–5	1–5	1–5	1–5

NOTE: nd — not determined

Table 87. Chemical analyses of samples from the Black Flag and Yindarlgooda palaeochannels in the Kalgoorlie area

GSWA no.	*103901*	*103902*	*103903*	*103904*	*103905*	*103906*	*103907*	*103908*	*10909*	*103910*	*103911*
						Percentage					
Al_2O_3	27.50	23.10	11.10	27.90	24.00	27.10	29.40	27.60	22.10	32.40	28.90
SiO_2	41.80	46.90	64.70	47.30	51.50	45.40	43.60	49.00	53.30	40.90	41.70
TiO_2	1.36	1.06	1.18	1.47	1.57	0.90	0.55	0.46	1.64	0.91	0.81
Fe_2O_3	10.90	11.20	12.80	3.69	3.90	5.31	3.59	3.46	6.76	3.56	4.57
MnO	<0.01	<0.01	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CaO	0.10	0.13	0.10	0.11	0.08	0.09	0.15	0.40	0.05	0.07	0.10
K_2O	0.07	0.09	0.06	0.27	0.32	0.22	0.27	1.62	0.26	0.25	0.19
MgO	0.62	0.63	0.46	0.68	0.57	0.64	0.72	0.99	0.36	0.75	0.53
P_2O_5	0.01	0.01	0.02	0.01	0.01	0.01	<0.01	0.01	0.01	0.04	<0.01
SO_3	0.24	0.31	0.18	0.22	0.16	0.16	0.18	0.16	0.30	0.36	0.40
Na_2O	0.80	0.85	0.58	1.64	1.58	1.89	1.76	1.49	1.75	1.71	2.17
LOI	16.20	15.50	8.84	16.80	16.00	17.40	19.10	13.10	13.00	19.30	20.70
Total	**99.60**	**99.78**	**100.06**	**100.09**	**99.69**	**99.12**	**99.32**	**98.29**	**99.53**	**100.25**	**100.07**

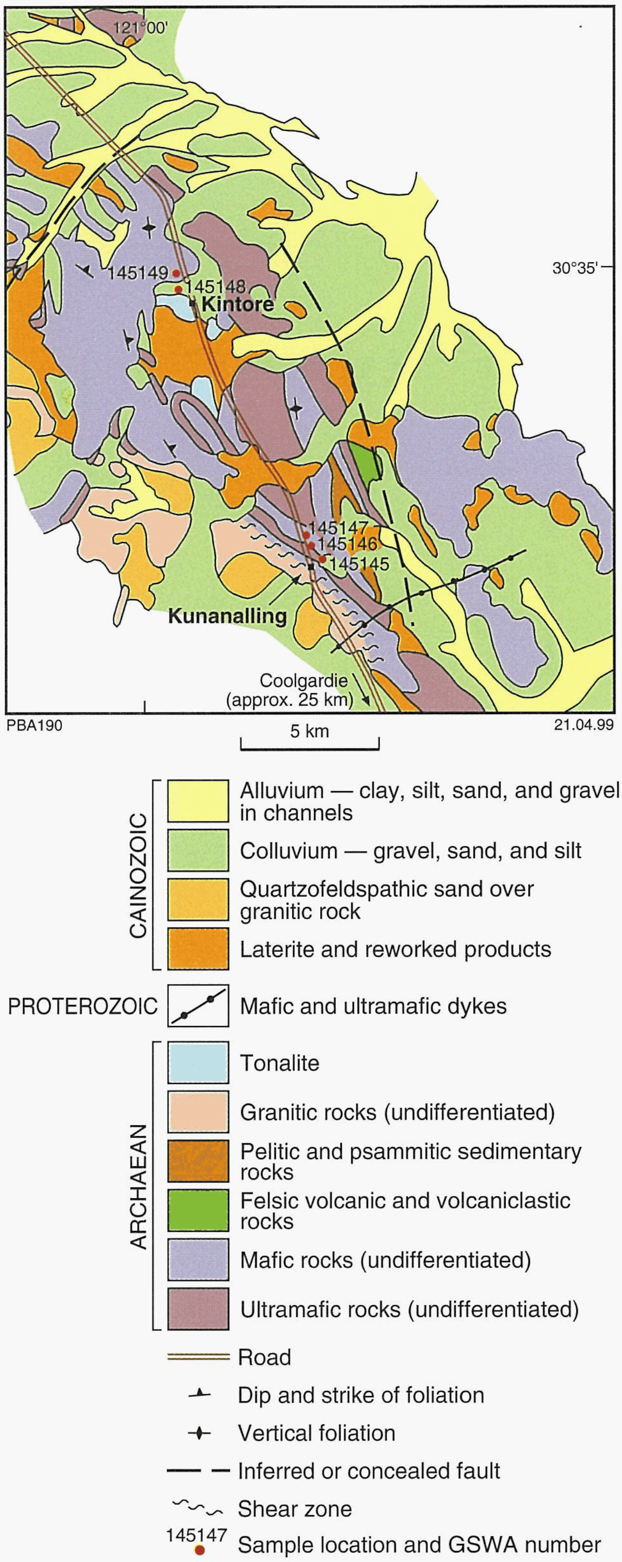

Figure 64. Regional geology around Kintore, north of Coolgardie (modified from Witt et al., 1993)

Chandlers Breakaway

At Chandlers Breakaway (Fig. 12), approximately 80 km north of Leonora and on the western side of the main road leading to Leinster, there is a series of prominent ridges about 25–30 m high, exposing white kaolin-rich horizons derived from weathered granitic rocks (Fig. 65). The top of the ridges contains 2–3 m of weathered granite rich in ferruginous material. These ridges appear to extend for several kilometres, and in numerous localities caves have formed in kaolinitic horizons of weathered leucocratic granite (Fig. 66). Kaolinitic scree material is abundant. The landscape at Chandlers Breakaway is very similar to that at Mount Magnet. The walls of old shafts located at the foot of some of these ridges show the depth of the kaolin layer to be more than 10 m, and the dump material from these shafts is rich in kaolin and quartz (Fig. 67). The predominant rock type in the area is granite, which is mostly covered by Cainozoic colluvial and alluvial deposits (Fig. 68).

Table 88. Particle-size fractionation results for kaolin samples from the Kunanalling and Kintore areas

Locality	*GSWA no.*	*<500 µm*	*<106 µm*	*<45 µm*	*H_2O*
			Percentage		
Kunanalling	145145	84.3	73.5	62.3	7.8
Kunanalling	145146	71.1	63.2	54.0	10.3
Kunanalling	145147	62.7	56.1	52.0	18.8
Kintore	145148	78.6	66.0	61.1	17.3
Kintore	145149	40.0	34.1	33.2	11.3

Three samples (GSWA 145159–61) were collected from the area for testing (Fig. 68). Sample GSWA 145159 was a quartz-rich kaolin, derived from weathered granite, and was collected from dump material near a shallow shaft located at the foot of the ridge. Sample GSWA 145160 was collected from scree material containing quartz-rich kaolin at a cliff face located near the above shaft. Sample GSWA 145161 was from dump material near a shaft located approximately 150 m north along the foot of the ridge from the other samples, and consisted of white coarse-grained quartz-rich kaolin derived from weathered granite.

The particle-size fractionation studies (Table 91) indicated that all three samples contained approximately 50% of relatively fine material (-45 µm). The XRD studies of the -10 µm fractions of these samples showed that they contained predominantly kaolinite, with a high proportion (10–50%) of mica, as well as minor (0–10%) quartz, and trace (<2%) amounts of feldspar and halite (Table 92). The ISO brightness ranged from 77 to 80% and could possibly be improved by separating out the mica and other impurities. The SEM studies indicated medium to coarse, thin to thick platelets of subhexagonal to hexagonal kaolin. The chemical compositions showed reasonably high-grade kaolin with 31.1–37.3% Al_2O_3, 43.3–48.6% SiO_2, and relatively low levels of TiO_2, Fe_2O_3, CaO, MgO, and Na_2O (Table 93). However, the K_2O contents were relatively high, and varied from 2.05 to 3.78%. The composition of the material may possibly be within acceptable levels for low-grade uses such as ceramics, but the material may not be suitable for paper grade applications. The material may also be suitable for other low-grade applications such as

Table 89. Mineralogy, brightness, and crystallinity of kaolin samples from the Kunanalling and Kintore areas

Locality	*GSWA no*	*Kaolinite*	*Quartz*	*Mica*	*Microcline*	*Halite*	*Brightness*	*Crystallinity (under SEM)*
				Percentage				
Kunanalling	145145	>50	2–10	<2	–	<2	68.0	Medium to coarse, thin platelets of subhexagonal kaolin
Kunanalling	145146	>50	2–10	2–10	<2	<5	75.3	Medium to coarse, thin platelets of subhexagonal kaolin
Kunanalling	145147	>50	2–10	2–10	–	–	81.6	Medium to coarse relatively thick subhexagonal platelets of kaolin
Kintore	145148	>50	<2	10–50	<2	<2	79.6	Coarse, subhexagonal thin platelets of kaolinite
Kintore	145149	>50	–	2–10	–	<5	81.0	Coarse, thin to thick subhexagonal kaolin platelets

NOTE: All tests were performed using -10 µm fractions

in the brick, tile, clay pipe or pottery industries, but would require further testing.

