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Department of Industry and Resources

SILICA RESOURCES OF WESTERN AUSTRALIA

by P. B. Abeysinghe

Geological Survey of Western Australia

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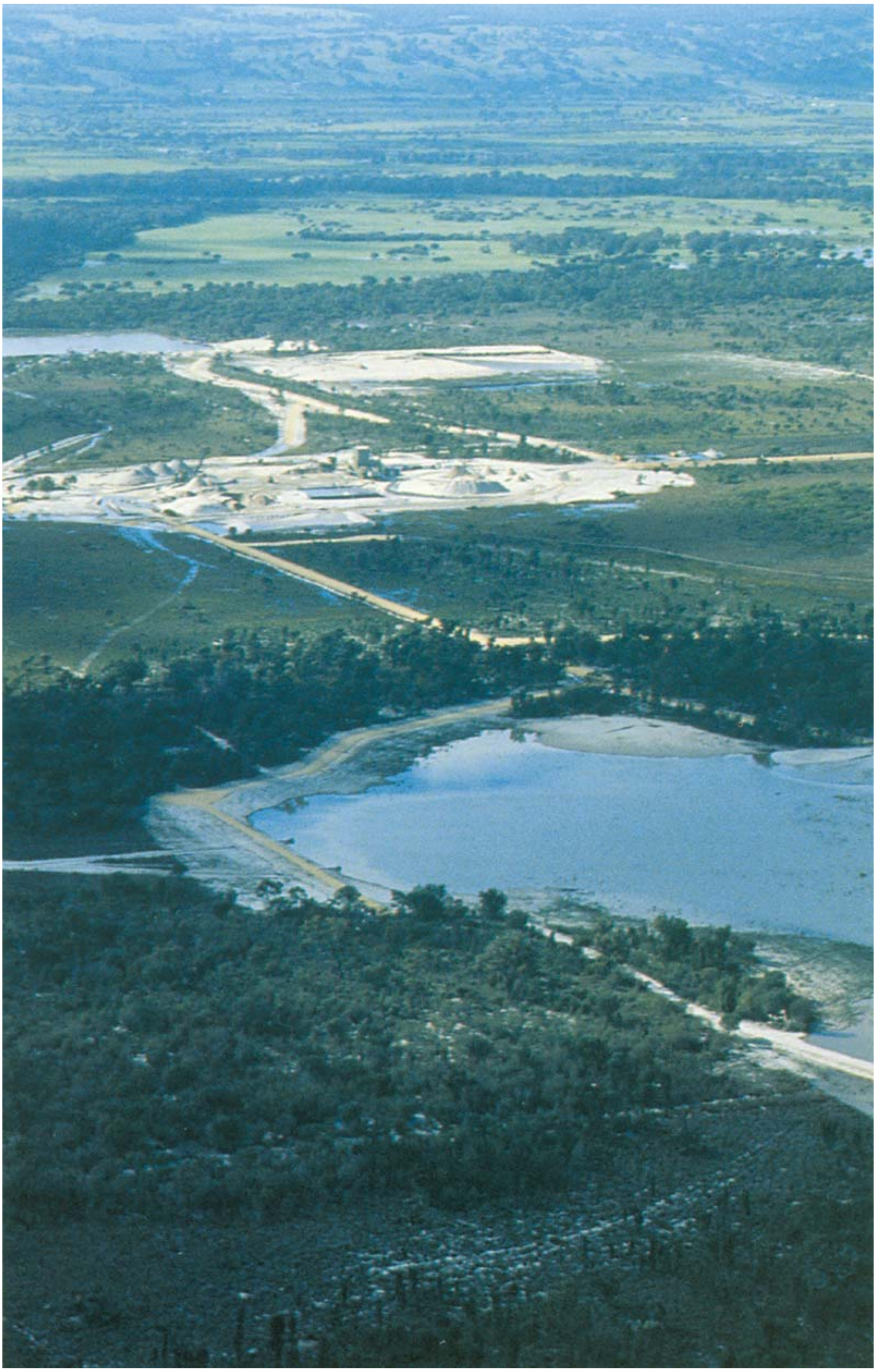
OF WESTERN AUSTRALIA



FRONTISPIECE

An aerial view of the Kemerston mine site showing the settlement pond in the foreground and the plant and dredge pond in the background (Photograph courtesy of Kemerton Silica Sand Pty Ltd).

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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Cover photograph:
Silica sand stockpile at Jandakot (photo by J. M. Fetherston).

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Silica resources of Western Australia

by
P. B. Abeysinghe

Abstract

Current world production of silica is estimated at 120–150 Mt per annum, of which Australia produces some 3% (3.9 Mtpa) with Western Australia's contribution around 0.9 Mtpa. In 2000, Western Australia produced 898 994 t of silica sand and 92 149 t of chert, with estimated ex-mine values of $11.3 million and $920 000 respectively.

In Western Australia, high-grade silica sand deposits are well known in the Pleistocene Bassendean Sand of the Perth Basin, and are currently mined at Gnangara, Jandakot, Bullsbrook (all near Perth), and at Kemerton, 25 km north of Bunbury. High-grade silica sand is also mined at Mindijup, 35 km northeast of Albany, and deposits in the broader southern region include those at Lake Don, Merivale, and Condingup. The sand in the Albany region and that from the Bassendean Sand on the west coast is of very high chemical quality, generally exceeding 99% silica, but grain size in the Albany region is finer. Sand from the Kalgoorlie region, derived from the mottled-pallid zone of laterite, is of inferior chemical quality.

The silica sand produced in Western Australia (over 98% is exported to Asia) is used in high-grade applications including glass, chemicals, refractories, foundry sand, and filtration. The total resource of silica sand in Western Australia is around 324 Mt, of which 292 Mt are in the Bassendean Sand. However, the actual resource of silica sand in the State is likely to be much higher.

The only production of high-quality silica rock in Western Australia is of chert from Moora, 200 km north of Perth. The measured resource in this deposit is estimated as 2 Mt at 99.3% silica. Moora chert is of high metallurgical and chemical quality and supplies a silicon production plant at Kemerton. This plant, one of the most efficient in the world, has the capacity to produce 31 000 tpa of silicon metal (4% of world production) and 10 000 tpa of silica fume.

Other prospective targets in Western Australia for chert and quartz rock suitable for silicon metal production include: quartz–feldspar pegmatite at Mukinbudin (290 km east of Perth) and Karloning (30 km north of Mukinbudin); quartz veins at Karratha (1535 km north of Perth), Nanutarra (1260 km north of Perth), and Bonnie Rock (345 km east of Perth); and chert formations southeast of Shaw River in the Pilbara Craton.

KEYWORDS: Western Australia, pegmatite, quartz veins, quartzite, chert, silicon, silica sands, silica, size distribution, chemical analysis, natural resources, industrial minerals, production.

Chapter 1

Introduction

Object and scope

The main objective of this Bulletin is to compile most of the available published and unpublished information on silica resources of Western Australia into one publication, as well as to provide some new data. The Bulletin is not intended to be an exhaustive study of all the known deposits and occurrences, but is a comprehensive summary highlighting the development potential of silica resources in Western Australia. The main emphasis of this Bulletin is on high-grade silica sand, and therefore the resources of low-grade sand, such as concrete and filling sands for construction applications, are not dealt with except in instances where such low-grade sand is mined as a byproduct from high-grade deposits.

The economic viability of silica resources depends mainly on the location of deposits in relation to transportation systems, processing facilities, markets, and major national and international distribution centres. Therefore, in the current study, more attention is paid to silica resources close to the Perth region and regional centres such as Albany, Esperance, Kalgoorlie, Port Hedland, and Karratha.

Other significant factors in the silica industry are global production and product end-use. Accordingly, these topics, together with mineralogical and geological aspects of silica sand and other silica raw materials, are discussed in this Bulletin. Also the mode of occurrence, uses, specifications, and local production of silica resources in Western Australia are presented in detail.

Sources of information

The sources of information are from both published and unpublished data, supplemented by field inspections. Unpublished information is derived from Geological Survey of Western Australia (GSWA) records, annual reports, technical files, and statutory exploration reports submitted to the Department of Industry and Resources (DoIR) by various mining companies.

Some of the major deposits, and others thought to be potentially significant, were visited and sampled by the author. Approximately 145 samples were collected for laboratory testing during field trips in May–June 2000. The main tests carried out on silica sand samples include chemical analyses and particle-size analyses. Tests carried out on silica rock samples include chemical analyses, petrographic studies, thermal stability, and thermal strength. All chemical and particle-size tests were carried out by SGS Australia Pty Ltd, Perth. Petrographic studies were conducted at Pontifex and Associates Pty Ltd, Rose Park, South Australia, and thermal tests were performed in the laboratories of Simcoa Pty Ltd, Kemerton, Western Australia. The reconnaissance nature of the sampling and the high costs for other tests precluded more detailed testing of the samples. However, the test results obtained do provide useful guidelines for those interested parties who may wish to carry out more detailed exploration and evaluation in selected areas.

All localities of samples collected by the author together with other deposits and occurrences referred to in the text are given in Appendix 1. Sample locations in the Perth Metropolitan Area (Gozzard, 1987a,b) are given in Appendix 2. Reference throughout the text to the Perth metropolitan region embraces the broader area lying within 100 km of the city of Perth, as defined in Landvision (1996).

All dollar values are in Australian currency unless otherwise indicated.

Abbreviations used in this Bulletin

Abbreviations used in this Bulletin are as follows:

AHD	Australian height datum or mean sea level
DoIR	Department of Industry and Resources
E	Exploration Licence
GSWA	Geological Survey of Western Australia
ICP	Inductively Coupled Plasma
JORC	Joint Ore Reserves Committee: Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists and Minerals Council of Australia — Australian code for reporting of mineral resources and ore reserves
MC	Mineral Claim
M	Mining Lease
ML	Mineral Lease
P	Prospecting Licence
pp	Private Property
PA	Prospecting Area
SEM	Scanning Electron Microscope
UK	United Kingdom

USA	United States of America
XRF	X-ray fluorescence

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Chapter 2

Mode of occurrence and uses of silica

Mode of occurrence

Silica, the chemically resistant dioxide (SiO_2) of silicon, is found in nearly every rock type of all geological ages and virtually everywhere in the world. It exists mostly in the crystalline form of quartz, but also in cryptocrystalline and amorphous forms, and combined in silicates as an essential constituent of many minerals. For industrial applications, silica is obtained from silica sand as well as the rock types quartzite, pegmatite, vein quartz, quartz sand, sandstone, novaculite, flint, chert, and quartz crystal. Although these rock types are very common in nature, high-grade silica deposits suitable for many specialty applications are not easily found.

These can form in a variety of geological environments and the following provides brief descriptions of the mode of occurrence and other geological characteristics.

Silica sand

Unconsolidated quartz-rich, sandy sediments derived from silica-rich rocks such as sandstone, acidic igneous rocks, quartzite, granite, granite gneiss, and pegmatite can give rise to high-grade silica sand deposits suitable for many applications varying from low-grade, such as filling sand, to high-grade applications such as glass sand. In most instances, high-grade deposits are formed as a result of geological processes that give rise to natural sorting and beneficiation of unconsolidated material. Depending on the degree of natural sorting, beneficiation, and other geological processes, the quality of such deposits can be variable, and understandably, the highest grade deposits are developed from material that has been reworked over several cycles of erosion and deposition. High-grade silica sand beds may be interspersed with beds or lenses of relatively low-grade sand, which is generally suitable only for such applications as concrete, or filling. The most favourable geological environments for silica sand deposits are current and ancient shorelines, low-lying alluvial and colluvial formations, palaeochannels, and palaeodrainages.

Silica sand is the largest single source of silica in Western Australia. The Bassendean Sand in the Perth Basin, which will be discussed in **Chapter 4**, is the best known geological unit in the State carrying high-grade silica sand.

Sandstone

Sandstone is a sedimentary rock consisting predominantly of quartz grains cemented together by argillaceous, calcareous, ferruginous, or siliceous material. Depending on the degree of cementation, the sandstone can vary from very hard to friable or loosely consolidated. Generally, the degree of induration or cementation will be higher as the grain size of the sandstone gets smaller. The colour of sandstone depends largely on the type of cementing material. Common impurities in sandstones include feldspar, mica with a wide variety of minerals in trace amounts, ilmenite, rutile, zircon, magnetite (and other iron oxide minerals), tourmaline, and kyanite. The purest sandstones, also known as quartz arenites, contain over 95% quartz, which is generally fine to medium grained, well sorted, and with well-rounded quartz grains. These sandstones are more common in near-shore facies environments.

To date, sandstone has not been used as a source of silica in Western Australia, although it is mined in the United States, United Kingdom, Canada, and Germany for silica used in specialty applications. In these countries, sandstones intended for industry, range from Cambrian to Carboniferous in age and thickness of useable strata can vary from 2 m to more than 85 m (Alsobrook, 1994).

Quartzite

Quartzite is a variety of metamorphosed sandstone and is distinguished from sandstone by its fracture pattern. Sandstone breaks along boundaries between constituent grains, whereas quartzite is so tightly cemented and indurated that it breaks across the grains. Orthoquartzite is a clastic sedimentary rock that is made up almost exclusively of quartz sand (with or without chert). It is also a term used for a quartzite of sedimentary origin comprising almost pure quartz sandstone. Orthoquartzite generally indicates a sandstone with 90–95% quartz and detrital chert grains that are well sorted, well rounded, and cemented primarily with secondary silica (sometimes with carbonate) in optical and crystallographic continuity with the grains. Metaquartzite is a term used for a quartzite formed by metamorphic recrystallization. In this material, grains of quartz have lost their individual identity and the rock no longer has the granular texture of sandstone (Alsobrook, 1994; Jackson, 1997).

Quartzite can exhibit diverse texture, friability, colour, and chemical purity depending on the type of cementing material present, grain size, mineral composition of the parent sandstone, and intensity of metamorphism. Quartzite derived from argillaceous sandstone often contains sericitic partings, which may raise its alumina and alkali content above acceptable limits for many uses, and cause it to crush into undesirable slabby pieces. Fine- to medium-grained, massive quartzite that contains little or no feldspar, mica, or carbonate mineral impurities tends to be dense, hard, and tough and crushes into sharp, brittle, angular fragments. Its chemical purity can be as high as 99.8% SiO_2. Coarser grained quartzite tends to be less pure and more friable, particularly when cementing material is argillaceous or calcareous. Colours of quartzite range from white and grey-white to shades of red, pink, purple, blue, and orange.

Countries using quartzite as a source of silica include the United States, Canada, Republic of South Africa, Norway, Sweden, Italy, and the Czech Republic.

Vein quartz

Vein quartz intruding igneous, metamorphic, or sedimentary rocks can be a source of massive quartz for specialty applications. Most vein quartz deposits are believed to have formed by hydrothermal processes. Quartz veins may be zoned with several generations of quartz. Commonly, the oldest generation of quartz is coarse and is found at the core of the veins while younger generation quartz is finer and is found away from the core. The early-phase coarse quartz tends to carry abundant inclusions and to be less pure than the younger quartz.

The countries using vein quartz as a source of silica include Brazil, USA, Angola, Republic of South Africa, Madagascar, India, Sri Lanka, Chile, and Canada (Alsobrook, 1994).

Novaculite

The term novaculite is derived from the Latin word ‘novacula’ meaning razor hone. Novaculite is a very dense, hard, fine-grained, homogeneous, and highly siliceous sedimentary rock similar to chert but characterized by a predominance of microcrystalline quartz over chalcedony. It was formerly believed to be the result of primary deposition of silica, but in the type occurrence in the Ouachita Mountains in Arkansas, Oklahoma, USA, it appears to be a thermally metamorphosed bedded chert, distinguished by a characteristic microscopic polygonal triple-point texture. The origin of novaculite has also been ascribed to crystallization of opaline skeletal material during diagenesis. Novaculite varies in colour from white to grey, light brown, bluish, or black, is translucent in thin edges, and breaks with an uneven or conchoidal–subconchoidal fracture. The lustre of novaculite varies from waxy to dull, the latter resembling that of unglazed porcelain. The chemical purity of novaculite can exceed 99% SiO_2 in the form of microcrystalline or cryptocrystalline quartz (Alsobrook, 1994; Harben and Kuzvart, 1996; Keller et al., 1977; Jackson, 1997).

Novaculite is used as a source of silica in the United States, and the main deposits are found in regions within Arkansas and Oklahoma.

Chert

Chert is a hard, extremely dense, or compact, dull to semi-vitreous, microcrystalline or cryptocrystalline sedimentary rock, consisting dominantly of interlocking crystals of quartz less than 30 µm in diameter; it may also contain amorphous opaline silica. Common impurities include calcite, iron oxide, clay, and the remains of siliceous and other organisms. It has a tough, splintery to conchoidal fracture and the colour can be white, grey, green, blue, pink, red, yellow, brown, or black. Chert is found as nodular or concretionary segregations in limestones and dolomites, and also as areally extensive layered deposits. It may also be found as an original organic or inorganic precipitate or a replacement product (Jackson, 1997).

Large deposits of layered high-quality chert found in the Moora region of Western Australia are used as a source of silica. The chert at Moora is developed predominantly within the Noondine Chert, which is a silicified, bedded, carbonate (siliceous limestone/dolomite) unit. Silicification of the chert is observed to a depth of 75 m below the surface (discussed in **Chapter 5**).

Flint

Flint is a very compact, hard, homogeneous silica rock that breaks with a conchoidal fracture, giving clean and smooth surfaces. It is commonly dark grey or black when fresh and on weathering acquires a chalky-white appearance on the surface. Typical flint consists entirely of silica, free from calcium carbonate and detrital particles. The term is often used as a name for homogeneous, dark-grey or black chert, and therefore use of the term can be confusing (Harben and Kuzvart, 1996).

In South Australia, flint (fossiliferous chert with granular, cherty matrix) occurs in four geological settings — beds and dykes in the Early Miocene – Late Oligocene Gambier Limestone, bouldery conglomerate of the Pleistocene Bridgewater Formation, Holocene beach deposits, and Holocene lag deposits. High-grade samples from several South Australian localities are chemically similar to flint produced from Northfleet Plant, UK, for use in ceramics (Flint et al., 1992). There are no significant occurrences of flint in Western Australia.

Pegmatite

Pegmatites can often be a good source of high-grade silica. For example, pegmatites associated with granitic intrusions may yield very pure quartz, especially in the case of microcline pegmatites that are devoid of muscovite and rare earth element oxides but have a well-developed quartz core. Some of the pegmatite bodies at Mukinbudin in Western Australia (discussed in **Chapter 5**) are known to contain high-grade quartz zones. Such zoned pegmatites are mined selectively to yield both high-grade feldspar and quartz.

Silica pebble

Silica pebble beds found in certain geological environments such as in fluvial deposits, sedimentary chalk and marl beds can be a good source of silica for specialty applications. For example, in the United States, one of the most important sources of metallurgical-grade silica gravel for silicon metal and high-purity ferrosilicon production is fluvial channel and bar deposits found in raised terraces that roughly parallel the present course of the Dee River in North Carolina and those of other major rivers in the coastal plain of South Carolina, Georgia, Florida, and Alabama (Alsobrook, 1994). Currently, two quartz pebble fluvial deposits are mined at Cowra in New South Wales, Australia.

Tripoli

Tripoli, or tripolite, is another source of silica, and the term tripoli is commonly used for residual material resulting from weathering of siliceous limestone. It is highly siliceous, microcrystalline, soft, friable, and porous. The silica content averages 98–99%, the remainder being alumina, titania, and iron oxide. The colour varies from white or yellow through brown to red depending on the iron oxide content. Commercially, white tripoli is classified as ‘cream’, and light pink to red tripoli as ‘rose’. Particle size ranges mostly from less than 0.1 to 7 μm, and when ground, individual grains may be as small as 0.02 μm. The porosity of this rock is about 45% (Harben and Kuzvart, 1996).

Other sources of silica

Some high-grade silica is recovered as a byproduct of kaolin mining in many regions of the world (e.g. California in USA). Feldspathic sand may yield large quantities of silica, one example being extensive feldspathic sand deposits at Carrascal del Rio, near Segovia in Spain, where the production of silica is twice that of feldspar.

In Brazil and Madagascar, optical- and piezoelectric-grade quartz crystal is common in pegmatites, hydrothermal veins, and placer deposits.

Uses of silica

The uses of silica are diverse and can vary from simple foundry sand to a large number of products used in daily life, including many types of glassware, computer chips, and fibre optics.

Silica sand

The following is a summary of the more common uses of silica sand. Extensive reference has been made to the work of Zdunczyk and Linkous (1994), Coope (1989), and Bolger (1996).

Glass

Silica sand, also commonly referred to as either quartz sand or simply glass sand, is the major raw material used in glassmaking. Glass manufacturers usually classify silica sand into separate groups on the basis of chemical and physical properties. Since the impurities of silica sand in different deposits in the world are dependent on numerous geological factors, glass producers have set specifications to each source of approved material and, in general, manufacturers are concerned mostly about the consistency of the approved material on a day-to-day basis. Minerals such as ilmenite, leucoxene, kyanite, and zircon are impurities on which strict limits are placed for a glass raw material. Because of their highly refractory nature, such minerals either do not melt or only partially melt, which results in stones or feathers in finished glass. Aluminosilicates, such as kyanite, also contribute unwanted alumina to the raw material as these only partially melt.

The main applications of glass sand are in the manufacture of colourless glass containers, flint glass (float, sheet and rolled plate or patterned glass), and coloured (amber and green) glass containers. The silica content of the sand used can vary depending on the particular application, but for many varieties should preferably exceed 98% (Tables 1 and 2). The physical requirements of the various grades of glass sand are similar, with a narrow grain-size distribution being required as the presence of oversize material and fines can cause difficulties in the melting and refining process.

Soda–lime–silica glass was the earliest man-made glass and still accounts for most of the glass manufactured for commercial uses. This type of glass is used in incandescent and fluorescent lamps, glass fibre, and flat glass products among many others (Zdunczyk and Linkous, 1994).

Foundry sand

In the foundry casting industry, the majority of moulds and cores are made primarily from silica sand. It is used in the manufacture of moulds and cores for casting metals such as steel, ductile iron, grey iron, and aluminium- and copper-based alloys. Foundry moulds and cores are the second largest industrial use of silica sand after the glass industry. Foundry sand must generally exceed 98% SiO_2 in purity and limits are placed on the percentages of CaO and MgO present. The greater the amount of CaO and MgO, especially CaO, the more synthetic binder is required in making a mould or core. In the past, many foundries used naturally bonded silica sands for moulding because the sand was held together to form a specific shape by its natural clay content, and little or no additional binder was needed. However, many foundries today use synthetic sand, which is silica sand free of clay and other deleterious material and thus has a very high SiO_2 content.

The important properties for commercial-grade foundry sand are grain size and shape, thermal character-

Table 1. Glass sand specifications for flat glass

Chemical specifications		*Physical specifications* Grain size (mm)	Cumulative % retained
SiO_2	>99.5%	1.18	0.0
Fe_2O_3	<0.04%	0.850	<0.01
Al_2O_3	<0.30%	0.425	<0.10
TiO_2	<0.1%	0.106	>92.0
Cr_2O_3	<2 ppm	0.075	>99.5
Co_3O_4	<2 ppm		
MnO_2	<0.002%		
H_2O	<0.05%		

SOURCE: after Zdunczyk and Linkous (1994)

Table 2. Glass sand specifications for flint container glass

Chemical specifications (%)		*Physical specifications* Grain size (mm)	Cumulative % retained
SiO_2	>98.5	1.18	0.0
Fe_2O_3	<0.035	0.850	0.0
Al_2O_3	<0.5	0.600	<4
CaO+MgO	<0.2	0.425	<25
TiO_2	<0.03	0.106	>95
ZrO_2	<0.01		
H_2O	<0.1		
Cr_2O_3	<0.001		

SOURCE: after Zdunczyk and Linkous (1994)

istics, and purity. Grain size largely determines the finish of the casting — the finer the sand the better the finish. However, this must be weighed up against core permeability, which is enhanced with coarser grains and prevents casting defects. In general, a grain size of 200–300 µm is preferred with a grain-size distribution spread over four to five consecutive sieves. There is an inverse relationship between the grain size of the sand and the 'green strength', which prevents the mould collapsing whilst being formed. Grain shape also influences the green strength and permeability of a mould. More-angular grains require higher levels of binders owing to their low packing density and high surface area. Rounded grains have better strength and flowability characteristics at lower ramming densities, but angular grains are better at higher ramming densities. Silica sands can have different thermal characteristics and sintering points due to the presence of impurities. Uneven thermal expansion can cause casting defects such as scabs and buckles. Therefore, in some instances it may be necessary to select a chromite, olivine or zircon sand instead of silica to achieve a more even rate of thermal expansion. Impurities such as feldspar and mica in the mould sand can cause detrimental effects such as 'burn-on' (Bolger, 1996).

Filtration sand

Filtration sand must be relatively pure and free of clay, dust, and organic matter. There are no strict specifications defining grain shape except that grains should not be elongate or flat. Angular and round grains appear to work equally well. However, sand must be uniform in size, with a narrow grain-size distribution. An excess of fine material reduces the efficiency of the filter bed by reducing porosity and permeability, thereby reducing the rate of water flow. Two important specifications that filtration sand must meet are 'effective size' and 'uniformity coefficient'. Effective size of sand is the size of a sieve opening that will just pass 10% by weight of a representative sample. For example, if a sand sample has 10% by weight passing through a sieve opening of 0.45 mm, then the sand has an effective size of 0.45 mm. The uniformity coefficient of a filter sand is a ratio calculated by dividing the size of a sieve opening that will pass just 60% of a representative sample of the sand by the size of a sieve opening that will pass just 10% (the effective size) of the same sample. Table 3 indicates typical grain size and chemical composition of filtration sand (Zdunczyk and Linkous, 1994).

Filtration sand is used in plants for water treatment, wastewater treatment, desalination, and tertiary treatment. In water treatment plants, the sand normally used has an effective size of 0.70 mm with a uniformity coefficient of 1.40–1.70. Wastewater treatment plants use sand with an effective size of 0.8–3.0 mm and a uniformity coefficient of 1.40 or less. Desalination treatment plants use sand to filter the particulates from the seawater before Reverse Osmosis Processing. Sand with an effective size of 0.70 mm and a uniformity coefficient of 1.40–1.70 is normally used. Tertiary treatment enables disposable water to be returned to its original source with minimal environmental impact. Sand enhances the quality of wastewater effluent by further decreasing the particulates and pollutants present (information pamphlet of Colorado Silica Sand Inc.).

Table 3. Typical grain size and chemical composition of filtration sand

Chemical composition (%)		*Grain size (mm)*	*Uniformity coefficient*
SiO_2	99.39	0.40–0.50	<1.60
Fe_2O_3	0.24	0.50–0.60	<1.60
Al_2O_3	0.19	0.60–0.70	<1.60
TiO_2	0.12	0.70–0.80	<1.60
CaO	0.01	0.80–1.00	<1.65
MgO	0.004	1.00–1.50	<1.70
LOI	0.046		

NOTES: Acid solubility (1:1 HCl) 0.08–0.11%
Specific gravity 2.64–2.66

SOURCE: after Zdunczyk and Linkous (1994)

Environmental sands

Specially graded filter media of silica sand can be used to remove hazardous and industrial particles from wastewater. The filter media produced for such applications are tightly graded and consist of round and spherical particles for uniform filtering action, deeper bed penetration and longer filtering periods. Unlike angular sands, the rounded and spherical particles rotate during backwash and scour adjacent grains, freeing the adhering solids. This reduces the backwashing pressure and also results in water and energy savings (information pamphlet of Colorado Silica Sand Inc.).

Blasting sand

Silica sand is used as an abrasive agent to clean metal, concrete, brick, and other surfaces. It is also used as a grinding or polishing medium and in stone sawing. For use as blasting sand, it should be free from impurities such as mica, organic material, carbonate, and clay and must have a particular angular shape and particle size. It must also be hard and durable. Coarse blasting sand is used on large steel or iron structures, whereas finer sand is used in cleaning brass, aluminium, and wood.

The use of silica sand as blasting sand faces stiff competition from other commodities such as slags, garnet, and fused alumina and (to a lesser extent) staurolite. Furthermore, the health risk associated with breathing fine crystalline silica dust has made alternative products much more attractive (Zdunczyk and Linkous, 1994). In Western Australia, garnet for abrasives is mined (approximately 100 000 tpa) from Port Gregory, approximately 75 km northwest of Geraldton, and Tiwest Joint Venture has the capacity to produce approximately 20 000 tpa of staurolite for abrasives from heavy mineral sand deposits at Cooljarloo, 170 km north of Perth (Flint and Abeysinghe, 2001; Elliott and Benson, 2001).

Chemicals — silica sand

Silica sand treated with soda fume (sodium carbonate) or caustic soda (sodium hydroxide) forms sodium silicate (also known as waterglass), an important chemical used in detergents, catalysts, pigments, adhesives, papermaking, ore treatment, and feed stock in the manufacture of aluminium silicate, calcium silicate, and synthetic zeolite. Sodium silicate is traditionally made by the ‘furnace process’, where silica sand and sodium carbonate are subjected to high temperature fusion (at a temperature of 1400ºC) in a glass tank type of furnace. The sodium silicate produced may subsequently be dissolved under pressure (in autoclaves) and processed to yield a comprehensive range of silicate solutions. Alternatively, liquid silicates can be obtained directly in a wet process known as the ‘hydrothermal process’ involving the hot dissolution of silica sand in sodium hydroxide. This process requires a temperature of 150–200ºC. Both processes are widely used and choice between the two is based on a combination of economic and technical factors.

A number of different grades of silica sand may be used for the manufacture of sodium silicate. Most grades consist of sand close to container glass grade specification (Table 2) and containing less than 5 ppm heavy minerals. However, both Al_2O_3 and CaO must not exceed 0.1%. For certain applications stricter purity requirements are imposed with 0.10–0.15% Fe_2O_3, and with Al_2O_3 and CaO contents in the region of 0.01–0.02% (Coope, 1989).

Proppant sand

Proppant sand, also known as hydraulic fracturing sand or ‘frac sand’, is used during recovery of hydrocarbons in order to increase reservoir yield, with the sand injected and propping open fissures and voids in reservoirs to increase the flow rate of gas, oil, and other fluids towards a well. The sand for this use should consist predominantly of highly durable well-rounded silica grains with only minor amounts of impurities such as clay, feldspar, and calcite. The most common screen sizes of proppant sand are: 1.0–3.35, 1.18–2.36, 0.850–1.7, 0.212–0.425, and 0.106–0.212 mm. For each sand product, 90% of the material should be within the size range specified. Within each major size classification is a series of sieves on which specified percentages of material must be retained (Zdunczyk and Linkous, 1994). A major source of proppant sands is from deposits at Colorado Springs, USA.

Filler, pigment extender, and fibreglass

Silica can be ground to produce silica products for use as functional fillers and pigment extenders in paints, plastics, sealants and adhesives, rubber, and many other industrial products. The term ‘silica flour’ is used for lower value filler applications, and the term ‘ground silica’ denotes a higher value functional filler that modifies the end-product in which it is used.

Finely ground crystalline silica (chemically treated as well as uncoated) is used as a functional filler to modify the physical properties of a final product in ways not readily achieved with other mineral fillers. Ground silica is used to improve toughness, increase scrubbability, improve weather resistance and prevent chalking, and as a pigment extender. It is also used as a flattening agent and dispersant in paint.