Boraginna Soak

Kaolin overlies granite in this area (Fig. 12) and random grab samples contained impurities of quartz (5%), hematite (<1%), and goethite (<1%) (Doepel, 1973).

Gambier Lass

Dumps from old shafts at this location (Fig. 69) contain appreciable quantities of quartz-rich kaolin. RAB holes drilled at this location, presumably for gold exploration, also show kaolin horizons 1–2 m thick below an overburden about 3–5 m thick. The kaolin is rich in quartz, creamy to slightly brown, and appears to have been derived from weathered granite during lateritization. Two samples (GSWA 145153 and 145155) from the area showed dominant kaolinite and quartz, and significant amounts of mica (Table 94). SEM studies indicated partly hexagonal to hexagonal, thin to relatively thick platelets of kaolin. ISO brightnesses of the samples were 75.6 and 68% respectively. Particle-size fractionation studies indicated that the raw samples contained significant proportions of relatively fine material (63.0–76.7% less than 45 µm; Table 95). Chemical compositions (Table 96) indicated kaolin of only average grade, with the material containing insufficient Al_2O_3 and excessive SiO_2 and K_2O for high-grade applications such as paper and ceramics. The material may be useful in relatively low-grade applications such as the brick, tile, clay pipe or pottery industries, but would require further testing.

Table 90. Chemical analyses of kaolin samples from the Kunanalling and Kintore areas

Locality *GSWA no.*	*Kunanalling* *145145*	*Kunanalling* *145146*	*Kunanalling* *145147*	*Kintore* *145148*	*Kintore* *145149*
			Percentage		
Al_2O_3	32.90	30.70	35.90	37.00	34.00
SiO_2	51.00	46.60	44.80	46.60	45.90
TiO_2	1.66	0.76	0.72	0.74	0.54
Fe_2O_3	0.72	0.64	1.17	0.74	1.23
MnO	<0.01	<0.01	<0.01	<0.01	<0.01
CaO	0.03	0.05	0.03	0.03	0.39
K_2O	0.35	0.82	1.49	1.78	0.95
MgO	0.07	0.90	0.35	0.29	0.25
P_2O_5	0.04	0.03	<0.01	0.04	0.02
SO_3	0.04	1.17	0.35	0.10	0.46
Na_2O	0.39	3.24	1.41	0.38	1.88
LOI	12.57	16.18	14.21	12.83	15.08
Total	**99.77**	**101.09**	**100.43**	**100.53**	**100.70**

NOTE: All analyses were performed using -10 µm fractions

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Figure 65. Ridges exposing white kaolinitic clay horizons derived from weathered leucocratic granite at Chandlers Breakaway (Lat. 28°15'10"S, Long. 121°05'30"E)

PBA 247 06.03.99

Figure 66. Small caves in kaolinitic horizons of weathered leucocratic granite at Chandlers Breakaway (Lat. 28°15'10"S, Long. 121°05'30"E)

PBA 248 06.03.99

Figure 67. Dump material containing kaolinitic clay near shallow shafts at Chandlers Breakaway (Lat. 28°15'10"S, Long. 121°05'30"E)

Jeedamya

In a small gravel quarry at Jeedamya (Fig. 12), kaolin underlies 1–1.5 m of limonitic and lateritic material. The kaolin is a weathering product of a quartzofeldspathic gneissic rock that is strongly foliated in a north–south direction, with approximately a 30° easterly dip. Two samples (GSWA 145151–52) of kaolin collected from the quarry showed kaolinite as the main mineral, with minor to trace quantities of quartz, mica, and halite (Table 94). Particle-size fractionation studies (Table 95) indicated that the raw samples contained relatively low proportions of fine material (27.4–32.3% less than 45 μm). SEM studies indicated medium to coarse, thin and relatively thick, subhexagonal to hexagonal platelets of kaolin. Chemical compositions (Table 96) showed reasonably high-grade kaolin with 30.3–34.1% Al_2O_3 and 44.7–48.8% SiO_2, but there appeared to be excessive Na_2O (2.79% in sample GSWA 145151) for ceramic applications. However, the material may be suitable for relatively low-grade applications such as the brick, tile, clay pipe or pottery industries, but would require further testing.

Jundee

Kaolinitic saprolite clay from the Desert Dragon prospect at Jundee (Fig 12) has been tested by Wiluna Mines Ltd to determine its suitability for high-grade applications, but the results remain confidential.

Kalgoorlie

During 1961–67, about 271 t of ball clay was produced from MC19, located approximately 13.5 km northwest of Kalgoorlie (Fig. 12).

Lake Ballard

Kaolinitic clay beds outcrop within the Perkolilli Shale at Lake Ballard (Fig. 12). The mineralogy of three samples (GSWA 93678–79, 93685) of this clay, collected from drilling for a hydrogeochemistry project, indicated over 80% kaolinite (Table 94). The clay formed as transported material in a lacustrine environment.

Laverton mine

White clay, at depths ranging from 3 m to more than 20 m, has been intersected in many RC drillholes in the vicinity of the Laverton mine (Fig. 12). The colour of the clay ranges from brown to white. Test results of two samples (GSWA 145163–64), collected from depths of about 15–20 m, indicated that the clay is of average grade and is unsuitable for high-quality applications such as paper or ceramics (Tables 94 and 96). However, the samples contained a relatively high proportion of finer fractions as shown by particle-size fractionation studies (84.6–90.6% less than 45 μm; Table 95).

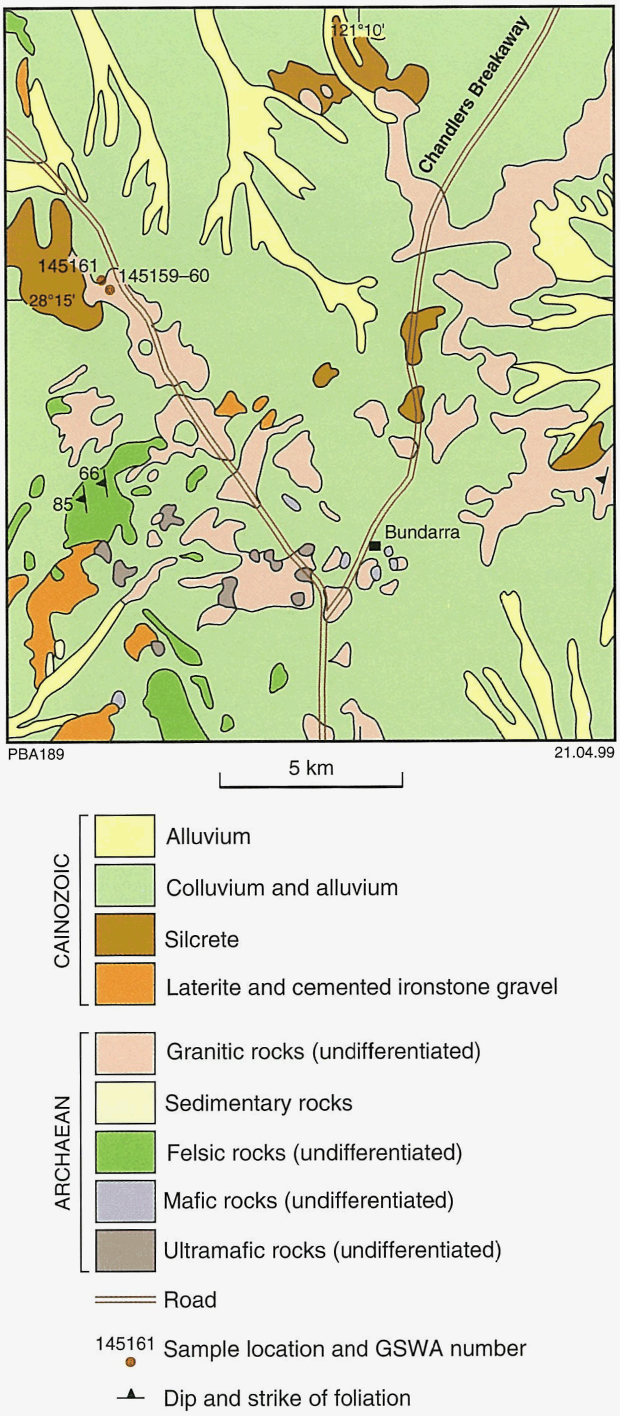

Figure 68. Regional geology around Chandlers Breakaway (modified from Thom and Barnes, 1975)

Leonora

Approximately 5 km towards Nambi Homestead from Leonora (Figs 12 and 69), a number of shallow RAB holes drilled on the northern side of the road have indicated the presence of a 10–20 m-thick creamy to white, soft kaolin horizon, below an overburden of about 3 m of laterite. Two samples (GSWA 145156–57) of kaolin from different holes showed kaolinite as their dominant mineral, with significant amounts of quartz and mica (Table 94).