Ground silica is a major component in the production of continuous strand fibreglass. Tables 4 and 5 indicate the

Table 4. Glass sand specifications for ground silica for use as filler

Chemical specifications (%)		*Physical specifications* Grain size (mm)	Cumulative % retained
Fe_2O_3	<0.10	0.250	0
Al_2O_3	<0.38	0.075	<1
Na_2O	<0.10	0.045	<3
K_2O	0.10		

SOURCE: after Zdunczyk and Linkous (1994)

Table 5. Glass sand specification for fibreglass

Chemical specifications (%)		Physical specifications Grain size (mm)	Cumulative % retained
SiO_2	>99	0.250	<0.01
Al_2O_3	<0.30	0.075	<0.6
Fe_2O_3	<0.50	0.045	<3.0
Na_2O	<0.10		
K_2O	<0.10		
LOI+H_2O	0.50		

SOURCE: after Zdunczyk and Linkous (1994)

general chemical and physical specifications for silica sand for use in ground silica products and fibreglass (Zdunczyk and Linkous, 1994; Harben and Kuzvart, 1996).

Fused silica powder and grain products

Fused silica powder and grain products are produced mainly from silica sands. The grades of fused silica powder range from 99.4–99.9% SiO_2. The three main markets served by these grades are refractories, investment casting, and as fillers in epoxy resins for the electronics industry. The refractory uses of fused silica are discussed under **Refractories** in silica rock resources.

The investment casting (coating) has applications in the production of aero engine parts (notably turbine blades and vanes), and parts for land-based turbines for power generation. In the investment casting industry, a refractory slurry is required to coat (invest) a wax assembly, which resembles the shape and pattern of the desired component. The assembly is further coated with a refractory stucco in layers to build up a shell. After drying, the shells are rapidly dewaxed and then fired to over 1000ºC to remove any residual wax, and to cure the stucco binder. Molten metal is poured into the shell (casting) and, after cooling, the shell is broken off the casting (knock-out) leaving the cast shape ready for final finishing. Other materials that are used as a refractory slurry include zircon and aluminosilicates. Technical and economic factors determine the choice of a particular refractory slurry (O'Driscoll, 1997).

Epoxy resin fillers or epoxy moulding compounds (EMC) are used in the electronics industry as an inert, low-expansion filler. Each chip or microcircuit is packaged in a blend of fused silica and epoxy for protection. Fused silica powders have excellent insulating and dielectric properties (O'Driscoll, 1997).

Silica rock

Silica raw materials (sandstone, quartz, quartzite, chert, quartz pebbles, silica gravel and lump, novaculite, and quartz crystals) are used in a variety of industrial applications depending on acceptable chemical and physical specifications. The following is a summary of the more common silica applications of these raw materials.

Metallurgy

Silicon metal and alloys

Metallurgical-quality quartz and chert, crushed quartzite, novaculite lumps, and round quartz and quartzite pebbles are used in the electric-arc furnace production of silicon metal, ferrosilicon (FeSi) and other silicon alloys.

Vein quartz can also be used for the production of ferrosilicon alloys, but some ferrosilicon producers prefer quartzite, even though its Al_2O_3 and Fe_2O_3 contents tend to be higher, because vein quartz is more brittle and therefore usually results in excessive fines during handling. Also, vein quartz contains fluid inclusions causing it to explode and form additional fines when exposed to furnace temperatures. For metallurgical uses, silica rock should not be friable, should have high thermal shock resistance, should be free of fines when delivered, and should not crumble or decrepitate into fines when heated. In electric-arc furnaces, fines must be avoided as they reduce the porosity of the charge, which results in blocking the flow of gases (CO and SiO) causing premature fusion and crusting. This results in a build-up of gas that may cause furnace blowouts, resulting in reduced efficiency through loss of silicon during the process (Alsobrook, 1994).

In the manufacture of silicon metal (Si), silica is reduced in a submerged-arc furnace using graphite electrodes at a temperature of 1780ºC. At this temperature silica (SiO_2) in the raw material will become molten and be reduced to gaseous silicon monoxide (SiO), while the reductant carbon in graphite is oxidized to gaseous carbon monoxide (CO). Some of the silicon monoxide liberated will react with the remaining carbon, at temperatures above 1566ºC, to form silicon carbide (SiC), which reacts with molten silica present in the system to form silicon metal. The remaining silicon monoxide, after leaving the furnace bed, will react with oxygen to form a finely divided form of silica, known as silica fume, which is predominantly amorphous silica, with some unreacted carbon, silicon carbide, and crystalline silica together with very low levels of silicon and graphite. The process involves the following main chemical reactions (Spratt et al., 1989):

$$SiO_2 + C \rightarrow SiO + CO$$
$$SiO + 2C \rightarrow SiC + CO$$
$$SiO_2 + SiC \rightarrow Si + SiO + CO$$
$$SiO + 0.5O_2 \rightarrow SiO_2$$

In the production of silicon metal, the most commonly used sizes of quartz and quartzite lumps are either 3.81–10.16 cm or 2.54 –7.62 cm in diameter. The rocks should typically contain 99.3–99.8% SiO_2, and less than 0.1% Fe_2O_3, 0.15% Al_2O_3, 0.2% CaO, 0.2% MgO, and 0.2% loss on ignition. The loss on ignition is directly proportional to the rock's tendency to decrepitate upon heating and has a direct relationship to the rock's thermal stability and strength, each of which should exceed 95%. Fe_2O_3 and CaO are critical impurities for metallurgical-grade and chemical-grade silicon (Alsobrook, 1994).

Ferrosilicon producers can accommodate lumps of silica rock, ranging from 0.32 to 10.16 cm in diameter, with the size varying in direct proportion to the silica content of the alloy produced. The rock should contain over 96% SiO_2 (preferably >98%), less than 0.4% Al_2O_3 (preferably <0.25%), and preferably less than 0.2% Fe_2O_3 (Alsobrook, 1994). The sulfur content of the rock should be very low, although the phosphorus contained can be up to 0.1%. Iron and carbon contents are not as critical as those of alumina, alkali, and alkaline earth metals. Typical analyses of quartz gravels used in ferrosilicon production in the southern United States are shown in Table 6. Metallurgical-grade silicon metal is used in the production of aluminium alloys, steel, superalloys, silicones and chemical feedstock. Electronic- and semiconductor-grade silicon requires several reprocessing stages to a much higher level of purity. Ferrosilicon is used as a deoxidizing and alloying agent to add strength to many specialist steels used in the automotive and engineering industries.

Chemical-grade silicon

For chemical-grade silicon production, the silica raw material should have high reactivity and a very low alumina content. Some grades of silicon metal require the feed to contain less than 0.05% Fe_2O_3, 0.10% Al_2O_3, 0.005% CaO, and 0.002% TiO_2. In all grades, the rock should not contain phosphorus, sulfur, or arsenic impurities because of the poisonous gases they form in the furnace (Alsobrook, 1994).

Silica flux

Lump quartz, quartz pebbles, or quartz river gravel can be used as a flux in various metallurgical processes. In the smelting of iron, nickel, zinc, lead, copper ores, and elemental phosphorus the choice of a flux is dependent as much on its price as its chemical purity. Therefore, locally available sources of stone, within the size (diameter) range 1.905–4.445 cm, are normally used.

In blast furnaces and basic open-hearth furnaces used in steelmaking, the flux used can be river gravel that contains over 99% SiO_2. Size ranges can be variable including those of 0.635–1.59 cm and 0.79–2.54 cm.

In electric-furnace production of elemental phosphorus, lump quartz (0.79–2.54 cm) or quartz pebble (0.635–3.175 cm) can be used as fluxstone. In general, quartz or quartzite used as fluxstone in metal phosphorus smelting should contain more than 90% SiO_2, and less than 1.5% Al_2O_3, 1.5% Fe_2O_3, and 0.2% combined CaO and MgO (Alsobrook, 1994).

Refractories

Sandstone, quartzite, quartz pebbles, conglomerate, and non-whetstone-grade novaculite are crushed and used as ganister (hard, fine-grained silica rock) mixture in manufacturing refractory bricks, tiles, kiln furniture, and other shapes as well as ramming mixes, mortars, patching compounds, and other monolithic (large upstanding mass of rock) specialities (Alsobrook, 1994). In New South Wales, Australia, high-purity silcrete was used in the manufacture of refractory bricks for open-hearth furnaces used in steelmaking.

Fused silica is primarily used in refractories for kiln and furnace walls and is commonly used in roofs of glass tanks and open-hearth furnaces. Fused silica is a useful refractory because it has excellent thermal shock resistance owing to an extremely low thermal expansion rate. The material also has good corrosion resistance against acids. Fused silica can be used in temperatures up to 1650ºC and cyclical temperatures up to 1094ºC. Above 1094ºC, fused silica/fused quartz may undergo a phase change into the crystalline form of cristobalite, which undergoes a volume expansion when heated, displaying a significantly higher thermal expansion than fused silica. Because of these properties, devitrified fused silica is not considered volumetrically or thermally stable at elevated temperatures (O'Driscoll, 1997).

Fused silica-based castables find applications in coke oven doors, zinc induction furnaces, glass forming dyes, and aluminium transfer ladles. Vitreous silica-based patching mixes are used for repairs of hot silica-brick crowns and sealing melter crown expansion joints. Fused silica is also used in saggers (boxes containing delicate ceramic pieces during firing) for the ceramics industry, and may account for up to 50% of the body. Other applications of fused silica refractories include uses in pouring accessories, casting runners, and transfer launders (channels for conveying molten metal from the furnace).

Table 6. Typical composition of quartz gravel for ferrosilicon manufacture

	SiO_2	*Al_2O_3*	*Fe_2O_3*	*CaO*	*P*	*Ti*	*Grain-size range (diameter)*
	wt%						*cm*
North Carolina terrace gravel	99.2	0.068	0.41	0.031	0.007	0.006	<5.08 and >0.3175
Alabama river gravel	98.7	0.27	0.53	0.039	0.009	0.018	Various sizes that include ranges <15.24 and >2.54, also <7.62 and >2.54

SOURCE: after Alsobrook (1994)

Table 7. Typical high-purity fused silica specifications

SiO_2	99.95%
Al	230 ppm
Ca	60 ppm
Fe	130 ppm
Li	10 ppm
Mg	50 ppm
K	45 ppm
Na	40 ppm
Ti	150 ppm
Density	2.15 g/cm^3
Compressive strength	2×10^3 mPa
Expansion	0.54×10^{-6}/°C

SOURCE: after O'Driscoll (1997)

Fused silica may be produced from high-purity silica sands, quartz crystal, or synthetic silica. The starting raw materials, fusion process, and furnace configuration dictate the purity of the fused silica end-product. Typical high-purity fused silica specifications are given in Table 7. The fused silica market is split into two sub-markets; fused silica powder and grain, and high-purity fused quartz (O'Driscoll, 1997). Fused silica powder and grain products have been discussed under **Uses of silica**.

High-purity fused quartz

High-purity fused quartz is produced mainly from quartz crystal or synthetic silica fused at temperatures in excess of 2000°C. Fusion is followed by moulding, extrusion, or fibering operations based on proprietary processes. Producers of high-purity fused quartz generally fabricate specialty end-products immediately or soon after the fusion process. Ultra-pure transparent quartz is used in various stages of the semiconductor manufacturing process. Some producers sell lump crude fused quartz to processors who in turn will supply to the fused quartz powder and grain markets. Grains produced by this sector are of exceptionally high purity (99.999% SiO_2) and find applications in a wide range of applications including heating and lighting, optical lenses and mirrors, semi-conductors, and fibres (O'Driscoll, 1997).

New isotropic types of fused silica are paving the way for the new generation of stepper systems, used to structure microchips. In order to produce structures in the sub-micrometre range, the lens systems of the steppers must be made from fused silica of the highest purity and homogeneity.

Abrasives

Quartzite, flint, jasper, and novaculite can be used as abrasive media in grinding mills and deburring equipment. However, the raw material must have high crushing strength, high specific gravity, toughness or durability, high purity, homogeneity, high hardness, and resistance to staining, fracturing, and chipping. Also, the raw material should have low porosity and must contain no toxic substances or dark-coloured metallic impurities such as iron and manganese. The raw material must be tightly cemented and chemically inert in the presence of strong alkalis and acids. The size and shape of constituent grains and their cleavage and fracture characteristics are also important (Alsobrook, 1994).

In Belgium and Arkansas (USA), novaculite is cut into whetstones, oilstones, hones, and other special shapes for residential, industrial, leisure, and craft uses. Residential uses include sharpening of kitchen knives and other cutlery such as scissors, shears, and lawn and garden tools. Industrial uses include sharpening and honing of cutting surfaces and the polishing of metal surfaces during manufacture and repair of watches, clocks, and reciprocating jet engines. Leisure applications include the sharpening of sports knives, arrowheads, spear points etc. and craft applications include sharpening of woodcarving tools, jewelry making, and engraving (Austin, 1991; Alsobrook, 1994).

Fine-grained sandstone is used to make oilstones for fine sharpening (e.g. in Ohio, USA). Hand-cut quartzite cubes are used in barrel tumbling and vibratory machines for light burr, rust, and scale removal, radius formation, cleaning, and degreasing. Rectangular blocks of quartzite (jasper) and chalcedonic silica are used in lining tube or cylindrical, tile-type ball and pebble mills. These mills are used primarily in applications where iron contamination from metal-alloy liners or alumina contamination from ceramic liners has to be avoided (Alsobrook, 1994).

Electronics and optics

Quartz crystals are used in electronics and optical applications. For these uses, crystals should weigh no less than 50–100 g. Piezoelectric-grade crystals should contain at least 16.4 cm^3 of flawless material. Even clear crystal is not suitable if it is optically or electrically twinned or contains phantoms (growth outlines commonly marked by very fine clay particles), cracks, fluid inclusions, rutile fibres, or intergrowths with other minerals (Alsobrook, 1994). The dielectric property of quartz is such that although it does not conduct electric current, it permits electric fields to exist and act across it. This piezoelectric property makes it possible to produce a negative charge on one of its surfaces and a positive charge on the other by mechanically deforming the crystal with properly directed pressure. These properties are used to provide accurate frequency control, timing, and filtration in electronic industry.

Optical applications of flawless quartz crystals include the manufacture of natural lenses and prisms. Since the early 1970s, synthetic quartz crystal manufacture has dominated the market. Today, small quantities of natural quartz crystals from Brazil are used as seed material for growing synthetic crystals in autoclaves. Synthetic high-purity, 'lascas-grade' (the feed material used to make synthetic quartz) quartz is now used in the manufacture of specialty lighting, fibre optic devices, precision optical and electro-optical devices, semiconductor industries, and special laboratory glassware.

Acid tanks and towers

Sandstone and quartzite blocks can be used for lining acid tanks, towers, and trays requiring resistance to hydrochloric and sulfuric acids (but cannot be used for hydrofluoric or high-temperature phosphoric acids). The blocks should have good abrasion resistance, a crushing strength of 55 000–70 000 kPa, and a transverse strength of 8300–9000 kPa.

Quartz and quartzite gravel can be used as a packing medium in acid towers, and for this the material should have low porosity (<3%), a high crushing strength, high degree of size uniformity, and high surface area per cubic metre. Also, the gravel should be resistant to dissolution by sulfuric acid and should have a neutral or slightly acid pH (Alsobrook, 1994).

Air pre-heaters

High-purity quartz river gravel is used in three of the four layers that serve as a heat transfer medium in the chambers of air pre-heaters. The bottom (or first) layer consists of gravel 12–15 mm in diameter, whereas the second and the topmost (fourth) consist of gravel 3–5 mm in diameter. The gravel must contain at least 99% SiO_2 and should be round in order for the bed to have sufficient void volume and void size to provide adequate heat transfer and pressure drop. Angular fragments restrict airflow, The gravel also should have high thermal conductivity, high heat-storage capacity, and high thermal efficiency of around 98% (Alsobrook, 1994).

Specialty silicas

The specialty silicas are specialized products often tailored to customer specifications. Many such products demand high levels of technical support and therefore the industry is characterized by large, multinational companies, particularly US and European, which maintain strong research and development programs to drive innovation. The global specialty silicas industry is considered to be worth around $3800 million, and the products include precipitated, fumed and colloidal silica, manufactured indirectly from silica sand or quartzite, as well as microsilica (silica fume) — a byproduct of silicon metal and ferrosilicon production (Kendall, 2000). Silica fume is used in the production of high-strength concrete and as an additive in refractory cements, castables, and bricks.