Table 91. Particle-size fractionation results for kaolin samples from Chandlers Breakaway

GSWA no.	*<500 µm*	*<106 µm*	*<45 µm*	*H_2O*
		Percentage		
145159	62.3	55.4	53.8	3.2
145160	59.0	52.5	50.0	2.9
145161	63.6	53.7	51.9	5.4

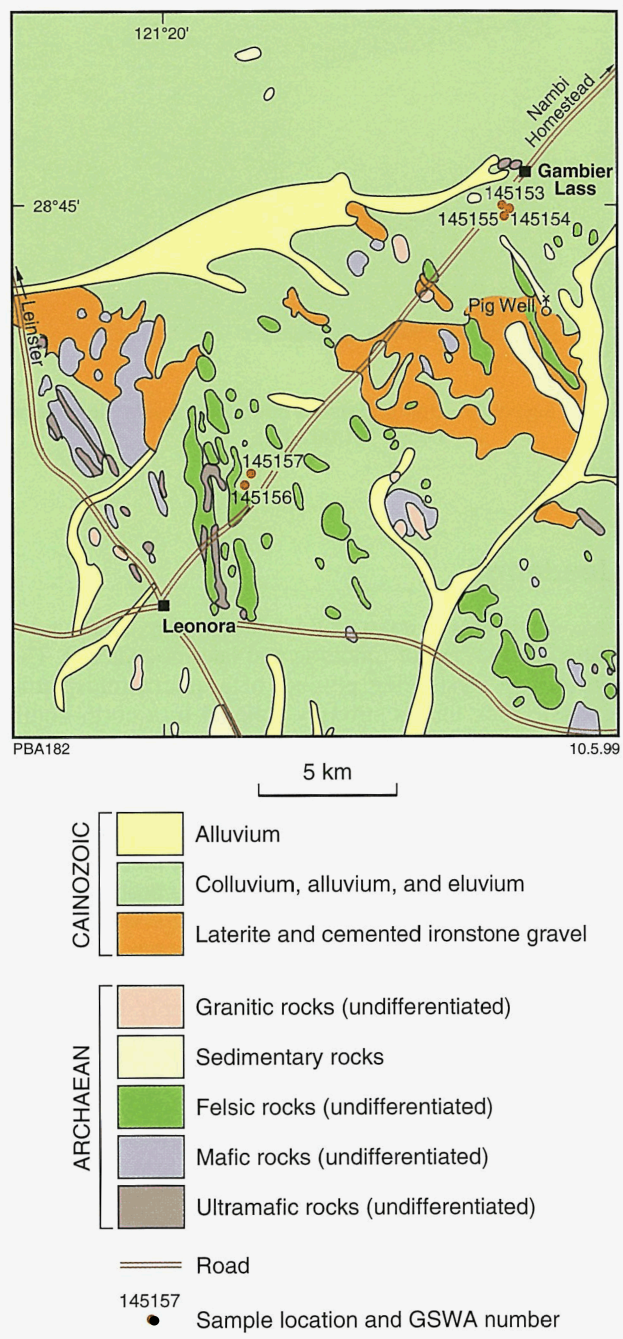

Figure 69. Regional geology around Leonora (modified from Thom and Barnes, 1975)

Table 92. Mineralogy, brightness, and crystallinity of kaolin samples from Chandlers Breakaway

GSWA no.	*Kaolinite*	*Quartz*	*Mica*	*Microcline*	*Halite*	*Brightness*	*Crystallinity (under SEM)*
				Percentage			
145159	>50	2–10	10–50	<2	<2	80.0	Coarse, relatively thick platelets of subhexagonal kaolin
145160	>50	<2	10–50	–	<2	77.2	Medium to coarse, thin to relatively thick platelets of subhexagonal to hexagonal kaolin
145161	>50	<2	10–50	<2	<2	78.4	Coarse, thin to relatively thick, subhexagonal to hexagonal platelets of kaolin

NOTE: All tests were performed using -10 µm fractions

Table 93. Chemical analyses of kaolin samples from Chandlers Breakaway

GSWA no.	*145159*	*145160*	*145161*
		Percentage	
Al_2O_3	31.10	37.30	34.60
SiO_2	43.30	47.10	48.60
TiO_2	0.62	0.54	0.59
Fe_2O_3	0.82	0.81	1.49
MnO	<0.01	<0.01	<0.01
CaO	0.03	0.04	0.05
K_2O	2.75	2.05	3.78
MgO	0.27	0.21	0.47
P_2O_5	0.02	0.01	0.13
SO_3	<0.01	0.02	0.01
Na_2O	0.11	0.15	0.17
LOI	20.76	12.30	10.22
Total	**99.78**	**100.53**	**100.11**

NOTE: All analyses were performed using -10 µm fractions

Table 94. Mineralogy, brightness, and crystallinity of kaolin samples from the Laverton–Leonora area

GSWA no.	*Locality*	*Kaolinite*	*Quartz*	*Mica*	*Microcline*	*Halite*	*Brightness*	*Crystallinity (under SEM)*
					Percentage			
145151	Jeedamya	>50	2–10	<2	<2	<5	77.0	Medium to coarse, thin and relatively thick platelets of subhexagonal kaolin
145152	Jeedamya	>50	2–10	2–10	–	<2	75.0	Medium to coarse, thick platelets of subhexagonal kaolin
145153	Gambier Lass	>50	10–50	10–50	<2	<2	75.6	Coarse, relatively thick, subhexagonal to hexagonal platelets of kaolin
145155	Gambier Lass	10–50	>50	10–50	–	<2	68.0	Coarse, thin, subhexagonal kaolin platelets
145156	Leonora	>50	10–50	10–50	–	<2	63.4	Coarse, thin to relatively thick, subhexagonal to hexagonal kaolin platelets
145157	Leonora	>50	10–50	10–50	–	<2	71.4	Coarse, thin to relatively thick, subhexagonal to hexagonal kaolin platelets
145158	Leonora	>50	2–10	10–50	<2	<2	63.0	Coarse, thin, subhexagonal kaolin platelets
145163	Laverton	10–50	10–50	10–50	<2	<2	53.3	Coarse, thick, subhexagonal to hexagonal platelets
145164	Laverton	10–50	10–50	10–50	–	–	63.0	Coarse, relatively thick subhexagonal to hexagonal platelets of kaolin and a trace of tubular ?halloysite
145165	Mount Phoenix	10–50	10–50	10–50	–	<2	67.6	Coarse, thin to relatively thick, subhexagonal platelets of kaolin
93678	Lake Ballard	90	5–10	–	trace	trace	–	
93679	Lake Ballard	80	5–10	–	5–10	<5	–	
93685	Lake Ballard	90	<5	–	trace	<5	–	

NOTE: -10 µm fractions used for samples GSWA 145151–64

Table 95. Particle-size fractionation results for samples from the Leonora–Laverton area

GSWA no.	*Locality*	*<500 μm*	*<106 μm*	*<45 μm*	H_2O
			Percentage		
145151	Jeedamya	71.6	51.0	27.4	7.2
145152	Jeedamya	89.1	51.2	32.3	5.7
145153	Gambier Lass	82.3	68.3	63.0	5.7
145155	Gambier Lass	89.7	79.1	76.7	5.8
145156	Leonora	96.5	92.7	91.2	6.0
145157	Leonora	97.7	95.3	93.8	6.6
145158	Leonora	76.2	61.4	56.9	6.3
145163	Laverton	94.3	88.2	84.6	4.5
145164	Laverton	97.9	94.4	90.6	17.2
145165	Mount Phoenix	55.9	40.5	37.3	5.3

Particle-size fractionation studies (Table 95) indicated that the raw samples contained very high proportions of relatively fine material (91.2–93.8% less than 45 μm). SEM studies indicated coarse, thin to relatively thick, partly hexagonal to hexagonal kaolin platelets. Chemical analyses (Table 96) showed only average grade kaolin, which appeared to be unsuitable for high-grade applications due to low Al_2O_3 and high SiO_2 and K_2O.

Approximately 34 km north of Leonora (about 200 m west of the main road), kaolin is present in dump material of an old shaft approximately 25 m deep. The kaolin is greenish white and is overlain by lateritic material of uncertain thickness. A sample (GSWA 145158) of kaolin from the dump material was tested for its mineralogy, crystallinity, brightness, particle-size distribution, and chemical composition (Tables 94–96). The kaolin appeared to be of average quality and had insufficient Al_2O_3 and excessive SiO_2 and K_2O for high-grade applications.

Mount Phoenix

A number of shallow RAB holes (approximately 10 m deep), presumably from road investigations, have been drilled on the northern side of the road from Leonora to Laverton (Fig. 12) and have intersected white quartzose kaolinitic clay units more than 8 m thick, below a lateritic overburden about 2 m thick. Test results of one composite sample (GSWA 145165), from a depth of 5–8 m, indicated that the clay is of average grade and is unsuitable for high-grade applications such as paper or ceramics (Tables 94–96).

Albany–Fraser Orogen

Known kaolin occurrences in this orogen are limited to four localities — Culham Inlet, Tingledale, Gibson, and Northcliffe (Fig. 17).

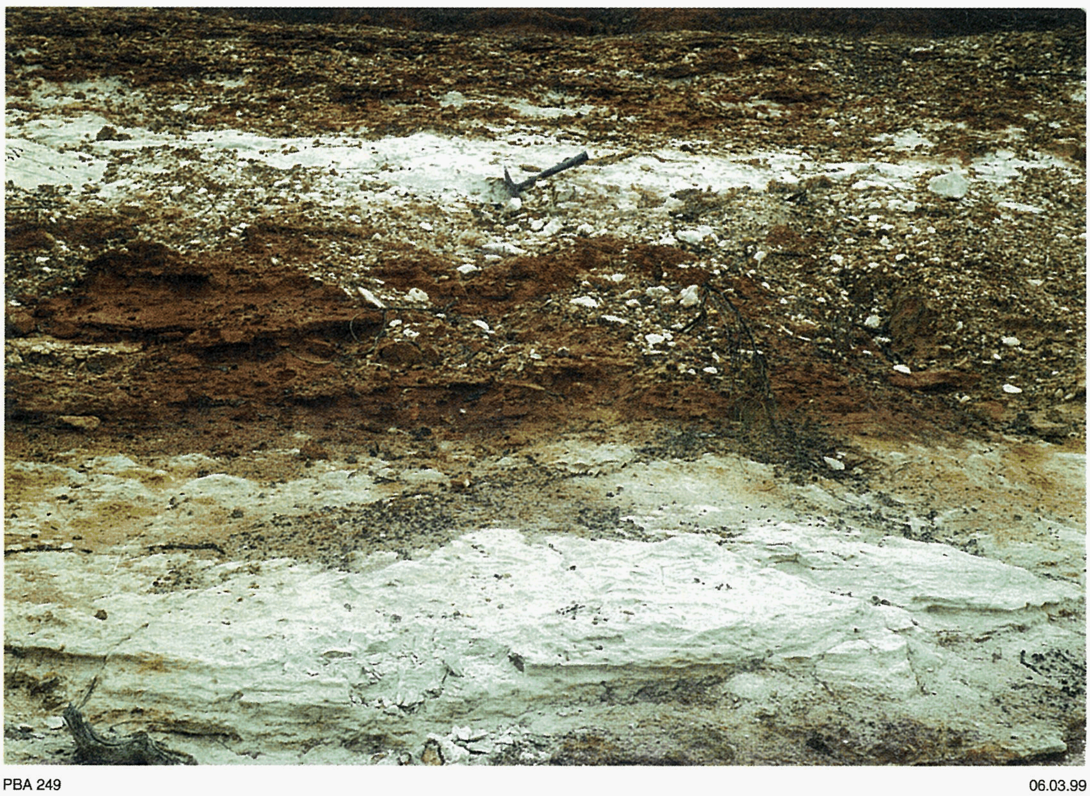

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Figure 70. Outcrops and thin beds of kaolinitic clay associated with lateritic material on an erosional surface near Phillips Road at Culham Inlet (Lat. 33°52'06"S, Long. 120°07'00"E)

Table 96. Chemical analyses of kaolin samples from various localities in the Eastern Goldfields terranes

Locality *GSWA no.*	*Jeedamya* *145151*	*Jeedamya* *145152*	*Gambier Lass* *145153*	*Gambier Lass* *145155*	*Leonora* *145156*	*Leonora* *145157*	*Leonora* *145158*	*Laverton* *145163*	*Laverton* *145164*	*Mount Phoenix* *145165*
					Percentage					
Al_2O_3	30.30	34.10	24.50	19.30	25.40	25.80	27.50	25.10	23.70	25.60
SiO_2	44.70	48.80	63.80	69.80	62.30	61.40	57.80	61.30	65.00	60.60
TiO_2	0.69	0.32	0.53	0.23	0.66	0.78	0.62	0.67	0.52	0.31
Fe_2O_3	0.81	0.82	0.36	0.66	0.81	0.73	1.25	1.76	0.67	1.43
MnO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CaO	0.53	0.20	0.02	0.04	0.09	0.03	0.04	0.06	0.04	0.35
K_2O	0.26	0.61	4.40	4.03	2.26	2.57	4.03	4.15	2.96	3.09
MgO	1.58	0.44	0.20	0.35	0.33	0.55	0.58	0.42	0.17	0.46
P_2O_5	0.03	<0.01	0.02	0.04	0.03	0.03	0.01	0.01	0.01	0.01
SO3	1.04	0.29	0.22	0.04	0.04	0.03	0.09	0.04	0.01	0.02
Na_2O	2.79	0.68	1.04	0.65	0.36	0.25	0.32	0.64	0.66	1.45
LOI	18.02	14.30	5.19	4.32	8.03	7.97	7.75	6.08	5.76	6.77
Total	**100.75**	**100.56**	**100.28**	**99.46**	**100.31**	**100.14**	**99.99**	**100.23**	**99.50**	**100.09**

NOTE: All analyses were performed using -10 µm fractions

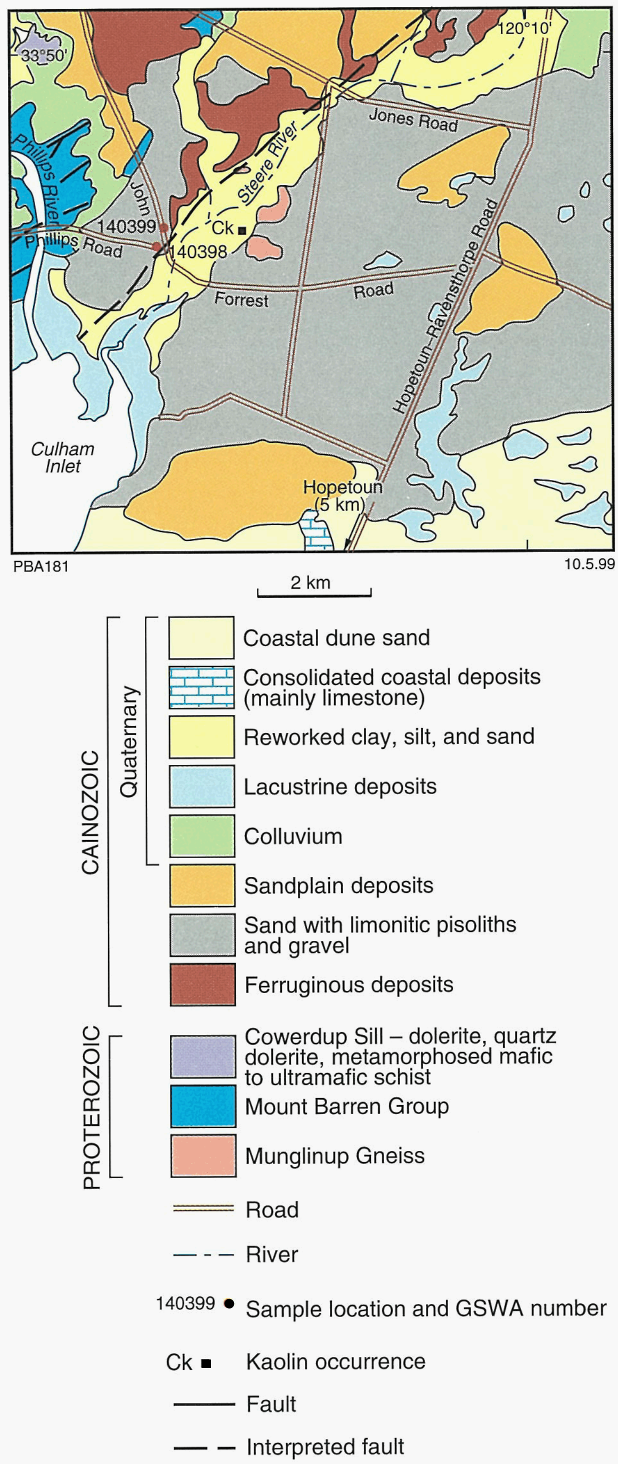

Figure 71. Regional geology north and east of Culham Inlet (modified from Witt, 1996)