Miscellaneous

Quartz is used for its decorative properties embedded in the exterior of concrete panels used in the construction industry, and as decorative landscaping and garden stone. It is also used for polishing of electronic microcircuit dice pedestals, as aggregate for swimming pool plaster, fine aggregate in abrasion resistant linings, and as aquarium chips (Alsobrook, 1994). Quartz, mixed with crushed oyster shells, is used as a poultry, pigeon, and parakeet grit.

Health and safety issues

Silicosis is an occupational disease of the respiratory tract that has been reported throughout history (Harben, 1999). The International Agency for Research on Cancer (IARC), a unit of the World Health Organisation, reclassified crystalline silica as a Class 1 known carcinogen (World Health Organization, 1997). As a result, industrial minerals and chemicals containing 0.1% or more crystalline silica are regulated by the Hazard Communication Standard in the USA. A European Union directive states that any material containing more than 0.1% of a category 1 or 2 carcinogen be treated as if it were 100% of that carcinogen. According to regulations of the Western Australian Mines Safety and Inspection Act 1995, the allowable limit of respirable quartz in workplace environments of Western Australia is 0.2 mg per cubic metre of air (Regulation 9. 11 (2) (a)).

Exploration

Silica sand

Any exploration program for silica sand, as for most low-value industrial minerals, should involve thorough research into marketing and transportation. Identifying the locations of other producers as well as consumers allows demarcation of exploration areas that are closer to transportation routes and markets. Even if a prospect is close to markets, success is not guaranteed, because other factors such as beneficiation, land costs, and environmental factors may have significant negative impacts. The market to be supplied defines the quality and quantity of material requiring to be found.

Once a prospect has been identified, a sampling program should be carried out of the leached, white silica sand horizon that generally overlies oxidized, brown sands of beach, dune or alluvial origin. Samples should then be evaluated in a laboratory and the minimum laboratory evaluation should involve grain-size analysis, and chemical oxide analysis mainly to assess levels of Fe_2O_3 and Al_2O_3 after the separation of magnetic and heavy minerals. This work should then be followed by geological mapping and more surface sampling, the results of which can then be used to plan drillholes and test pits. Auger drilling can be used in unconsolidated deposits, with drill cuttings examined for the matrix material present, particularly noting the degree of iron staining on the silica grains. Opaque minerals, staining and inclusions within the quartz grains, and all accessory minerals should be noted. The dimensions and grade of the deposit should then be established to estimate the resource available.

Laboratory tests

As stated earlier, the laboratory testing involved in the preliminary exploration stage of a deposit are grain-size analysis, chemical oxide analysis, magnetic separation, wet scrubbing, and flotation.

Grain-size analysis

Most of the applications of silica sand depend on the grain size (Tables 1–5), and the most commonly tested size range of silica sand in the laboratory is between 53 and 850 µm. In the foundry sand industry, a common term used in the size analysis is AFS (American Foundrymen's Society) value, which is an approximate measure of the average size of grains in the sample. The AFS value depends on the number of openings per inch corresponding to a sieve that would pass a sand sample if its grains were of uniform size. The higher the AFS value, the smaller the average grain size. For example, a sample of AFS20 contains around 80% of the >600 µm fraction and a sample of AFS30 contains around 70% of the <600 µm fraction.

Chemical analysis

A knowledge of chemical composition is important for the assessment of silica sand deposits for various applications (Tables 1–7). The method used for chemical analyses can be any standard one such as XRF or ICP, both of which can be used to determine major as well as trace elements. Major elements are usually determined by a full oxide analysis. For a proper assessment of silica sand quality, chemical analysis should be carried out after removing the magnetic and heavy fractions.

Silica rock

The exploration for silica rocks such as sandstone, quartzite, chert, and vein quartz is initially guided by a knowledge of geological formations that are likely to contain silica-bearing rocks or minerals of suitable quality. After identifying suitable geological formations, reconnaissance sampling and mapping need to be carried out. Further evaluation of deposits requires drilling and sample testing to establish the quantity and quality available. Chip samples from percussion drilling provide some indication of chemical purity, but are unsuitable for many physical property measurements. Therefore, at some stage, diamond core drilling will be required. If the search is for silica gravel, or in cases where the host rocks enclosing quartz veins are deeply weathered, drilling may be impractical. In such formations, a better approach for sampling would be to dig trenches with bulldozers or backhoes. Samples from the excavations can then be washed and screened to determine yield of product per cubic metre excavated. Exploration for deposits of river gravel in active river systems is carried out by dredging (Zdunczyk and Linkous, 1994; Alsobrook, 1994).

Laboratory tests

As part of the exploration program, samples must be tested to obtain a knowledge of mineralogy and chemical composition. If the intended end-use involves silicon metal, production samples should also be tested for their thermal behaviour.

Mineralogy

A knowledge of mineralogy is important to gain an understanding of those impurities that may be present. Since high-grade applications such as silicon metal production require a very high degree of purity in terms of silica content, the presence of trace amounts of particular minerals such as chlorite, rutile, ilmenite, limonite, feldspar, and apatite may prove the raw material to be unsuitable. Mineralogical studies may be generally restricted to petrographic studies, but in some instances X-ray diffraction (XRD) and/or scanning electron microscopy (SEM) can yield valuable information for a better understanding of the raw material.

Chemical composition

Depending on end-use, the specified composition of silica raw material can be variable, but in general the material should contain over 97% SiO_2, with very low impurities. For metallurgical- and chemical-grade material, the silicon raw material should generally contain less than the following amounts: 0.1% Fe_2O_3, 0.3% Al_2O_3, 0.2% TiO_2, 0.05% P_2O_5, 0.1% $CaCO_3$, and 0.1% MgO. However, these values can vary depending upon customer specifications.

Thermal stability and strength

A knowledge of the thermal stability or fragmentation of silica-bearing feedstock, in response to high furnace temperatures, is an important factor in assessing the suitability of raw material for use in the production of silicon metal. Such knowledge will help to estimate the levels of thermal disaggregation in the furnace so as to minimize formation of crystalline silica in the fume; this is critical from an occupational health and safety perspective. This knowledge is also important to minimize impurity levels and thus achieve the highest possible purity of silicon product.

There is no globally accepted method of carrying out thermal stability tests for silica rock raw materials. In Western Australia, Simcoa Pty Ltd uses the following method, which is found to be effective in assessing the suitability of a raw material for the production of silicon metal.

The test originates from Demag in Germany and has been developed specifically for silicon and ferrosilicon submerged-arc furnaces. The test involves heating approximately 200 g of quartz of 20–30 mm size to 1000°C for an hour. The disaggregated sample is then carefully sifted to a set of 19 mm, 9.5 mm, 4.8 mm, and 2.0 mm screens. The percentage on the 19 mm screen is considered to be the thermal stability. To obtain the thermal strength, the fraction exceeding 19 mm is placed in a drum of 200 mm diameter, 100 mm depth, and with four 17 mm ribs on the side. The drum is then rotated 80 times at approximately 40 revolutions per minute, after which the sample is once again passed through a set of 19 mm, 9.5 mm, 4.8 mm, and 2.0 mm screens. The cumulative percentage on 4.8 mm screen size is taken as the thermal strength. Although Simcoa uses the above screen sizes for definition of thermal stability and strength, other producers of silicon may have their own methods of defining these parameters. Samples with values below 80% for both thermal stability and thermal strength are considered to be too low and unsuitable as furnace feed. Simcoa considers quartz having thermal stability and strength above 95% to be excellent.

Mining

Silica sand

The method of mining silica sand deposits depends on the nature of the deposit. In unconsolidated or loosely consolidated deposits above the watertable, mining can be directly from the mining face using a front-end loader, hydraulic excavator, or power shovel. The material is then stockpiled as feed to a processing plant. Another method for such deposits is to wash material from the working face using a high-pressure water monitor. Washed sand is then collected in a sump, from which it is pumped into the processing plant.

In deposits where the watertable is shallow, mining is accomplished in man-made lakes with floating dredges. A hydraulic dredge uses a suction pump to excavate the sand, which is pumped through a pipeline to a processing plant. In deposits with hard clay lenses, the suction pump is equipped with a cutter head to facilitate excavation of material from a mining bank below waterlevel (Zdunczyk and Linkous, 1994).

Silica rock

Well-consolidated deposits such as sandstone, quartzite, and chert are mined by standard openpit methods, which involve drilling and blasting. The blasted material is then loaded by either front-end loaders or power shovels into trucks for transport to the processing facilities. In some instances well-consolidated deposits are mined by underground methods, but these are more expensive than openpit mining. The underground mining methods involve drilling and blasting, loading the blasted material by power equipment, and hauling to a processing plant (Zdunczyk and Linkous, 1994; Alsobrook, 1994). Underground mining of silica rock is not carried out in Australia owing to cost and health considerations.

Beneficiation and processing

Silica sand

Beneficiation and processing are key factors for the production of high-quality silica sand for use in applications such as in the glass or foundry industry. The first step of beneficiation involves removal of clay coatings from the sand grains. This is done by pumping a sand–water slurry to a primary desliming circuit in which hydrocyclones remove <0.01 mm material, which is pumped into settling ponds. The clean sand is then sized, either by hydrosizing in hindered settling tanks and/or on vibrating screens, to remove the coarse (>0.6 mm) fraction. The sand is then dewatered in hydrocyclones to 70% solids prior to attrition scrubbing, which is carried out in tanks equipped with propeller-type blades. Scrubbing removes the iron oxides, clay, and other materials that coat the sand-grain surfaces. Also, scrubbing produces fresh surfaces on non-quartz minerals such as heavy minerals, thereby enhancing reagent attachment during the next step, which is flotation. One method of flotation used is anionic flotation, where petroleum sulfonate is used as a collector in an acid circuit to remove heavy minerals. For most applications, the finished product must be dried. This is normally performed in rotary or fluid-bed dryers equipped with wet scrubbers for removing dust from the exhaust gases. Many glass sand producers use fluid-bed dryers because of their high reliability and thermal efficiency. After drying, the sand is usually cooled and conveyed to another set of screens for final sizing (Zdunczyk and Linkous, 1994).

Saller (1999) listed the following essential features in a modern silica sand processing plant.

- Crusher
- Screen
- Grinder
- Hydro-classifier
- Dryer
- Magnetic separator to remove heavy minerals, or
- Flotation to extract heavy minerals

In Australia, many silica sand deposits are of such high natural purity and optimum grainsize that processes such as scrubbing, crushing, and grinding are unnecessary.

Silica producers must have some type of quality control laboratory to ensure the products supplied to customers meet required specifications. The testing done in these laboratories includes one or more of the following: sieve analysis, X-ray diffraction and/or fluorescence (for mineral and chemical composition), heavy media separation, magnetic or electrostatic separation, and microscopic analysis.

Silica rock

Processing of metallurgical-grade silica-bearing rocks such as quartzite and chert consist only of crushing, washing, and screening to sizes ranging from 3.81 to 10.16 cm, and from 0.32 to 3.81 cm. The processing of metallurgical-grade quartz and quartz gravels from river-channel and raised-terrace deposits are similar, but no crushing is required. The processing of quartz and vein quartz for various other applications (such as the electronic industry) involves hand sorting and other steps such as leaching in vats of hot oxalic acid, drying, and further examination on light tables for detecting any defects.

For applications that require quartzite, sandstone, and jasper in block form, the raw material is cut by wire saws and is split hydraulically. Blocks produced for use in acid tanks and towers have either two or four sides sawed smooth with the other sides hydraulically split and rough. These blocks consist of beams and slabs sawed to a thickness of 10.16–20.32 cm. Grinding mill and chute liner blocks are usually sawn on all six sides (Alsobrook, 1994).

Chapter 3

Production and market trends

Silica and quartz are produced or mined in most countries of the world. The current world production of silica and quartz is estimated at 120–150 Mtpa (Harben, 1999). However, precise production figures are not readily available. The abundant supplies of lower-grade silica and quartz in the world have led to low prices of the raw material, thereby generally restricting transportation of the material for long distances to markets. However, high-grade silica raw materials with desired specifications may be shipped to distant markets. For example, Kemerton Silica Sand Pty Ltd (a joint venture project between Sons of Gwalia Limited, Itochu Australia Pty Ltd, and Tochu Co Ltd) exports large tonnages (approximately 0.4 Mtpa) of high-grade silica sand from Western Australia to Japan for the glass industry.

Global production

The leading producers of silica in the world are the United States and the Netherlands. The production in the United States is about 29 Mtpa (24% of global production) and that of the Netherlands is about 24 Mtpa (20% of global production). France, Austria, Germany, Belgium, and Paraguay each produce in excess of 5 Mtpa. Australia produces about 3.9 Mtpa, which is nearly 3% of the global output (Fig. 1). Japan, Spain, Brazil, South Africa, and Czech Republic each produce in excess of 2 Mtpa (Harben and Kuzvart, 1996; Harben, 1999; ABARE, 1999).

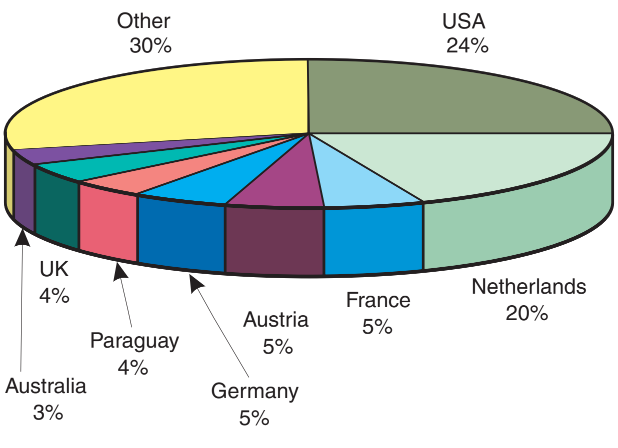

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Figure 1. Silica sand production of the world (after Harben, 1999; ABARE, 1999)

The following are brief geological descriptions of the silica sand and other silica resources of the major producers of the world.

United States

The following descriptions are based on Zdunczyk and Linkous (1994), Harben and Kuzvart (1996), and Alsobrook (1994).

Silica sand

Silica sand deposits in the United States can be grouped within five geological provinces, based on geological history that has influenced the grain size, shape, composition, accessory minerals, and distribution of sand. These five geological provinces are (Fig. 2): Atlantic Coastal Plain, Appalachian Belt, Mid-Continent, Rocky Mountain Cordillera, and Pacific Coast (Table 8).

Atlantic Coastal Plain

There are four important areas of sand mining along the Atlantic Coastal Plain; southern New Jersey, the Sand Hills District of the Carolinas, central Florida, and western Tennessee.

In the coastal plain of southern New Jersey silica sand of the Miocene Cohansey Formation is mined extensively

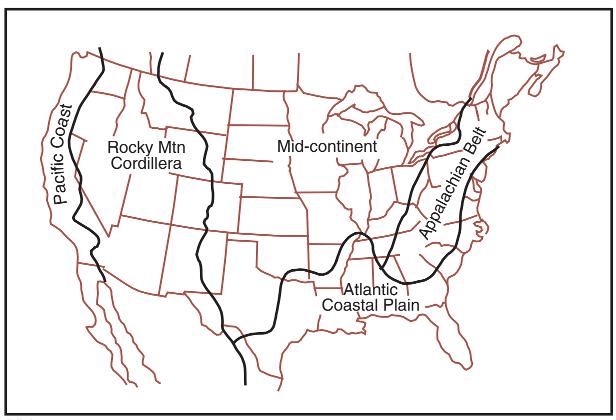

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Figure 2. General geological provinces for silica sand and sandstone resources in the United States (after Zdunczyk and Linkous, 1994)

Table 8. Summary of geological environments and ages of silica sand deposits in the United States and Australia

Country	*Region*		*Geological unit*	*Origin*
United States	Atlantic Coastal Plain	Southern New Jersey	Miocene Cohansey Formation	Eroded and reworked Cretaceous beach sand
		Sand Hills District	Miocene Pinehurst Formation	Dune sand
		Central Florida	Pliocene–Pleistocene Citronelle Formation	Fluvial blanket deposit of highly crossbedded sands, clays, and gravel
	Appalachian Belt	Northern Valley and Ridge areas of Tennessee	Silurian Clinch Sandstone	History of deposition includes alluvial fan, coastal plain, tidal river environment, near-shore, and wave complexes
		Pennsylvania, Hancock, Berkley Springs	Lower Devonian Oriskany Sandstone	Well-sorted marine quartz arenite
	Mid-Continent	Ottawa District, Minnesota, eastern Iowa	Ordovician St Peter Sandstone	Marine sand
		Southeastern Michigan	Devonian Sylvania Formation	Eolian sand deposited in a near-shore environment
		Minnesota	Late Cambrian Jordan Sandstone	Near-shore environment
	Rocky Mountain Cordillera Pacific Coast	Northeastern Washington California	Cambrian–Ordovician Addy Quartzite Eocene Ione Formation	Structurally controlled friable sandstone. Source of sediments was deeply weathered granitic and metamorphic rocks. Sands were then upgraded by chemical leaching in a near-tropical environment
			Pliocene–Pleistocene Saugus Formation	Freshwater deposition as sea regressed at the end of Pliocene
			Eocene Domengine Formation	Shallow marine environment
			Paleocene Silvarado Formation	Brackish water environment
Australia	Queensland	Southern Queensland: Gold Coast to Fraser Island	Pleistocene white sand	Coastal dune sand
		Central Queensland: Hervey Bay to Whitsunday Island	Pleistocene to Holocene sand	Coastal dune sand
		Townsville to the Cape York Peninsula	Quaternary Cape Flattery – Cape Bedford dunefield	Dunes in low-lying coastal plain
	Western Australia	West coastal region: Perth to Busselton	Pleistocene Bassendean Sand	Coastal dune sand
		Albany region	Tertiary and Quaternary sand units overlying the Eocene Bremer Basin, Pallinup Siltstone	Variably reworked, eolian to fluvial sand
		Esperance region	Pleistocene or younger dune sand and coastal dune sand	Dune sand and coastal dune sand
	New South Wales	Port Stephens area, 50 km north of Newcastle	Pleistocene sand	Coastal dune sand

SOURCES: after Cooper (1993); Cooper and Sawers (1990); Zdunczyk and Linkous (19940; Harben and Kuzvart (1996); and Alsobrook (1994) for use in the manufacture of glass containers, specialty glass, borosilicate glass, ceramic sanitaryware, and electric porcelain insulators. The sand from this formation is also used as construction, foundry, filtration, and golf-trap sand. The Cohansey Formation consists of a 30–75 m-thick section of poorly sorted, subangular, fine- to medium-grained sand containing minor amounts of clay and coarse sand. Heavy minerals in this sand include rutile, leucoxene, and zircon.

The Sand Hills District of the Carolinas consists of very high quality eolian sands of possibly Late Miocene to Early Miocene Pinehurst Formation. The thickness of the sand formation, where mined in central South Carolina and south-central North Carolina, varies from a thin veneer to more than 10 m. The sand consists of about 90% quartz and is angular to subrounded, poorly sorted, medium to coarse grained, and varies from nearly white to yellow-orange.

In Florida, glass-grade sand is produced near Davenport, Plant City, and Edgar from marine terraces of Pleistocene age, and from the closely associated Citronelle Formation of Pliocene–Pleistocene age. The Pleistocene marine terraces consist of fine- to medium-grained, well-sorted, unconsolidated quartz sand. These sand deposits do not contain clay, but contain trace amounts of heavy minerals and apatite. The Citronelle Formation is a fluvial blanket deposit of highly crossbedded sands, clays, and gravel extending across western Florida, Alabama, and Mississippi and reaches a maximum thickness of about 50 m.

In western Tennessee, high-quality silica sand is mined from the McNairy Sand, which is part of the Gulf Coastal Plain – upper Mississippi Embayment. Outcrops of the McNairy Sand generally parallel the Tennessee River and vary from about 19 km wide in McNairy County to about 13 km wide in Benton County. The sand in this unit has been deposited in a cyclic near-shore geologic environment and contains a basal horizon of fine-grained sand with heavy minerals, a middle wedge of coarser grained sand, and an upper transgressive marine sand.

Appalachian Belt

The Silurian Clinch Sandstone and the Lower Devonian Oriskany Sandstone in the Appalachian Belt are important sources of high-quality industrial silica sand. These sandstones have formed by the deposition of thick wedges of non-marine clastics during the Taconic Orogeny in Late Ordovician time. Subsequent erosion and slowing of tectonic activities led to the accumulation of siliciclastic sediments in the foreland basin, and these were then reworked into pure quartz sandstones. The Clinch Sandstone in the northern Valley and Ridge area of Tennessee is mined for glass-grade sand. Economic occurrences of Oriskany Sandstone are restricted to a folded belt of the Central Appalachian in the Virginia and Pennsylvania tri-state area. In these localities the Oriskany Sandstone is well sorted and averages some 90 m in thickness. Fracturing and jointing of the sandstone have allowed the groundwater to leach out the calcareous matrix, resulting in a more friable, or even loose, sand.

Mid-Continent

Some of the highest quality silica sands in the world are produced in the Mid-Continent of the United States. These sands are found in Palaeozoic sandstone formations — St Peter, Sylvania, Jordan, Oil Creek, and McLish, which occur as flat-lying, moderately consolidated, mature to supermature, multicycle sheet sands. The quality of the sand is enhanced by repeated cycles of erosion, winnowing, and redeposition.

The Ordovician St Peter Sandstone is a remarkably uniform, widespread, quartz arenite sheet sand, which is used in many applications. It outcrops in southeastern Minnesota and along the southern margin of the Wisconsin Dome into eastern Iowa, continuing southward into Illinois and across the flanks of the Ozark Dome in eastern Missouri and northern Arkansas. The best known area for production of St Peter Sandstone is the Ottawa District in northern Illinois. Most producers restrict their mining to the upper half of the formation, because iron, alumina, and carbonate contents generally increase below 30 m in depth.

The Middle Devonian Sylvania Formation in south-eastern Michigan is a basal blanket quartz arenite, and is one of the premier glass-sand resources in North America. However, the economic significance of this unit is limited because it outcrops only in a narrow, northeast-trending belt across the southeastern corner of Michigan and to a lesser extent in northern Ontario.

Late Cambrian Jordan Sandstone is white to yellow, well rounded, well sorted, and medium to coarse grained and is mined in Minnesota primarily for hydrofracturing or proppant sand. Both the Oil Creek and McLish Formations are Ordovician in age and yield high-quality glass sand from beds that were folded into anticlines and synclines during Upper Carboniferous.

In central eastern Colorado there are extensive sheets of Quaternary eolian silica sands extending eastward from the base of the Rocky Mountains. The sand is composed of well-rounded, to very well rounded quartz grains averaging 1.5 mm in diameter with minor subrounded feldspar grains. This material is suitable for the production of frac sands for use as a proppant in both oil and water-well applications. It is also used as filtration and environmental sand in the treatment of fresh and waste water.

Rocky Mountain Cordillera

Although Ordovician orthoquartzites constitute immense deposits in the Rocky Mountain Cordilleran region, extending from British Columbia to Southern Carolina, economic exploitation is limited because of their distance from large industrial markets along the Pacific Coast. One of these quartzites, the Addy Quartzite, is mined in northeastern Washington and supplies markets in northern Oregon, Washington, and western Canada. The Addy Quartzite is Cambrian–Ordovician in age and the nature of the rock varies from unconsolidated sand to true quartzite. This unit appears to be a 60–90 m-thick tabular mass extending to a distance of about 5 km along strike.

Pacific Coast

On the Pacific Coast in California, immature, feldspathic, clayey sands of Paleocene to Eocene to Pleistocene age are mined for the glass industry. These include sands in the Eocene Ione Formation, Pliocene–Pleistocene Saugus Formation, Eocene Domengine Formation, and Paleocene Silvarado Formation. The sands in these formations are not of sufficient quality to produce ground silica, and most manufacturers of flat glass and container glass upgrade these sands by blending them with more expensive, higher quality sand mined from deposits in Nevada and Mid-Continent.

Silica rock

Sandstones in quartz-pebble conglomerate facies of the Sharon and Olean Formations of the Lower Pennsylvanian (Carboniferous) Pottsville Group have been mined in New York, Pennsylvania, Tennessee, and Ohio as a source of ganister for refractory brick and also as a source of metallurgical gravel for silicon metal and ferrosilicon production. The Sharon Conglomerate facies is the lowermost member of the Pottsville Group. The sandstone in this formation is friable, medium to coarse grained, grades 95–99% SiO_2, and varies in thickness from 15 to 70 m (Alsobrook, 1994).

Metallurgical-grade quartz pebbles have also been mined from the Sewanee Conglomerate Member of the Pennsylvanian Crab Orchard Formation in Franklin County on the Cumberland Plateau of east central Tennessee. These quartz pebbles contain 99% SiO_2. At Keck Center in Fulton County, New York, a white granular sandstone containing 99% SiO_2 has been mined for ferrosilicon production (Alsobrook, 1994).

In addition to those noted above, sandstones from many localities in the United States have been mined for various non-construction applications, and some of these are summarized in Table 9.

Massive quartzite of the Lower Cambrian Erwin Formation has been quarried for silicon metal and ferrosilicon manufacture in Virginia (e.g. Sand Mountain) and east central Tennessee. This formation is more than 100 m thick and contains 97.63–99.37% SiO_2. Quartzite from the Lower Silurian Tuscarora (Medina) Formation has been mined in Carbon, Bedford, Blair, and Huntingdon Counties, Pennsylvania, for use as ganister in refractory bricks for furnace linings. In central Pennsylvania, in localities such as Lock Mountain near Point View, Tuscarora quartzite is light grey to white and 120–180 m thick. This quartzite has also been quarried in Virginia and near Minnehaha Springs in Pocohontas, West Virginia, for use as a metallurgical stone. Quartzite from Chikies Formation in southeastern Pennsylvania has been used as refractory ganister and for tube-mill linings.

In the central United States, one of the most important sources of specialty silica stone is Precambrian Sioux Quartzite (also known as the Sioux Falls Granite), which is fine grained and has a thickness range of 460–1220 m. The colour of the Sioux Quartzite ranges from pink to orange, purple, and blue, and its silica content varies from 96% to nearly 99%. The Sioux Quartzite outcrops in a belt more than 95 km wide covering an area of over 15 540 km^2 from the junction of the Cottonwood and Minnesota Rivers at Redstone, extending westward to Mitchell on the James River in South Dakota. Outcrops are most predominant in river valleys, such as those of the Big Sioux at Dell Rapids and South Falls, the Vermillion at Parker, the James south of Mitchell, Wolf Creek at Salem, and Pierre Creek at Alexandria, all in southeastern Dakota. One of the most productive portions of the outcrop belt of the Sioux Quartzite extends from Jasper in the southwest corner of Minnesota westward to Sioux Falls, Spencer, and Mitchell. The quartzite produced from these localities is used in metallurgical-grade applications (production of ferrosilicon), in the construction industry, and in the production of artificially rounded grinding pebbles. Other significant sources of specialty silica stone in the central United States include Precambrian Baraboo Quartzite in Sauk and Columbia Counties of south-central Wisconsin and Precambrian Nesnard Quartzite in Michigan (Alsobrook, 1994).

High-purity quartzite is widespread in the western United States, especially in eastern Washington. One important source has been the Cambrian Addy Quartzite covering an area of around 650 km^2 in Stevens County, which has been quarried for ferrosilicon production. Another important source of specialty silica stone in the United States is the Middle Ordovician Eureka Quartzite extending from Idaho into southern California, covering an area of more than 260 km^2. The Eureka Quartzite has a range of SiO_2 up to 99.9% and has been mined in Clark County, Nevada, for refractory, metallurgical, and other uses. Other sources of high-purity quartzite in the United States include the Precambrian Dripping Spring Formation at Oracle, Arizona, Tintinnic Formation in Tooele County, Utah, and Late Cambrian Sawatch Quartzite in the Mosquito Range of Colorado.

In the United States, another significant source of silica is silica gravel. One of the most important sources of metallurgical-grade silica gravel for silicon metal and high-purity ferrosilicon production is the high-level terrace deposits in the Pliocene or Holocene Citronelle Formation, in the eastern United States. The silica gravel deposits in this formation are found as raised terraces roughly parallel to the present course of the Pee Dee River in North Carolina, and of other major rivers in the coastal plain of South Carolina, Georgia, Florida, and Alabama. The Pee Dee terraces, near Lilesville in Anson County, contain a well-developed basal gravel zone 1.5–6 m thick overlain by sand and a few lenses of gravel and clay. In the southeastern United States, lower purity ferrosilicon is manufactured from silica gravel dredged from the Coosa River north of Montgomery, and from the Alabama River between Montgomery and Selma, Alabama (Alsobrook, 1994).

Canada

Silica rock

Late Cambrian to Early Ordovician Potsdam (Nepean) Sandstone at St Canut, north of Montreal, Quebec, has

Table 9. High-grade sandstone localities in the United States

Locality	*Geological Unit*	*Comments*
Allentown in Lehigh County, Pennsylvania	Cambrian sandstone	Quarried for whetstone production
Lancaster County, Pennsylvania	Cambrian sandstone	Used as ganister for millstone production
Montgomery County, Pennsylvania	Cambrian sandstone	Used for ganister production
Ouachita Mountains of Oklahoma	Fine-grained quartzites and quartzitic sandstones	Suitable for the fabrication of millstones
Columbus in Stillwater County in Montana	Sandstone	Used for production of grindstones
Dillon in Beaverhead County in Montana	Sandstone	Used for the production of metallurgical fluxtone and refractory ganister
Shawangunk Mountains and near Kyserike, St Hosen, Granite, and Kerhonkson, NY	A well-cemented and hard, light grey, pebbly sandstone of the Shawangunk Conglomerate. A belt extending from Kingston, New York,southward into New Jersey and Pennsylvania	Quarried extensively for millstone in all locations given
Rawlins in Carbon County and on Baldwin Creek near Lander in Fremony County, WY	Tough, fine-grained sandstone	Used for production of grindstones
Northeast of Eaglemont, NE, near South Dakota Border	Dakota Sandstone	Used for production of grindstones
Pierce, Wilkerson, and Skagit Counties, Washington	Sandstone	Used for production of pulpstones
Between Salmon and Stevenson in Skamania County, Washington	2.5 m-thick bed of sandstone	Used for production of whetstones
Ohio, West Virginia, and Michigan	Dunkard and Berea Sandstones	Used for production of pulpstones
South Amherst in Lorain County, OH	Berea Sandstone (a part of Waverly Series of Mississippian age)	Used for refractory bricks and blocks

SOURCE: after Alsobrook (1994)

been mined for use in the glass industry, foundries, ceramics, and in the manufacture of silicon carbide. The sandstone has a thickness varying from 20 to 85 m, and consists of well-indurated grains 75–850 µm in size (Alsobrook, 1994).

At Melocheville in Beauharnois County, Quebec, quartzitic sandstone is mined for use in the production of ferrosilicon. Carboniferous and Permo-Carboniferous sandstones in New Brunswick, Nova Scotia, and British Columbia have been used to produce grindstones, millstones, and pulpstones (Alsobrook, 1994).