Culham Inlet

At Culham Inlet (Fig. 12), kaolin extends over an area of approximately 100 hectares and to a depth of about 6 m (Thom et al., 1977). Fine-grained, relatively hard white kaolin is exposed in a number of road cuttings and cliffs, generally as subhorizontal bands within lateritic material (Fig. 70). The kaolin appears to have been deposited either from transported material that was derived from nearby gneiss or developed as part of the laterization process. The -10 µm fractions of two samples (GSWA 140398–99) from this area (Fig. 71) were studied using XRD, and showed greater than 50% kaolinite, 2–10% quartz, less than 2% mica, and less than 5% halite. The ISO brightnesses of the two samples were 71.6 and 62.2%, which were too low for high-grade applications. Particle-size fractionation studies of the raw samples indicated a relatively small proportion (31.4–43.4%) of -45 µm material (Table 97). SEM studies indicated coarse platelets of subhexagonal to hexagonal kaolinite. The chemical composition reflected an average grade kaolin with relatively low Al_2O_3, and high Na_2O, MgO, TiO_2, and Fe_2O_3 (Table 98), indicating that it is unsuitable for high-grade applications. The material is possibly suitable for the brick, tile, clay pipe, or pottery industries, but would require further testing.

Table 97. Particle-size fractionation results for samples from Culham Inlet

GSWA no.	*<500 µm*	*<106 µm*	*<45 µm*	*H_2O*
		Percentage		
140398	78.4	53.7	43.4	23.9
140399	68.9	46.7	31.4	15.5

Tingledale

Two samples (GSWA 132212–13) of clay were collected from Location 1812 at Tingledale (Fig. 17), approximately 7 km west of Bow Bridge. XRD studies showed 41–55% kaolinite, 32–40% quartz, and 4% mica in sample GSWA 132212, and 24% nontronite in sample GSWA 132213. The SiO_2 content (60.62–67.02%) of these samples (Table 99) was too high for good quality

Table 98. Chemical analyses of two samples from the Culham Inlet area

GSWA no.	*140398*	*140399*
	Percentage	
Al_2O_3	25.30	25.00
SiO_2	48.90	51.70
TiO_2	1.42	1.30
Fe_2O_3	1.17	1.83
MnO	<0.01	<0.01
CaO	0.05	0.04
K_2O	0.61	0.68
MgO	1.24	1.12
P_2O_5	0.01	0.01
SO_3	0.94	0.62
Na_2O	3.68	2.40
LOI	17.74	16.14
Total	**101.06**	**100.84**

NOTE: All analyses were performed using -10 µm fractions

Table 99. Chemical analyses of Tingledale clay

GSWA no.	*132212*	*132213*
	Percentage	
Al_2O_3	20.69	17.56
SiO_2	67.07	60.62
TiO_2	0.83	0.69
Fe_2O_3	1.59	6.90
MnO	<0.01	<0.01
CaO	0.03	0.36
K_2O	0.68	0.14
MgO	<0.01	0.18
P_2O_5	<0.01	<0.01
Na_2O	<0.01	0.11
LOI	8.31	13.38
Total	**99.20**	**99.94**

NOTE: All analyses were performed using -10 µm fractions

kaolin, and was due to the presence of a high percentage of free quartz as well as some mica. The analysis also indicated an elevated level of Fe_2O_3.

Gibson

There is a kaolin prospect located 17.5 km west-northwest of Gibson and 30 km north-northeast of Esperance (Figs 12 and 17). Kaolin mineralization covers an area of 10 km^2 and overlies granitic gneiss basement. Western Mining Corporation, on behalf of Simmons Holdings Pty Ltd, conducted exploration for kaolin in the area during 1989–91.

In 1988, Mr Roger Gough of Simmons Holdings contacted Western Mining Corporation regarding exploration for kaolin in the above area. As a result, Western Mining Corporation carried out some preliminary sampling that involved a few surface dam samples and one auger sample (8.5 m depth). Results of this sampling led to the drilling of 47 aircore holes, totalling 626 m, by Western Mining Corporation in 1990. The aim was to identify kaolin for use in high-quality paper coating or filling applications. The depth of these holes varied from around 2 to 28 m. The holes revealed that the depth of the weathering profile ranged from about 2 to 26 m. The rock types intersected in these holes were foliated gneiss, unfoliated granite, and occasional mafic dykes. The kaolin was mainly restricted to zones of weathered granite and gneiss, and had formed in situ as residual material.

Testing of 23 samples gave good brightness values, with some greater than 85 at 457 mµ and greater than 90 at 570 mµ. These were well within paper coating grade specifications. Viscosity was generally variable and below the required specifications (Bonwick, 1991a,b).

Northcliffe

A kaolin sample from a location 16 km southwest of Northcliffe (Figs 12 and 17) had a brightness (at 467 mµ) of 82% (-75 µm fraction) and particle-size fractionation indicated 22% of the material was less than 2 µm and 24% less than 75 µm (Lipple, 1977). No other information is available.

Other regions of the State

Roebuck Bay

During 1996–97, Messrs G. Mansfield and J. Towers explored for kaolin on Exploration Licences E04/936 and E04/954, located approximately 10 km south of Roebuck Bay in the Canning Basin. A number of holes drilled in the area indicated thick kaolin horizons, but the results at this stage remain confidential.

Chapter 6

Summary

Industry defines kaolin as a clay consisting of substantially pure kaolinite, or related clay minerals, that is naturally, or can be beneficiated to be, white or nearly white, will fire white or nearly white, and is amenable to beneficiation by known methods to make it suitable for use in whiteware, paper, rubber, paint, and similar uses. Other important varieties of this group are ball clay, refractory clay, and flint clay.

Kaolin is mined and processed in many countries, and it is one of the few industrial minerals of sufficient value, in its highly refined state, to be widely exported into international markets. The global kaolin production in 1996 was approximately 19 Mt. The main countries producing refined kaolin are the USA, UK, Germany, the Czech Republic, Ukraine, China, and Brazil. Until 1997, Australia was about the 14th largest producer of kaolin in the world, and produced around 190 000 t of kaolin in 1996. Australia was a major exporter of paper coating grade kaolin until the closure of the Weipa deposit in Queensland in 1997. Significant producers of kaolin in the Asian region are Indonesia, Malaysia, Thailand, and India.

The paper industry is the largest consumer of kaolin and utilizes around 47% of the world annual production, which represents 55–60% of all minerals consumed worldwide in paper filling and coating. Other important users of kaolin include the paint, ceramics, refractories, plastics, fibreglass, chemical, and pharmaceutical industries. The demand for kaolin in the ceramics industry is steady and is showing signs of increasing in many countries. The demand for paper grade kaolin in Japan is increasing. Japan imports paper coating grade kaolin from the USA, Brazil, and Australia (until 1997), and filler grade from Malaysia and Indonesia.

The known kaolin deposits in Western Australia are largely limited to the Yilgarn Craton and the Albany–Fraser Orogen. The geology of the Yilgarn Craton is favourable for the development of significant deposits of kaolin as it contains extensive bodies of granite and granitic gneiss, combined with deep weathering profiles. Also, the mature drainage systems and palaeochannels in the Southwest Drainage Division are potential areas for thick clay horizons. Evaluation of the deposits will require laboratory testing of drilled samples. The most common tests are brightness, particle size, mineralogy, chemical analysis, and viscosity. Costs often limit the number of tests actually performed.

The total recorded production of kaolin in Western Australia (from 1939–97) amounts to 60 586 t, and the average annual production from 1990–97 was around 3900 t. The largest recorded production of kaolin in the State is from the Greenbushes deposit. Western Australia has also produced 715 355 t of ball clay (1932–97) and 5.7 Mt of variable grade fireclay (1922–97).

In addition to the Greenbushes deposit, other large deposits in the South-West terranes include Jubuk, Ockley–Wickepin, Kerrigan, and Tambellup, all of which are of residual origin, but none of these deposits (other than Greenbushes) have yet been mined. Some of these deposits contain kaolin suitable for the paper, ceramics, and refractories industries. The total known resource of kaolin in the State is estimated at 300 Mt (223 Mt inferred and 77 Mt indicated), of which about 50 Mt are suitable for high-grade applications such as paper (Table 100).