The Bar River Formation at the top of the Neoproterozoic Cobalt Group has been quarried at Shequiandah on the Manitoulin Island south of Little Current to obtain lump quartzite for ferrosilicon manufacture. The Bar River Formation quartzite has also been used as metallurgical fluxstone in nickel smelting. The quartzite of the Bar River Formation is dense, massive, white, fine to medium grained, cemented by secondary quartz, and is of high purity. The Lorrain Formation quartzite within the Cobalt Group approaches the purity of the Bar River quartzite, but contains more alumina, and has been used for the manufacture of refractory bricks and ferrosilicon manufacture. It is exposed along the northern shore of Lake Huron between Sault Ste. Marie and Killarney, Ontario. Several quartzite mines in Beauharnois County, Quebec, supply metallurgical-grade quartzite to local ferrosilicon manufacturers. In eastern Canada high-purity quartzite is found near Labrador City, Labrador. In Cape Breton County in Nova Scotia a fine-grained, brittle quartzite of Precambrian age has been quarried for use as ganister for the refractory brick linings. In western Canada the Ordovician Mount Wilson Formation consists of massive, uniform, white, medium-grained orthoquartzite or quartz arenite cemented with silica and is quarried at Nicholson, 11 km from Golden in southeastern British Columbia, for use in silicon metal and ferrosilicon production. The quartzite from this formation assays as high as 99.85–99.9% SiO_2 with only 0.10% Al_2O_3, and 0.04% Fe_2O_3.

The major producers of ferrosilicon and silica in Canada include SKW Canada Inc and Elkem ASA.

Other sources of high-grade quartz in Canada include a high-purity, lascas-grade vein quartz deposit, known as the Mount Rose deposit, near Armstrong, British Columbia, and ‘Fs’ (?feldspar) quartz vein, 40 km northeast of Kamloops, British Columbia, which has supplied milky quartz for silicon carbide manufacture in Oregon. Also, a large deposit of well-rounded quartzite pebbles is found near Cypress Hills, Alberta. The pebbles from this deposit are found to have good grinding media properties and compare favourably with flint pebbles produced in Denmark (Greenland) (Alsobrook, 1994).

Europe

Silica sand

In Europe, major silica sand operations are generally located in the same areas as glass manufacturing facilities. The active centres in the glass industry are concentrated in Belgium, the Netherlands, Germany, UK, France, Spain, and Turkey. The major companies operating in Europe are SCR-Sibelco SA (in Belgium), Quarzwerke GmbH (in Germany), Hepworth Minerals and Chemicals Ltd (in UK), and Saint-Gobain (in France).

Netherlands and Belgium

High-quality silica sand is produced on a large scale in the ‘silversand’ area around Heerlen, in the Netherlands and in the Mol, Maasmechelen, and Charleroi districts of Belgium. The sands in these regions of Belgium and the Netherlands are Pliocene in age and are distinguished by an iron content that may be as low as 0.01% Fe_2O_3, making them suitable for the manufacture of crystal glass. Lower-quality material is used in the production of sheet glass, ceramics, silica flour, and silicon carbide, and in the construction industry. Belgian-based SCR-Sibelco SA has sites at Mol, Dessel, Lommel and Maasmechelen, and in Heerlen in the Netherlands. The glass sand supply market in the Netherlands is dominated by the company Lieben Mineral BV, which has it headquarters in Maastricht (Harben and Kuzvart, 1996; Saller, 1999).

United Kingdom (UK)

In the UK, silica sand is mined from deposits ranging in age from Carboniferous to Recent. More than half of the production is from the Pleistocene and Holocene deposits of fluvioglacial, interstadial (formed during warmer intervals of an ice age), and eolian origin. Examples include the large deposits in Cheshire and Lancashire in the north of England, which are used in the glass, ceramics, and foundry industries. Production from the Cretaceous beds, particularly Lower Cretaceous sands south of London, amounts to about one-third of the total output from the UK. Hepworth Minerals and Chemical Ltd (HMC) is the leading supplier of glass sand (about 1 Mt) in the UK and has a total capacity of 3.5 Mt of silica sand to suit a wide range of applications. The company has operations in Cheshire, Norfolk, Humberside, Staffordshire, Surrey, and Scotland (Harben and Kuzvart, 1996; Saller, 1999).

Spain

In Spain, silica sand production almost doubled between 1996 and 1999 to a total of about 2.3 Mt. Around 70% of the production is from selected silica sand mining, 23% is a byproduct of washing feldspathic sands in Segovia, 5% is from kaolin extraction in Valencia, and 2% is from sandstone and quartzite operations. Spain is Europe’s leading producer of metallurgical-grade lump quartz. Much of the quartz is used in ferrosilicon production in Spain as well as in Sweden, Norway, and Iceland. The country’s market leader, producing around 1.5 Mtpa, is Arenas de Arija SA (95% owned by SCR-Sibelco SA). Sibelco operates a 250 000 tpa silica micronizing plant in Utiel, Valencia. Arenas Siliceas SA (ASSA) is Spain’s second largest producer with 0.5 Mt and around 22% of the market. ASSA is particularly active in southern Spain, where it has four operations and 75% of the production is for container glass, which is mainly exported to Italy. The remainder is used in ceramics, abrasives and filters, special concrete, and resin sands. Caobar, a kaolin producer based in Guadalajara, produces 330 000 tpa of silica sand. During 1998–2000, the use of silica obtained from fly ash has shown considerable increase, for example in glazes (González-Barros and Sanz, 2000).

France

In France, Saint-Gobain is Europe’s biggest and oldest flat-glass producer, having four operations in Moru, Rozet, Marcheprime, and Roncevaux. This company is the largest single container-glass producer in Europe, and also differs from other leading producers in Europe in that it is a leader in the overall glass industry, not solely in glass packaging (Saller, 1999; Moore, 2001).

Germany

The German family-owned company Quarzwerke GmbH is the second biggest European producer (after SCR-Sibelco SA in Belgium) of glass sand. The company owns glass sand operations in Germany, Austria, Poland, the Czech Republic and South Africa, and has five sites in Germany located in Frechen, Haltern, Weferlingen, Gambach, and Hohenbock (Saller, 1999).

The German container-glass market is the largest in Europe with production of container glass in excess of 4 Mtpa. Although a large number of companies produce container glass in Germany, the market is dominated by five companies. The Saint-Gobain subsidiary, Ober-landGlass AG, and BSN Glasspack make up almost 50% of the market, with market shares estimated at 25% and 23% respectively. The other three most significant producers of container glass are Lüner Glashüttenwerke GmbH, Heye-Glass, and Rexam (Moore, 2001).

Turkey

Turkey is another major glass-producing country in Europe, with an annual of growth rate of the glass industry around 5%. The glass industry in the country is dominated by the company Ûiúe ve Cam Fab. AS (Ûiúecam), which has doubled its production capacity since 1995. Ûiúecam primarily serves the domestic market, and produces silica through its subsidiary, Camis Madencilik AS, which has an annual glass sand output of approximately 140 000 t. Camis Madencilik obtains its raw materials from sand deposits, as well as quartzite and sandstone. Higher quality silica sand is imported from western Europe and the Middle East. Other glass producers in Turkey include Kaltun (45 000 tpa) and Polat Maden (45 000 tpa) (Saller, 1999).

Silica rock

United Kingdom (UK)

In the UK, one of the principal sources of grindstones, pulpstones, and millstones has been the fine-grained Newcastle Stone quarried from Carboniferous sandstone associated with the coal measures near Newcastle. Other rocks used for such applications in the UK include Derbyshire and Yorkshire Stones (Alsobrook, 1994).

Norway

With relatively low-cost hydroelectric power and large reserves of high-purity quartzite, Norway is a key player in silicon and ferrosilicon production. Two of the leading global producers, Elkem ASA and Fesil ASA, are based in Norway. In 1998, Elkem's four ferrosilicon and three silicon metal plants in Norway had capacities of 375 000 tpa and 140 000 tpa respectively. Fesil ASA operates ten ferrosilicon and silicon furnaces in Norway, with a combined capacity of 200 000 tpa of ferrosilicon and 34 000 tpa of silicon (Kendall, 2000).

Quartzite is quarried at Tana, in northern Norway, for use in ferrosilicon manufacture. Lump quartzite from Tana has also been shipped to Iceland, 2600 km away, for ferrosilicon manufacture (Alsobrook, 1994).

Spain

Spain supplies most of the quartz used for silicon metal and ferrosilicon production in Europe, especially to Iceland, Norway, and Sweden. Metallurgical-grade lump quartz produced at La Coruna in Galicia, northwestern Spain, contains less than 0.05% Fe_2O_3, 0.02% Al_2O_3, and 0.01% CaO (Alsobrook, 1994).

Sweden

In Sweden, quartzite is quarried at Amal in Dalsland. The production from this locality has been used in ferrosilicon manufacture and in monolithic refractories (Alsobrook, 1994).

Italy

Quartz produced at Montioni, Sanfront, Martiniana Po, and Sondalo is used in a number of industries including ferrosilicon production, refractories, filtration, abrasives, chemicals, and blast furnace steelmaking (Alsobrook, 1994).

New Zealand

Silica sand

The principal localities of silica sand deposits in New Zealand are found in Northland, at Parengarenga Harbour (about 80 Mt of resources) on the east coast and around Kaipara Harbour (about 10 Mt of resources) on the west coast. Silica sand from Parengarenga Harbour has 95.7–97.7% SiO_2, 0.05–0.42% Fe_2O_3, and 0.004–0.013% Cr_2O_3 and has been used in the glass industry. Other significant deposits of silica sand in New Zealand are found as concentrations on erosional land surfaces associated with coal measures at Mount Somers in Canterbury and at Charleston in Westland, both in the South Island. The sand from Mount Somers is used in glass, foundry, and building industries, whereas sand from Charleston is found to be unsuitable for the glass industry, but has been used locally in the cement industry (Christie et al., 2000).

Silica rock

Quartz gravels, with potential for use in the ferrosilicon or silicon metal industries, are widespread around Southland, particularly at Pebbly Hills – Mable Bush, in the central Southland. The deposits are estimated to contain resources of more than 350 Mt averaging 98% SiO_2, and 30–40% of this quantity is suitable for use in ferrosilicon production.

Extensive deposits of chert beds containing 90–93.7% SiO_2 are found in greywacke in eastern Northland. About 1 Mt of quartzite assaying 97–97.6% SiO_2, suitable for the ferrosilicon industry, is found in at Aorere Valley in the South Island.

Amorphous silica is deposited by hot springs and also by hydrothermal alteration of rocks in volcanically active areas. For example, in the Taupo Volcanic Zone, acid sulfate alteration in the surface rocks of the active geothermal systems has resulted in the alteration of all minerals, except primary quartz, to an assemblage of amorphous silica, cristobalite(–native sulfur), alunite, cinnabar, and barite. The resulting rock is of low density, white, porous, and is composed primarily of amorphous silica with residual quartz phenocrysts (Christie et al., 2000). However, this rock is not mined at present as a source of silica.

Australia

During 1998–99, Australia had a reported production of 3.9 Mt of silica sand and rock (Table 10), of which 3.7 Mt (95%) is silica sand. Production of silica sand from the various States, in order of importance, is Queensland (2.1 Mt, 57% of total), Western Australia (0.85 Mt, 23% of total), New South Wales (0.27 Mt, 8% of total), Victoria (0.21 Mt, about 6% of total), and South Australia (0.2 Mt, about 6% of total).

At present the States producing silica rocks are New South Wales, Western Australia, and South Australia and

Table 10. Australian production (kt) of silica sand and rock

Year	*New South Wales*	*Victoria*	*Queensland*	*Western Australia*	*South Australia*	*Tasmania*	***Total***
1988–89	480	na	1 683	365	110	158	**2 795**
1989–90	574	na	1 802	478	112	150	**3 116**
1990–91	551	na	2 145	862	104	172	**3 835**
1991–92	553	na	2 020	655	120	na	**3 347**
1992–93	495	na	2 421	518	136	na	**3 570**
1993–94	na	na	2 494	568	na	na	**3 063**
1994–95	565	220	2 829	615	174	174	**4 576**
1995–96	636	na	na	742	132	na	**1 510**
1996–97	699	na	2 681	700	157	na	**4 237**
1997–98	614	na	2 851	784	131	158	**4 538**
1998–99	438	210	2 087	939	215	na	**3 889**

NOTE: na: not available

SOURCE: ABARE (1999); Driessen, A., written comm. (2001); Pain, M., written comm. (2001)

the production during 1998–99 was 161 078 t, 90 069 t, and 18 000 t respectively. Although Tasmania has produced silica rock in the past, there appears to be no reported production since 1993.

Queensland

Silica sand

Silica sand deposits in Pleistocene to Holocene coastal sand dunes are found along most of the Queensland coastline. The deposits are about 3 km wide and reach over 12 km inland. The major deposits have an average thickness of 25–30 m of sand and contain about 99% silica and 1% heavy minerals. The large deposits form as high transgressive or parabolic dunes, as beachridge barriers parallel to the coast, and as tidal delta sands. Beachridge barrier deposits that formed parallel to the coast also incorporate former beach strand lines. The dune systems are the prime source of high-purity silica sand for glass and foundry industries (Cooper, 1993; Bruvel, 1999).

The major sand deposits in Queensland are found in three coastal regions: southern Queensland from Gold Coast to Fraser Island, central Queensland from Hervey Bay to Whitsunday Island, and north Queensland from Townsville to the Cape York Peninsula.

Deposits of Pleistocene white sand are found in all major sand masses in southern Queensland. These include the high dune systems on North Stradbroke, Moreton, and Fraser Islands; the beach ridge barriers of Bribie Island; the coastal high dunes at Peregian–Noosa; the Cooloola sand mass between Noosa and Fraser Island; and the tidal deltas of Moreton Bay. Along the central Queensland coast, silica sand deposits are located from Hervey Bay to Curtis Island, and at Byfield, Shoalwater Bay, and Whitsunday Island. The most important silica sand deposits in North Queensland are those in the Cape Flattery – Cape Bedford dunefield, and the Olive River dunefield at Shelburne Bay (Cooper, 1993).

Most of the production of silica sand in Queensland is from Cape Flattery followed by North Stradbroke Island, Beachmere (44 km north of Brisbane), Moreton Bay, and Coonarr (near Hervey Bay). The Cape Flattery – Cape Bedford dunefield occupies about 580 km^2, and consists predominantly of white, well-defined, transgressive, elongate–parabolic active dunes, and rounded degraded dunes stabilized by vegetation. Sand from this deposit is mined by large front-end loaders and transported on a continuous belt to a stationary wet mill for washing and heavy mineral removal. At North Stradbroke Island, extensive deposits of white sand up to 10 m thick are mined. Heavy minerals are removed in a stationary wet mill. At Beachmore, high-quality silica sand is mined from a low-lying coastal barrier dune system. In Morton Bay, extensive tidal delta sand deposits exist in both the South Passage and the North Entrance tidal deltas. At Coonarr, beachridge barriers up to 6 m thick are worked by a number of companies mainly for specialist foundry sand (Bruvel, 1999).

Western Australia

Silica sand

Western Australia is the second largest producer of silica sand in Australia. The State has produced 12.8 Mt valued at $92.7 million (dollar value of the day) (present day value $114.1 million) during the period 1939–2000 (Tables 11 and 12). About 73% (9.3 Mt) of this production has been from the Perth Metropolitan Area, principally around Gnangara, 20 km north of Perth, and the Jandakot area, some 15 km south of Perth. Since 1995, two major mines began production from Kemerton, 25 km north-northeast of Bunbury, and Mindijup, 40 km northeast of Albany. During 2000, the Kemerton mine produced 405 828 t of silica sand (Sons of Gwalia Ltd; June, September, and December 2000 Quarterly Reports). This production remains unreported to MPR as the deposit is located within a lease registered prior to January 1899, which is alienated from fees, and therefore reporting of production, for all commodities other than precious metals. The annual production from Mindijup mine is around 88 500 t.