For the kaolin industry to be commercially viable, it is essential that there is value adding, involving processing of the material locally for various specifications. Since

Table 100. Kaolin resources in Western Australia

Deposit	*Inferred resource (Mt)*	*Indicated resource (Mt)*
Gabbin		
Castlemain claim	[a]27.6 (gross ore)	–
Watts, Ottey and Whitsed claims	15.1 (raw clay)	–
Jubuk	43.2	8.0
Ockley–Wickepin		
Sparks deposit	–	29.0
Kerrigan	80.0	–
Tambellup	–	7.1
Mount Kokeby	0.17	–
Mount Kokeby–Murray deposit	5.9	–
Mullewa	–	2.04
Mount Gibson	27.3	30.5
Greenbushes	2.3	–
Goomalling	–	0.045
Bromus	21.0	–
Total	**222.6**	**76.7**

NOTE: (a) Gross ore — calculated on the basis of 61% kaolin in ore most of the high-grade kaolin deposits are located a few hundred kilometres from port facilities, it is essential that issues such as infrastructure and transport costs are effectively addressed by the relevant agencies, in order to promote such industries. Another important constraint in developing the kaolin industry is the apparent lack of availability of freshwater close to some of these deposits. Therefore, it would be advisable for the State's service organizations, such as the Water and Rivers Commission, to include these areas in their regional programs for hydrogeological investigations. Such investigations will not only help in opening up kaolin-based industries in such areas, but would also be helpful in the promotion of other industrial activities.

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Appendix 1

GSWA sample locations

GSWA. no.	*Latitude*	*Longitude*	*Prospect*	*1:250 000 Map sheet*	*Comments*
93678	29°30'00"	121°10'00"	Lake Ballard	MENZIES	Location approximate
93679	29°30'00"	121°10'00"	Lake Ballard	MENZIES	Location approximate
93685	29°30'00"	121°10'00"	Lake Ballard	MENZIES	Location approximate
93685	29°30'00"	121°10'00"	Lake Ballard	MENZIES	Location approximate
94442	28°28'30"	115°33'00"	Mullewa	YALGOO	Kaolin deposit at Wenmillia Dam
94443	32°45'45"	118°00'00"	East of Ockley	CORRIGIN	
94444	32°45'20"	118°00'50"	East of Ockley	CORRIGIN	
94456	31°45'00"	116°27'00"	Bakers Hill	PERTH	Location approximate (near Coates Siding)
94457	28°28'30"	115°33'00"	Mullewa	YALGOO	Kaolin deposit at Wenmillia Dam
94458	28°28'30"	115°33'00"	Mullewa	YALGOO	Kaolin deposit at Wenmillia Dam
94459	28°28'30"	115°33'00"	Mullewa	YALGOO	Kaolin deposit at Wenmillia Dam
94460	33°15'00"	119°11'00"	Lake Magenta	NEWDEGATE	
94462	29°12'00"	115°50'00"	West Morawa	PERENJORI	
94473	33°46'18"	118°35'00"	Ongerup	NEWDEGATE	
94474	33°46'18"	118°35'00"	Ongerup	NEWDEGATE	
94475	29°21'50"	116°23'25"	Perangery	PERENJORI	
94476	30°13'45"	117°48'30"	Tampu	BENCUBBIN	From boreholes at Tampu Prospect
94477	30°13'45"	117°48'30"	Tampu	BENCUBBIN	From boreholes at Tampu Prospect
94478	30°13'45"	117°48'30"	Tampu	BENCUBBIN	From boreholes at Tampu Prospect
94482	30°13'45"	117°48'30"	Tampu	BENCUBBIN	From boreholes at Tampu Prospect
94483	30°13'45"	117°48'30"	Tampu	BENCUBBIN	From boreholes at Tampu Prospect
94484	30°13'45"	117°48'30"	Tampu	BENCUBBIN	From boreholes at Tampu Prospect
94485	30°55'05"	116°26'55"	Yerecoin	MOORA	
94486	30°55'05"	116°26'55"	Yerecoin	MOORA	
94487	30°55'05"	116°26'55"	Yerecoin	MOORA	
94488	31°40'30"	118°48'30"	Noombenberry Rock	SOUTHERN CROSS	2 km northeast of Noombenberry Rock
94489	31°40'30"	118°48'30"	Noombenberry Rock	SOUTHERN CROSS	2 km northeast of Noombenberry Rock
94490	31°40'30"	118°48'30"	Noombenberry Rock	SOUTHERN CROSS	2 km northeast of Noombenberry Rock
94498	30°53'50"	117°15'00"	Cadoux	BENCUBBIN	10 km east of GSWA sample numbers 145139–43
94499	31°18'00"	116°39'00"	Goomalling	PERTH	
95161	30°57'00"	118°20'00"	Lake Brown	BENCUBBIN	Morrison property, near Lake Brown
95161	30°57'00"	118°20'00"	Lake Brown	BENCUBBIN	Morrison property, near Lake Brown
103901	30°33'10"	121°09'50"	Black Flag	KALGOORLIE	From drillhole in a palaeochannel
103902	30°33'10"	121°09'50"	Black Flag	KALGOORLIE	From drillhole in a palaeochannel
103903	30°33'10"	121°09'50"	Black Flag	KALGOORLIE	From drillhole in a palaeochannel
103904	30°32'07"	121°26'34"	Black Flag	KALGOORLIE	From drillhole in a palaeochannel
103905	30°32'07"	121°26'34"	Black Flag	KALGOORLIE	From drillhole in a palaeochannel
103906	30°32'07"	121°26'34"	Black Flag	KALGOORLIE	From drillhole in a palaeochannel
103907	30°32'07"	121°26'34"	Black Flag	KALGOORLIE	From drillhole in a palaeochannel
103908	30°32'07"	121°26'34"	Black Flag	KALGOORLIE	From drillhole in a palaeochannel
103909	30°32'28"	121°42'52"	Yindarlgooda	KURNALPI	From drillhole in a palaeochannel
103910	30°32'28"	121°42'52"	Yindarlgooda	KURNALPI	From drillhole in a palaeochannel
103911	30°32'28"	121°42'52"	Yindarlgooda	KURNALPI	From drillhole in a palaeochannel
132212	34°58'20"	116°52'42"	Tingledale	PEMBERTON	
132213	34°58'20"	116°52'42"	Tingledale	PEMBERTON	
132214	30°22'00"	117°07'00"	Kalannie	BENCUBBIN	
140383	32°15'55"	116°52'50"	Murray deposit (Mount Kokeby)	PINJARRA	
140384	32°20'10"	117°23'55"	Kweda	CORRIGIN	
140385	32°20'00"	117°25'54"	Kweda	CORRIGIN	
140386	32°35'00"	117°39'55"	Yealering	CORRIGIN	
140387	32°42'20"	117°36'00"	Boyning Gully	CORRIGIN	
140389	32°47'00"	117°44'20"	Borning Soak	CORRIGIN	
140390	32°47'20"	117°58'55"	Jitarning	CORRIGIN	
140391	32°31'10"	118°41'40"	Karlgarin	HYDEN	
140393	32°34'00"	118°43'36"	Mount Mallet	HYDEN	
140394	32°37'00"	118°45'40"	Around Kerrigan	HYDEN	
140395	32°39'40"	118°44'40"	Around Kerrigan	HYDEN	
140396	32°40'45"	118°47'00"	Around Kerrigan	HYDEN	
140397	32°43'50"	118°37'35"	Pingaring	HYDEN	
140398	33°52'05"	120°05'55"	Culham Inlet	RAVENSTHORPE	

Appendix 1 (continued)

GSWA. no.	*Latitude*	*Longitude*	*Prospect*	*1:250 000 Map sheet*	*Comments*
140399	33°52'05"	120°05'55"	Culham Inlet	RAVENSTHORPE	
140400	33°39'50"	119°44'00"	West River	NEWDEGATE	
145101	34°20'10"	118°41'30"	Boxwood Hill	BREMER BAY	Approximately 8 km west of Boxwood Hill along Borden Road
145102	34°20'05"	118°40'55"	Boxwood Hill	BREMER BAY	Approximately 1.5 km west of GSWA sample number 145101
145103	34°19'55"	118°39'50"	Boxwood Hill	BREMER BAY	Approximately 1.5 km west of GSWA sample number 145102
145104	33°57'55"	117°59'30"	Gnowangerup	DUMBLEYUNG	Southwest of Gnowangerup
145105	34°00'55"	117°54'10"	Gnowangerup	DUMBLEYUNG	Southwest of Gnowangerup
145107	34°02'55"	117°31'15"	Saddlers property (Tambellup)	MOUNT BARKER	
145108	33°52'00"	116°04'00"	Greenbushes	COLLIE	
145109	33°52'00"	116°04'00"	Greenbushes	COLLIE	
145110	33°52'00"	116°04'00"	Greenbushes	COLLIE	
145113	31°09'10"	116°37'55"	Calingiri	PERTH	Between Goomalling and Calingiri
145114	31°06'55"	116°31'30"	Calingiri	PERTH	Between Goomalling and Calingiri
145115	31°07'40"	116°29'40"	Calingiri	PERTH	Between Goomalling and Calingiri
145116	31°06'10"	116°28'15"	Calingiri	PERTH	Between Goomalling and Calingiri
145117	30°52'30"	116°22'55"	Yerecoin	MOORA	6 km north of Yerecoin
145118	30°36'35"	117°39'10"	Close to Castlemain prospect, Gabbin	BENCUBBIN	
145120	30°35'10"	117°39'05"	Close to Castlemain prospect, Gabbin	BENCUBBIN	
145121	30°34'30"	117°33'55"	Mollerin Lake	BENCUBBIN	
145122	30°32'05"	117°29'55"	Mollerin	BENCUBBIN	
145123	30°23'20"	117°38'55"	Cleary	BENCUBBIN	
145124	30°30'05"	117°13'50"	Kulja	BENCUBBIN	
145125	29°50'10"	116°56'35"	Jibberding	NINGHAN	
145126	28°31'12"	115°30'30"	Mullewa	YALGOO	Wooderarung Gully
145127	28°31'12"	115°30'30"	Mullewa	YALGOO	Wooderarung Gully
145128	28°30'50"	115°30'24"	Mullewa	YALGOO	Wooderarung Gully
145134	28°00'30"	117°51'10"	Mount Magnet	KIRKALOCKA	
145135	28°00'30"	117°51'10"	Mount Magnet	KIRKALOCKA	
145136	28°00'25"	117°51'40"	Mount Magnet	KIRKALOCKA	
145137	28°00'10"	117°51'35"	Mount Magnet	KIRKALOCKA	
145138	28°00'10"	117°51'35"	Mount Magnet	KIRKALOCKA	
145139	30°54'25"	117°08'50"	Cadoux	BENCUBBIN	Borehole samples
145140	30°54'25"	117°08'50"	Cadoux	BENCUBBIN	Borehole samples
145141	30°54'25"	117°08'50"	Cadoux	BENCUBBIN	Borehole samples
145142	30°54'25"	117°08'50"	Cadoux	BENCUBBIN	Borehole samples
145143	30°54'25"	117°08'50"	Cadoux	BENCUBBIN	Borehole samples
145144	29°34'42"	117°20'00"	Mount Gibson	NINGHAN	
145145	30°40'30"	121°03'35"	Kunanalling	KALGOORLIE	
145146	30°40'10"	121°03'30"	Kunanalling	KALGOORLIE	
145147	30°36'10"	121°01'12"	Kunanalling	KALGOORLIE	
145148	30°35'35"	121°00'55"	Kintore	KALGOORLIE	
145149	30°35'25"	121°00'42"	Kintore	KALGOORLIE	
145151	29°16'55"	121°16'50"	Jeedamya	MENZIES	15 km north of Jeedamya
145152	29°16'55"	121°16'50"	Jeedamya	MENZIES	15 km north of Jeedamya
145153	28°45'00"	121°27'50"	Gambier Lass	LAVERTON	
145155	28°45'00"	121°27'50"	Gambier Lass	LAVERTON	
145156	28°50'40"	121°21'55"	Leonora	LEONORA	Approximately 5 km north of Leonora
145157	28°50'40"	121°21'55"	Leonora	LEONORA	Approximately 5 km north of Leonora
145158	28°36'55"	121°11'50"	Leonora	LEONORA	Approximately 34 km north of Leonora
145159	28°15'20"	121°05'40"	Chandlers Breakaway	LEONORA	
145160	28°15'20"	121°05'40"	Chandlers Breakaway	LEONORA	
145161	28°15'10"	121°05'30"	Chandlers Breakaway	LEONORA	
145163	28°36'55"	122°29'55"	Laverton mine	LAVERTON	Approximately 200 m north of the mine
145164	28°36'55"	122°29'55"	Laverton mine	LAVERTON	Approximately 200 m north of the mine
145165	28°45'50"	121°58'20"	Mount Phoenix	LAVERTON	
145166	28°30'00"	115°32'30"	Mullewa	YALGOO	Eda Creek North (drillhole M134, exact location unknown)
145167	28°30'00"	115°30'30"	Mullewa	YALGOO	Kaolin deposit at Wenmilla Dam
145168	28°30'00"	115°32'30"	Mullewa	YALGOO	Eda Creek North (drillhole M134, exact location unknown)
145169	30°57'00"	118°20'00"	Lake Brown	BENCUBBIN	Morrison property, near Lake Brown

Appendix 2

Kaolin deposits, prospects and occurrences in Western Australia

Prospect	*1:250 000 Map sheet*	*Latitude*	*Longitude*	*Deposit type*	*Tectonic unit*	*Comments*
Bakers Hill	Perth	31°45'00"	116°27'00"	Uncertain	South-West terranes	Location approximate (Near Coates Siding)
Balkuling	Kellerberrin	31°59'00"	117°07'00"	Uncertain	South-West terranes	Location approximate
Black Flag	Kalgoorlie	30°33'10"	121°09'50"	Transported	Eastern Goldfields terranes	
Boraginna Soak	Norseman	32°25'00"	121°46'00"	Uncertain	Eastern Goldfields terranes	
Boxwood Hill	Bremer Bay	34°20'10"	118°41'30"	Uncertain	South-West terranes	
Bromus	Norseman	32°29'00"	121°38'00"	Residual	Southern Cross terranes	
Brookton	Corrigin	32°15'00"	117°16'00"	Residual	South-West terranes	
Bruce Rock	Kellerberrin	31°53'00"	118°15'30"	Uncertain	South-West terranes	10 km east of Bruce Rock
Cadoux	Bencubbin	30°54'25"	117°08'50"	Uncertain	South-West terranes	
Calingiri	Perth	31°09'10"	116°37'55"	Uncertain	South-West terranes	
Carlinga Well	Yalgoo	28°01'25"	115°52'30"	Residual	Murchison terranes	Also known as Tallering
Chandlers Breakaway	Leonora	28°15'20"	121°05'40"	Uncertain	Eastern Goldfields terranes	
Clackline	Perth	31°43'00"	116°31'00"	Residual	South-West terranes	
Cleary	Bencubbin	30°23'20"	117°38'55"	Uncertain	South-West terranes	5 km north of Cleary
Collie	Collie	33°23'00"	116°16'00"	Uncertain	South-West terranes	Vicinity of Shotts and at Premier mine, 4 km east of Shotts
Corrigin	Corrigin	32°20'00"	117°52'00"	Uncertain	South-West terranes	Location approximate
Cue	Cue	27°26'00"	117°53'00"	Uncertain	Murchison terranes	Location approximate
Culham Inlet	Ravensthorpe	33°52'06"	120°07'00"	Uncertain	Albany–Fraser Orogen	Location approximate
Cunderdin	Kellerberrin	31°46'00"	117°19'36"	Uncertain	South-West terranes	Location approximate (14 km southeast of Cunderdin)
Dale River	Pinjarra	32°14'35"	116°49'10"	Uncertain	South-West terranes	17.6 km southwest of Beverley
Darling Range	Perth					
Upper Swan		31°46'00"	116°06'00"	Uncertain	South-West terranes	
Smiths Mill Hill		31°41'00"	116°11'00"	Uncertain	South-West terranes	
Berry Brow Hill		31°49'00"	116°27'00"	Uncertain	South-West terranes	
Gidgegannup Hill		31°48'00"	116°08'30"	Uncertain	South-West terranes	
Nunamullen Lake		31°39'00"	116°29'00"	Uncertain	South-West terranes	
Dowerin	Kellerberrin	31°12'00"	117°02'00"	Uncertain	South-West terranes	Location approximate
Gabbin	Bencubbin					
Castlemain claim		30°35'30"	117°38'30"	Residual	South-West terranes	
Watts, Ottey and Whitsed claims		30°36'50"	117°43'10"	Residual	South-West terranes	
Gairdner South	Bremer Bay	34°13'50"	118°56'10"	Uncertain	South-West terranes	Location approximate
Gambier Lass	Laverton	28°45'00"	121°27'50"	Uncertain	Eastern Goldfields terranes	
Gibson	Esperance	33°35'30"	122°00'00"	Residual	Albany–Fraser Orogen	
Glen Forrest	Perth	31°55'00"	116°06'00"	Uncertain	South-West terranes	Number of localities (some with past recorded production)
Gnowangerup	Dumbleyung	33°57'55"	117°59'30"	Uncertain	South-West terranes	
Goomalling	Perth	31°18'38"	116°39'15"	Transported	South-West terranes	
Greenbushes	Collie	33°51'36"	116°03'53"	Residual	South-West terranes	
Hillman	Collie	33°19'00"	116°48'00"	Uncertain	South-West terranes	