During 2000, Western Australia produced 898 994 t of silica sand (with an estimated ex-mine value of

Table 11. Western Australian silica sand production (tonnes) from 1939 to 2000

Year	*Perth (metro area)*	*Albany*	*Coolgardie*	*Kemerton[(a)]*	*Other regions*	***Total***
1939	16	–	–	–	–	**16**
1940	14	–	–	–	–	**14**
1941	22	–	–	–	–	**22**
1942	113	–	–	–	–	**113**
1943	345	–	–	–	–	**345**
1944	161	–	–	–	–	**161**
1945	178	–	–	–	–	**178**
1946	184	–	–	–	–	**184**
1947	370	–	–	–	–	**370**
1948	525	–	–	–	–	**525**
1949	1 002	–	–	–	–	**1 002**
1950	5 214	–	–	–	–	**5 214**
1951	6 272	–	–	–	–	**6 272**
1952	7 793	–	–	–	–	**7 793**
1953	7 017	–	–	–	–	**7 017**
1954	7 928	–	–	–	–	**7 928**
1955	6 867	–	–	–	–	**6 867**
1956	7 461	–	–	–	–	**7 461**
1957	5 784	–	–	–	–	**5 784**
1958	6 523	–	–	–	–	**6 523**
1959	6 938	–	–	–	–	**6 938**
1960	8 776	–	–	–	–	**8 776**
1961	8 347	–	–	–	–	**8 347**
1962	10 492	–	–	–	–	**10 492**
1963	10 085	–	–	–	–	**10 085**
1964	10 208	–	–	–	–	**10 208**
1965	9 408	–	–	–	–	**9 408**
1966	28 671	–	–	–	–	**28 671**
1967	42 438	–	–	–	–	**42 438**
1968	20 890	–	–	–	–	**20 890**
1969	49 706	–	–	–	10	**49 716**
1970	96 078	–	–	–	1 024	**97 102**
1971	174 990	–	–	–	749	**175 739**
1972	164 454	–	–	–	920	**165 374**
1973	220 572	–	–	–	2 097	**222 669**
1974	280 645	–	–	–	24	**280 669**
1975	107 266	–	–	–	40	**107 306**
1976	109 218	–	–	–	325	**109 543**
1977	136 871	–	–	–	310	**137 181**
1978	103 697	–	–	–	1 000	**104 697**
1979	278 091	–	–	–	–	**278 091**
1980	127 907	–	–	–	1 460	**129 367**
1981	111 419	–	–	–	1 820	**113 239**
1982	122 905	–	–	–	–	**122 905**
1983	150 627	–	141 376	–	–	**292 003**
1984	247 243	–	98 171	–	7 163	**352 577**
1985	305 283	–	87 834	–	–	**393 117**
1986	310 226	–	80 155	–	–	**390 381**
1987	323 927	–	62 121	–	8 036	**394 084**
1988	315 913	–	24 998	–	–	**340 911**
1989	401 928	–	31 821	–	–	**433 749**
1990	555 624	–	66 933	–	–	**622 557**
1991	576 834	–	92 550	–	–	**669 384**
1992	444 139	–	75 503	–	–	**519 642**
1993	385 954	–	73 843	–	–	**459 797**
1994	443 406	–	112 987	–	2 306	**558 699**
1995	386 507	24 682	114 746	–	–	**525 935**
1996	455 942	55 343	107 993	117 094	312	**736 684**
1997	511 834	88 729	119 592	339 396	–	**1 059 551**
1998	417 224	89 145	148 082	380 777	–	**1 035 228**
1999	369 744	88 474	–	337 454	–	**795 672**
2000	373 800	119 366	–	405 828	–	**898 994**
Total	**9 280 016**	**465 739**	**1 438 705**	**1 580 549**	**27 596**	**12 792 606**

NOTE: (a) Information from Sons of Gwalia Ltd 1996 to 2000 Annual Reports

Table 12. Value ($ of the day) of Western Australian silica sand production from 1939 to 2000

Year	*Perth (metro area)*	*Albany*	*Coolgardie*	*Kemerton*[(a)]	*Other regions*	***Total***
1939	36	–	–	–	–	**36**
1940	30	–	–	–	–	**30**
1941	50	–	–	–	–	**50**
1942	283	–	–	–	–	**283**
1943	608	–	–	–	–	**608**
1944	408	–	–	–	–	**408**
1945	454	–	–	–	–	**454**
1946	454	–	–	–	–	**454**
1947	938	–	–	–	–	**938**
1948	1 287	–	–	–	–	**1 287**
1949	2 029	–	–	–	–	**2 029**
1950	7 131	–	–	–	–	**7 131**
1951	8 833	–	–	–	–	**8 833**
1952	11 259	–	–	–	–	**11 259**
1953	9 379	–	–	–	–	**9 379**
1954	11 083	–	–	–	–	**11 083**
1955	9 602	–	–	–	–	**9 602**
1956	10 307	–	–	–	–	**10 307**
1957	7 829	–	–	–	–	**7 829**
1958	8 535	–	–	–	–	**8 535**
1959	9 110	–	–	–	–	**9 110**
1960	12 204	–	–	–	–	**12 204**
1961	11 723	–	–	–	–	**11 723**
1962	15 417	–	–	–	–	**15 417**
1963	15 109	–	–	–	–	**15 109**
1964	14 057	–	–	–	–	**14 057**
1965	12 169	–	–	–	–	**12 169**
1966	16 482	–	–	–	–	**16 482**
1967	19 909	–	–	–	–	**19 909**
1968	18 547	–	–	–	–	**18 547**
1969	26 600	–	–	–	30	**26 630**
1970	31 330	–	–	–	2 716	**34 046**
1971	79 898	–	–	–	3 029	**82 927**
1972	123 626	–	–	–	4 251	**127 877**
1973	132 487	–	–	–	7 499	**139 986**
1974	306 065	–	–	–	10	**306 075**
1975	105 392	–	–	–	16	**105 408**
1976	75 533	–	–	–	128	**75 661**
1977	72 976	–	–	–	155	**73 131**
1978	36 005	–	–	–	500	**36 505**
1979	425 288	–	–	–	–	**425 288**
1980	37 823	–	–	–	1 460	**39 283**
1981	54 523	–	–	–	1 820	**56 343**
1982	115 768	–	–	–	–	**115 768**
1983	112 079	–	346 420	–	–	**458 499**
1984	847 340	–	240 518	–	73 368	**1 161 226**
1985	575 874	–	215 193	–	–	**791 067**
1986	388 683	–	196 380	–	–	**585 063**
1987	2 501 109	–	152 196	–	104 468	**2 757 773**
1988	2 461 078	–	61 242	–	56 100	**2 578 420**
1989	3 554 134	–	77 964	–	–	**3 632 098**
1990	4 701 629	–	188 131	–	–	**4 889 760**
1991	6 163 440	–	226 748	–	–	**6 390 188**
1992	4 788 848	–	184 982	–	–	**4 973 830**
1993	4 128 884	–	180 918	–	–	**4 309 802**
1994	4 677 313	–	276 818	–	25 366	**4 979 497**
1995	4 113 532	367 242	281 125	–	–	**4 761 899**
1996	4 924 408	830 145	264 583	1 138 713	6 240	**7 164 089**
1997	5 576 027	1 330 935	292 999	3 393 211	–	**10 593 172**
1998	4 562 390	1 337 205	362 800	3 643 628	–	**9 906 023**
1999	4 037 469	1 484 642	–	4 066 751	–	**9 588 862**
2000	4 060 356	2 133 080	–	5 096 600	–	**11 290 036**
Total	**64 033 169**	**7 483 249**	**3 549 017**	**17 338 903**	**287 156**	**92 691 494**

NOTE: (a) estimated value

Table 13. Western Australian quartzite and chert production (tonnes) from 1966 to 2000

Year	*Moora* (*chert*)	*Toodyay* (*quartzite*)	*Yannery Hills (West Pilbara)* (*quartzite*)	***Total***
1966	–	1 301	–	**1 301**
1967	–	1 339	–	**1 339**
1968	–	1 339	–	**1 339**
1969	–	1 338	–	**1 338**
1970	–	1 540	–	**1 540**
1971	–	1 289	–	**1 289**
1972	–	1 109	–	**1 109**
1973	–	770	–	**770**
1974	–	608	–	**608**
1975	–	509	–	**509**
1976	–	524	–	**524**
1977	–	730	–	**730**
1978	–	615	–	**615**
1979	–	1 135	–	**1 135**
1980	–	1 535	–	**1 535**
1981	–	847	–	**847**
1982	–	444	–	**444**
1983	–	448	–	**448**
1984	–	160	–	**160**
1985	–	–	–	**–**
1986	–	–	–	**–**
1987	–	–	–	**–**
1988	–	–	–	**–**
1989	6 197	–	60	**6 257**
1990	69 021	–	–	**69 021**
1991	76 612	–	–	**76 612**
1992	66 253	–	–	**66 253**
1993	67 732	–	–	**67 732**
1994	78 552	–	–	**78 552**
1995	84 696	–	–	**84 696**
1996	79 048	–	–	**79 048**
1997	84 582	–	–	**84 582**
1998	91 821	–	–	**91 821**
1999	92 739	–	–	**92 739**
2000	92 149	–	–	**92 149**
Total	**889 402**	**17 580**	**60**	**907 042**

approximately $11.3 million), which includes production of 405 828 t from the Kemerton mine. Currently, the State exports about 0.75 Mtpa of high-grade silica sand to Japan and other South East Asian countries.

Detailed descriptions of the geology and resources of silica sand in Western Australia are found in **Chapter 4**.

Silica rock

During 1966–2000, Western Australia produced 907 042 t of chert and quartzite, both valued at $8.2 million (dollar value of the day; present day value $9.8 million), from two main localities, Moora and Toodyay (Tables 13 and 14). Chert is mined from a deposit at Moora, 204 km north of Perth, and quartzite mainly from the Toodyay area, about 100 km east of Perth. As a source of silica, chert is the more important. Mining of chert in Western Australia began in 1989 from the Moora deposit. During 2000, the State produced 92 149 t of chert, valued at $921 493, from the Moora deposit (compared with 90 069 t produced in 1998–99). This chert is used in the production of silicon metal by Simcoa Operations Pty Ltd, which has a plant located 15 km north-northeast of Bunbury. The Kemerton plant has the capacity to produce 30 000 t of silicon metal and 10 000 t of silica fume annually.

During 1966–84, Western Australia produced 17 580 t of quartzite from the Toodyay area. This rock, known as Toodyay Stone or Toodyay Quartzite, is used as dimension stone in the building industry. Since 1984, there has been no reported production of this quartzite to MPR, but it is likely to have been produced under extractive industry licences obtained from local governing bodies. This rock has not been used as a source of silica.

During 1964–90, there is reported production of 69 486 t of quartz, valued at $1.8 million (dollar value of the day; present-day value $6.72 million), from a number of localities in Western Australia (Tables 15 and 16). About 82% (56 977 t) of the production was from a

Table 14. Value ($ of the day) of Western Australian quartzite and chert production from 1966 to 2000

Year	*Moora* (*chert*)	*Toodyay* (*quartzite*)	*Yannery Hills (West Pilbara)* (*quartzite*)	***Total***
1966	–	5 120	–	**5 120**
1967	–	5 464	–	**5 464**
1968	–	5 260	–	**5 260**
1969	–	6 515	–	**6 515**
1970	–	7 240	–	**7 240**
1971	–	5 490	–	**5 490**
1972	–	4 410	–	**4 410**
1973	–	5 070	–	**5 070**
1974	–	5 850	–	**5 850**
1975	–	5 320	–	**5 320**
1976	–	6 630	–	**6 630**
1977	–	7 670	–	**7 670**
1978	–	7 466	–	**7 466**
1979	–	13 775	–	**13 775**
1980	–	19 230	–	**19 230**
1981	–	13 600	–	**13 600**
1982	–	8 805	–	**8 805**
1983	–	7 958	–	**7 958**
1984	–	2 880	–	**2 880**
1985	–	–	–	**–**
1986	–	–	–	**–**
1987	–	–	–	**–**
1988	–	–	–	**–**
1989	61 967	–	2 360	**64 327**
1990	703 953	–	–	**703 953**
1991	782 017	–	–	**782 017**
1992	697 757	–	–	**697 757**
1993	687 362	–	–	**687 362**
1994	785 526	–	–	**785 526**
1995	846 971	–	–	**846 971**
1996	790 479	–	–	**790 479**
1997	845 819	–	–	**845 819**
1998	918 215	–	–	**918 215**
1999	927 387	–	–	**927 387**
2000	921 493	–	–	**921 493**
Total	**8 968 946**	**1 384 155**	**2 360**	**8 193 566**

quartz–feldspar pegmatite body at Mukinbudin, about 330 km east of Perth. This quartz has been mostly used in gardens, as building stone, and as decorative stone, but some was exported to Japan and Europe for use in the production of silicon metal, refractories, ceramics, and glassware (Fetherston, 1990).

Cretaceous Donnybrook Sandstone, found in the Donnybrook region, about 200 km south of Perth, is a source of building stone (dimension stone). The quarrying operations began in the late 1800s and continue today. But production has not been continuous, and often remains unreported to MPR. The sandstone has been used in the past for many buildings in both Perth and Fremantle. The sandstone is yellow to grey, fine and medium grained. The type section of the sandstone is found north of Donnybrook at latitude 33°32'S, longitude 115°49'E. It correlates with the Lower Cretaceous Warnbro Group, which consists of the lower South Perth Shale and the upper Leederville Formation (Cockbain, 1990).

Detailed descriptions of the geology and resources of chert and other silica rocks in Western Australia are given in **Chapter 5**.

New South Wales

Silica sand

The main sources of silica sand in New South Wales are the coastal dune sand deposits of the Port Stephens area, about 50 km north of Newcastle. The deposits in this area, particularly Pleistocene sand on the Tilligerry Peninsula (assaying around 99.89% SiO_2), is New South Wales' source of sand for use in the manufacture of colourless glass. The companies using this sand are ACI Industrial Minerals and PB White Minerals. In March 2001, Unimin Australia Ltd acquired ACI Industrial Minerals Division of ACI Operations Pty Ltd (Industrial Minerals, 2000). The above deposits also have the potential to be feedstock material for production of fused silica. At nearby Salt Ash, ACI Industrial Minerals produces sand for use in the

Table 15. Western Australian quartz production (tonnes) from 1964 to 1990

Year	*Mukinbudin*	*Coolgardie*	*Mount Magnet*	*Manjimup*	*Taurus Dam (Bulong District)*	*Gibraltar (Coolgardie District)*	*Dunns Eight Mile (Kunanalling District)*	***Total***
1964	–	–	–	–	–	117	–	**117**
1965	–	–	–	–	–	249	–	**249**
1966	–	–	–	–	–	–	–	**0**
1967	–	596	2	–	–	–	–	**598**
1968	–	393	–	–	–	–	46	**439**
1969	–	–	–	–	205	257	–	**462**
1970	5 040	–	–	–	–	–	–	**5 040**
1971	9 996	–	–	–	–	–	–	**9 996**
1972	4 055	–	–	–	–	–	–	**4 055**
1973	3 996	–	–	–	–	–	–	**3 996**
1974	2 537	–	–	1 669	–	–	–	**4 206**
1975	3 417	–	–	1 659	–	–	–	**5 076**
1976	2 197	–	–	1 894	–	–	–	**4 091**
1977	3 111	–	–	1 277	–	–	–	**4 388**
1978	2 263	–	–	1 253	–	–	–	**3 516**
1979	1 030	–	–	644	–	–	–	**1 674**
1980	2 133	–	–	315	–	–	–	**2 448**
1981	3 156	–	–	150	–	–	–	**3 306**
1982	2 045	–	–	1 784	–	–	–	**3 829**
1983	2 503	–	–	–	–	–	–	**2 503**
1984	2 272	–	–	–	–	–	–	**2 272**
1985	2 292	–	–	–	–	–	–	**2 292**
1986	1 117	–	–	–	–	–	–	**1 117**
1987	1 334	–	–	–	–	–	–	**1 334**
1988	334	–	–	–	–	–	–	**334**
1989	1 471	–	–	–	–	–	–	**1 471**
1990	678	–	–	–	–	–	–	**678**
Total	**56 977**	**989**	**2**	**10 645**	**205**	**623**	**46**	**69 486**

NOTE: no reported quartz production 1991–2000

manufacture of coloured glass. These deposits are also New South Wales' principal source of foundry sand; the main producers being Quality Sand and Ceramics, Robinson's Anna Bay Sand, and Metromix Pty Ltd. PB White Minerals produces amber-grade glass sand from a deposit at Londonderry, on the western fringes of Sydney.