Appendix 2 (continued)

Prospect	*1:250 000 Map sheet*	*Latitude*	*Longitude*	*Deposit type*	*Tectonic unit*	*Comments*
Jacup Creek	NEWDEGATE	33°46'00"	119°10'00"	Uncertain	South-West terranes	35 km northeast of Jerramungup
Jeedamya	MENZIES	29°16'55"	121°16'50"	Uncertain	Eastern Goldfields terranes	15 km north of Jeedamya
Jibberding	NINGHAN	29°50'10"	116°56'35"	Uncertain	Murchison terranes	17 km northwest of Jibberding
Jubuk	CORRIGIN	32°25'00"	117°41'30"	Residual	South-West terranes	
Jundee	WILUNA	26°15'30"	120°31'30"	Uncertain	Eastern Goldfields terranes	
Kalannie	BENCUBBIN	30°22'00"	117°07'00"	Uncertain	South-West terranes	
Kalgoorlie	KALGOORLIE	30°40'00"	121°22'30"	Uncertain	Eastern Goldfields terranes	Location approximate (13.5 km northwest of Kalgoorlie)
Karlgarin	HYDEN	32°31'10"	118°41'40"	Uncertain	South-West terranes	1 km south of Karlgarin
Katanning	DUMBLEYUNG	33°41'00"	117°33'00"	Uncertain	South-West terranes	Location approximate
Kellerberrin	KELLERBERRIN	31°38'00"	117°43'00"	Uncertain	South-West terranes	Location approximate
Kerrigan	HYDEN	32°39'33"	118°50'03"	Residual	South-West terranes	
Kintore	KALGOORLIE	30°35'00"	121°00'45"	Uncertain	Eastern Goldfields terranes	
Kirup	COLLIE	33°40'00"	115°59'00"	Uncertain	South-West terranes	MC 17109 and MC 17110
Koorda	KELLERBERRIN	31°01'25"	117°35'00"	Uncertain	South-West terranes	
Kulja	BENCUBBIN	30°30'05"	117°13'50"	Uncertain	South-West terranes	
Kunanalling	KALGOORLIE	30°40'30"	121°03'40"	Uncertain	Eastern Goldfields terranes	
Kweda	CORRIGIN	32°20'10"	117°23'55"	Uncertain	South-West terranes	Two adjacent occurrences 5 km north of Kweda
		32°20'00"	117°25'55"	Uncertain	South-West terranes	
Lake Ballard	MENZIES	29°30'00"	121°10'00"	Uncertain	Eastern Goldfields terranes	Location approximate
Lake Brown	BENCUBBIN	30°57'00"	118°20'00"	Uncertain	South-West terranes	At Morrison property near Lake Brown
Lake Magenta	NEWDEGATE	33°15'00"	119°11'00"	Uncertain	South-West terranes	
Laverton mine	LAVERTON	28°36'55"	122°29'55"	Uncertain	Eastern Goldfields terranes	Mine owned by Gwalia Consolidated Ltd
Leonora	LEONORA	28°50'40"	121°21'55"	Uncertain	Eastern Goldfields terranes	Two localities 5 km northeast of Leonora and 34 km north of
	LEONORA	28°36'55"	121°11'50"	Uncertain	Eastern Goldfields terranes	Leonora
Lomos	CORRIGIN	32°24'00"	117°50'00"	Uncertain	South-West terranes	South, southeast, and west of Corrigin
Lort River	RAVENSTHORPE	33°01'48"	121°03'18"	Residual	Southern Cross terranes	
Manjimup	PEMBERTON	34°15'00"	116°09'00"	Uncertain	South-West terranes	Location approximate
Meckering	KELLERBERRIN	31°30'00"	117°05'00"	Uncertain	South-West terranes	Location approximate (14 km northeast of Meckering)
Mollerin Lake	BENCUBBIN	30°34'30"	117°33'55"	Uncertain	South-West terranes	Two localities between 5–7 km south of Mollerin Lake
		30°32'05"	117°29'55"	Uncertain	South-West terranes	
Mount Gibson	NINGHAN	29°35'04"	117°20'53"	Residual	Murchison terranes	
Mount Kokeby	PINJARRA	32°16'48"	116°52'12"	Transported	South-West terranes	
Mount Kokeby	PINJARRA	32°16'00"	116°53'00"	Transported	South-West terranes	
Murray Deposit, Mount Kokeby	PERTH	32°15'57"	116°52'49"	Residual	South-West terranes	
Mount Magnet	KIRKALOCKA	28°00'30"	117°51'10"	Residual	Murchison terranes	
Mount Mallet	HYDEN	32°34'00"	118°43'36"	Uncertain	South-West terranes	
Mount Phoenix	LAVERTON	28°45'50"	121°58'20"	Uncertain	Eastern Goldfields terranes	
Mukinbudin	BENCUBBIN	30°53'30"	118°08'30"	Uncertain	South-West terranes	
Mullewa	YALGOO	28°28'27"	115°33'02"	Residual	Murchison terranes	
Narrogin	CORRIGIN	32°56'00"	117°10'00"	Uncertain	South-West terranes	
Newlands	COLLIE	33°39'00"	115°53'00"	Uncertain	South-West terranes	Location approximate (1.5 km north of Newlands)
Noombenberry Rock	SOUTHERN CROSS	31°40'30"	118°48'30"	Uncertain	South-West terranes	
Northcliffe	PEMBERTON	34°43'00"	115°59'00"	Uncertain	Albany–Fraser Orogen	

Appendix 2 (continued)

Prospect	*1:250 000 Map sheet*	*Latitude*	*Longitude*	*Deposit type*	*Tectonic unit*	*Comments*
Ockley–Wickepin	CORRIGIN	32°49'40"	117°43'40"	Residual	South-West terranes	
Ongerup	NEWDEGATE	33°46'18"	118°35'00"	Uncertain	South-West terranes	25 km north-northeast of Ongerup
Pallinup River	BREMER BAY	34°19'20"	118°31'40"	Uncertain	South-West terranes	Plantagenet Location 2634
Perangery	PERENJORI	29°21'50"	116°23'25"	Uncertain	Murchison terranes	Two localities at Locations 10578 and 7670, 15–17 km northeast of Perenjori
		29°21'50"	116°24'00"	Uncertain	Murchison terranes	
Piawaning	MOORA	30°52'24"	116°22'48"	Uncertain	South-West terranes	2 km southwest of Piawaning
Pingaring	HYDEN	32°43'50"	118°37'35"	Uncertain	South-West terranes	3 km north of Pingaring
Quairading	CORRIGIN	32°01'00"	117°24'00"	Uncertain	South-West terranes	
Roebuck Bay	LAGRANGE	18°11'30"	122°17'30"	Uncertain	Canning Basin	
Roelands	COLLIE	33°17'10"	115°54'10"	Uncertain	South-West terranes	
Ryans Find	KALGOORLIE	30°56'00"	120°12'20"	Uncertain	Southern Cross terranes	
Skeleton Rocks	HYDEN	32°03'18"	119°30'48"	Uncertain	Southern Cross terranes	
Tambellup	MOUNT BARKER	34°03'14"	117°35'06"	Residual	South-West terranes	
Tampu	BENCUBBIN	30°13'45"	117°48'30"	Residual	Murchison terranes	
Tingledale	PEMBERTON	34°58'20"	116°52'42"	Uncertain	Albany–Fraser Orogen	
Upper Yeriminup Pool	PEMBERTON	34°12'30"	116°54'12"	Uncertain	South-West terranes	
Wagin	DUMBLEYUNG	33°16'45"	117°18'30"	Uncertain	South-West terranes	Location 3533, 3 km northwest of Wagin
Wandering South	PINJARRA	32°41'25"	116°37'40"	Uncertain	South-West terranes	Location 28199
West Morawa Hill	PERENJORI	29°12'00"	115°50'00"	Uncertain	Murchison terranes	Location approximate
West River	NEWDEGATE	33°39'55"	119°44'00"	Uncertain	South-West terranes	
Yerecoin	MOORA	30°52'05"	116°24'00"	Transported	South-West terranes	
Yindarlgooda	KURNALPI	30°32'28"	121°42'52"	Transported	Eastern Goldfields terranes	

Appendix 3

Index of kaolin localities in Western Australia