The enormous friable sandstone deposits of the Newnes Plateau near Lithgow, about 120 km west of Sydney, are currently quarried for construction use, but have the potential to become long-term alternative sources of glass-grade and other industrial sands (Lishmund et al., 1999).

Silica rock

In 1998–99, 161 078 t of silica rock were produced in New South Wales. High-purity quartz suitable for high-grade applications is found in a number of pipe-like bodies in the Tenterfield district. At Bolivia, 30 km south of Tenterfield, high-purity quartz has been mined from a quartz pipe and exported to Japan to produce high-grade fused silica used as a filler in semi-conductors for the electronics industry. The remaining recoverable resource in this deposit is limited. High-purity quartz pebbles associated with old river systems near Cowra are currently quarried at two locations by Glenella Aggregates Pty Ltd at Glenella, and TJ Bryant Pty Ltd at The Mulyan for use as decorative aggregate and filtration gravel. The area has potential for the discovery of further resources of high-purity quartz pebbles. Portman Mining Ltd and Doral Mineral Industries Ltd carried out a feasibility study into establishing a 30 000 tpa silicon smelter at Lithgow, using quartz pebbles from the Glenella deposit at Cowra (Lishmund et al., 1999). However, in December 2000 Portman announced that they, together with Doral, would seek a replacement party to acquire 90% interest in the Lithgow Silica Project (Australian Journal of Mining, 2001). In July 2001, Quaestus Limited announced the acquisition of the Lithgow silica project (Portman Mining Australian Stock Exchange announcement on 23 July 2001).

Victoria

Silica sand and gravel

Most of the known commercial silica deposits in Victoria comprise sands and gravels of Tertiary age. Most of the silica mined is used in glassmaking, the remainder being used in fibreglass manufacture, abrasives, foundry sands, ceramics, paint additives, and ornamental stone (McHaffie and Buckley, 1995).

At Lang Lang, Tertiary alluvial sands and overlying Quaternary dune/shallow marine sands are used by ACI

Table 16. Value ($ of the day) of Western Australian quartz production from 1964 to 1990

Year	*Mukinbudin*	*Coolgardie*	*Mount Magnet*	*Manjimup*	*Taurus Dam (Bulong District)*	*Gibraltar (Coolgardie District)*	*Dunns Eight Mile (Kunanalling District)*	***Total***
1964	–	–	–	–	–	1 730	–	**1 730**
1965	–	–	–	–	–	4 110	–	**4 110**
1966	–	–	–	–	–	–	–	**0**
1967	–	11 842	355	–	–	–	–	**12 197**
1968	–	8 694	–	–	–	–	1 080	**9 774**
1969	–	–	–	–	5 252	6 144	–	**11 396**
1970	60 682	–	–	–	–	–	–	**60 682**
1971	117 077	–	–	–	–	–	–	**117 077**
1972	41 002	–	–	–	–	–	–	**41 002**
1973	40 437	–	–	–	–	–	–	**40 437**
1974	109 122	–	–	1 643	–	–	–	**110 765**
1975	114 718	–	–	1 642	–	–	–	**116 360**
1976	79 588	–	–	1 894	–	–	–	**81 482**
1977	140 137	–	–	1 277	–	–	–	**141 414**
1978	101 835	–	–	1 253	–	–	–	**103 088**
1979	46 350	–	–	644	–	–	–	**46 994**
1980	94 635	–	–	338	–	–	–	**94 973**
1981	142 020	–	–	200	–	–	–	**142 220**
1982	85 359	–	–	2 140	–	–	–	**87 499**
1983	112 815	–	–	–	–	–	–	**112 815**
1984	102 224	–	–	–	–	–	–	**102 224**
1985	134 640	–	–	–	–	–	–	**134 640**
1986	50 261	–	–	–	–	–	–	**50 261**
1987	60 035	–	–	–	–	–	–	**60 035**
1988	15 035	–	–	–	–	–	–	**15 035**
1989	64 842	–	–	–	–	–	–	**64 842**
1990	30 445	–	–	–	–	–	–	**30 445**
Total	**1 743 259**	**20 536**	**355**	**11 031**	**5 252**	**11 984**	**1 080**	**1 793 497**

NOTE: no reported quartz production 1991–2000

Industrial Minerals to produce high-grade silica sand products. The sands, which are fine to medium grained with low levels of iron, TiO_2, and clay impurities, have 99% silica and 1% heavy minerals. Production from the deposit exceeds 200 000 tpa. Commercial Minerals Ltd (now owned by Unimin Australia Ltd) has sand production facilities at Cranbourne producing foundry sand, ceramic sand, specialized graded sand, resin-coated foundry sand, and construction sands. The sand is sourced from Lang Lang, Cranbourne, and other deposits in west Gippsland. Pioneer Concrete (Victoria) Pty Ltd produces a range of specially processed, high-silica sands at its plant at Clayton. The sand is obtained from various sources to the southeast of Melbourne, including alluvial sands of Tertiary age and dune sands of Quaternary age. Quaternary dune sands of the Malanganee Formation, west of Portland, are used in cement manufacture (McHaffie and Buckley, 1995).

Silica rock

Orthoquartzites, such as those of the Upper Devonian Mansfield Basin and Mitchell Syncline, may prove to be significant lump-silica sources. In the Mitchell Syncline, thickly bedded, grey, quartzose, medium-grained sandstone outcrops over an area of more than 50 km^2. In this syncline, sandstone containing up to 90% quartz grains with minimal matrix and variable hematitic cement are known. Quartz-rich sandstones, with secondary silicification, are also known within the Macalister Synclinorium. Quartz reefs and 'blows', which are common in the highland areas of the State, are also considered to be of interest as a source of silica. Quartz crystals were mined at the Crystal King Mine near Tallangallok, during the 1940s, for use in radio transmitters (McHaffie and Buckley, 1995).

South Australia

Silica sand

In South Australia, both white and amber sand are mined at Glenshera near Mount Compass, south of Adelaide, by ACI Industrial Minerals to supply Australia's largest container-glass plant at Croydon, a western suburb of Adelaide. ACI Industrial Minerals is the main silica sand producer in South Australia. ACI Industrial Minerals has also mined silica sand from a deposit at Normanville. The mine at Glenshera is in Permian fluvioglacial sand. Up to 10 m of yellow and orange sand, which, is upgraded for amber glass and foundry sand, overlies cream-coloured sand which, after processing, is used for colourless container glass. The mineable thickness of white sand is 10–80 m, depending on the depth to the watertable. The

1999 production of 105 000 t of glass sand was used to manufacture container glass for the wine, brewing, food, and soft drink industries; 38 000 t of foundry sand was produced for use by local foundries.

A program of 64 RC drillholes totalling 2463 m, undertaken in 1998 by Primary Industries and Resources South Australia (PIRSA) to evaluate sand resources in the Mount Compass area, indicated that there is considerable potential to prove up additional deposits of glass sand (Pain, M., 2001, written comm.).

Foundry sand has also been produced from Tertiary deposits at Sandy Creek, Tailem Bend, and Balaklava (Keeling et al., 1990; McHaffie and Buckley, 1995; Pain, M., 2001, written comm.).

Silica rock

Lump silica from a massive quartz reef at the 23-Mile deposit, 37 km northwest of Whyalla, has been quarried by BHP Ltd for use in blast furnace slag control. The 23-Mile deposit was opened to supply a ferroalloy plant at Newcastle, until 1976, and the Bell Bay ferroalloy plant in Tasmania from 1976 until 1991. The deposit also supplies silica for use as an additive in blast furnace flux at the Whyalla Steelworks. Production in 1999 for this purpose was 18 000 t. The deposit is now operated by OneSteel Manufacturing Pty Ltd. The silica quarry is located at the southern end of a long quartz ridge, 15–20 m wide, which forms part of a series of discontinuous ridges extending almost 8 km. The quartz vein outcrops up to about 15 m above the surrounding plain and cuts across Proterozoic bedrock of volcaniclastic grit and sandstone. The quarry is located 1.6 km north of the Whyalla to Iron Knob railway (Keeling et al., 1990; Pain, M., 2001, written comm.).

Flint deposits in the southeast of South Australia have been mined for use as grinding media and as a source of high-grade silica for ceramics. These deposits are found in four geological settings: beds and dykes in the Lower Miocene to Upper Oligocene Gambier Limestone; boulder conglomerate of the Pleistocene Bridgewater Formation; Holocene beach deposits; and Holocene surface lag deposits. Silica content of the flint varies from 78 to 96% (Flint et al., 1992).

Tasmania

Silica sand

There is no reported production of silica sand from Tasmania in recent years, but sand for glassmaking by ACI Industrial Minerals has been obtained from dune deposits at Sandford near Hobart (McHaffie and Buckley, 1995).

Silica rock

Deposits of natural silica flour of high quality are found between the township of Savage River and the old gold mining settlement of Corinna, about 20 km inland from the west coast of Tasmania. Most of the deposits, particularly the highest quality deposits, are found overlying a major dolomite horizon of Proterozoic age. The origin of silica flour is poorly understood, but the close association of silica flour and silicified dolomite, and the dolomite nuclei in many silica flour grains, suggest that the silica flour is derived from dolomite. These deposits have been mined to produce silica flour, which was exported to Japan for use in optical glass manufacture. Quartzite has been mined from the Beaconsfield deposit, owned by Boral Ltd, for use in the production of ferrosilicon and silico-manganese, in a plant at Bell Bay (Harrison et al., 1988). Along the north coast between Burnie and Smithton are a number of deposits of high-grade quartzite, as well as thick river terraces, composed largely of quartz gravel of possible fluvioglacial origin. These deposits have been prospected for potential feedstock for silicon metal production.

Pakistan

Silica sand

In Pakistan, silica sand deposits are found in the provinces of Punjab, Sind, and the North West Frontier. Domestic silica sand production is around 120 000 tpa, of which around 70% is from Mianwali in the Punjab province (Benbow, 1989).

Silica rock

Lump quartzite for use as a steel mill flux is produced in the Lasbela region of Baluchistan (Alsobrook, 1994).

India

Silica sand

In India, silica sand operations are found near Jaipur in the Rajastan State and at Phodaghat in the Sindhudurg district of Maharashtra State. The silica sand produced from the Jaipur region has average grades of 99.2% SiO_2, 0.02–0.04% Fe_2O_3, and 0.62% Al_2O_3 and is used in glass, foundry, and ceramic industries. The silica sand from Phodaghat has typically 98.5% SiO_2, 0.02% Fe_2O_3, and 0.5% Al_2O_3 and is used in the foundry and glass industries, and in sodium silicate manufacture (Benbow, 1989).

Silica rock

India produces lump quartz containing 99.8% SiO_2 for domestic as well as for export (mostly to Japan) for use in the manufacture of fused quartzware for the electronics industry. The leading producing area is Andhra Pradesh. Other areas of production include Karnataka, Rajastan, Gujarat, Tamil Nadu, Haryana, Madhya Pradesh, and the Tiruchirapalli District in Orissa (Alsobrook, 1994).

Philippines

Silica sand

Along the northwestern coast of Palawan Island, southeast of Manila, is the major centre of silica sand production in the Philippines. The high-grade silica sand used in the container-glass industry from this area has a minimum of 98% SiO_2 and a maximum of 0.07% Fe_2O_3, and the silica sand used in the coloured-glass industry has 97% SiO_2 and 0.15% Fe_2O_3. The foundry-grade silica sand from the area has a minimum of 95% SiO_2 and a maximum of 0.2% Fe_2O_3 (Benbow, 1989).

Vietnam

Silica sand

The major deposits of silica sand in Vietnam are distributed along the eastern coastline. Three large deposits are found in the provinces of Khanh Hoa, Quang Ninh, and Quang Nam. The deposit in the Khanh Hoa province is considered to be the most commercially viable, and is located at Thuy Trieu, 18 km south of Nha Trang and 19 km north of Cam Rahn harbour. The Thuy Trieu silica sand deposit, commonly known as the Cam Ranh deposit, is owned by Khanh Hoa Mineral Exploiting-Processing and Export Co. (Minexco), and has proven and probable reserves estimated at 36.5 Mt. Production from the deposit is about 200 000 tpa of silica sand, and is exported mainly to Japan, South Korea, Philippines, and Taiwan for use in glass, ceramics, and fillers. The Van Hai deposit, 110 km from Haiphong port in Quang Ninh province, has a total proven reserve estimated at 10.2 Mt of silica sand, of which 5.6 Mt grade 98.1–98.5% SiO_2 and 0.09–0.2% Fe_2O_3. The Nam O deposit, 6 km north of Danang in the Quang Nam Province, has proven and probable reserves estimated at 6.3 Mt grading 98.06% SiO_2 and 0.08% Fe_2O_3 (O'Driscoll, 1996).

Brazil

Silica sand

The silica sand deposits in Brazil are concentrated in the States of São Paulo, Minas Gerais, Rio de Janeiro, and Santa Catrina. Approximately 80% of the production is from São Paulo State. The silica sand company Mineracão Jundu produces around 1.2 Mtpa of very pure, white quartz sand from its deposit near Descalvado, about 120 km from São Paulo. The processing of this sand essentially involves washing, sizing, and drying. Most of the silica sand produced in Brazil is consumed by the foundry, metallurgical, and glass industries, particularly as sheet glass for cladding new office buildings, with smaller quantities used in cement, ceramics, and chemical industries (Benbow, 1989; Kendall, 1996).

Silica rock

Brazil has the largest known reserves (around 27 Mt) of natural piezoelectric-grade quartz crystal and lascas-grade quartz in the world. There are hundreds of small, deeply weathered vein and alluvial quartz deposits scattered over thousands of square kilometres along the southeastern margin of the Brazilian Shield. The production is mostly from the States of Minas Gerais, Santa Catarina, São Paulo, and Bahía, although significant resources are also known in Espírito Santo, Paraiba, Paraná, Rio de Janeiro, and Rio Grande do Sul (Alsobrook, 1994).

South Africa

Silica rock

In South Africa, quartzite and/or sandstone is produced at Delmas (85 km from Johannesburg), Donkerhoek (20 km east of Pretoria), and Witkop near Pietersburg (380 km north of Johannesburg). The Delmas deposit is a high-grade sandstone with an average grade of 98.8% SiO_2, 0.5% Fe_2O_3, and less than 0.5% Al_2O_3, and has been used by producers of ferroalloys and refractories. The quartzite at Donkerhoek contains more than 95% SiO_2 and less than 0.18% alkalis and 1.7% Al_2O_3 and has been used as a blast furnace flux in the steel industry. The Witkop mine has produced high-purity quartz for use in silicon metal manufacture (Benbow, 1989; Alsobrook, 1994).

Sri Lanka

Silica rock

Veins of high-purity quartz, assaying more than 99.8% SiO_2, are known in more than 50 localities in Sri Lanka. The best known deposits are found at Opanayake, Galaha, Pelmadulla, Pussella, Matale, Ratnapura, Galaha, and Mahagama, all in the central part of Sri Lanka. In 1998, about 78% of the production was exported to Japan and Germany, and the remainder was used in the local ceramic industry. Since 1998, there have been government restrictions on the export of vein quartz (Alsobrook, 1994; Geological Survey and Mines Bureau, Sri Lanka, 1999).

Market trends

High-grade silica raw materials with desired specifications continue to be in demand, irrespective of long distances involved and shipping costs. For example, Japan continues to import high-grade silica sand from Australia and Asian countries such as Vietnam. Western Australia currently exports around 0.75 Mtpa of high-grade silica sand to Japan and South East Asian countries. In Europe, high-grade silica sand from Spain is exported to Italy, Sweden, Norway and Iceland, and countries such as Turkey import high-grade silica sand from western Europe and the Middle East.

The production of glass sand is naturally dominated by the status of the glass industry it serves. Two important sectors that drive demand for flat and container glass are the construction and packaging industries. In recent years, some sectors of the glass industry in Europe have remained stable, and producers have reported a 2–3% increase in glass sand consumption. The European glass sands industry serves very mature end-consuming markets in western Europe, and the producers are likely to attempt to gain a foothold in emerging markets such as eastern Europe, Russia, and the Ukraine. The flat-glass industry in Europe remains a good growth prospect for silica sand.

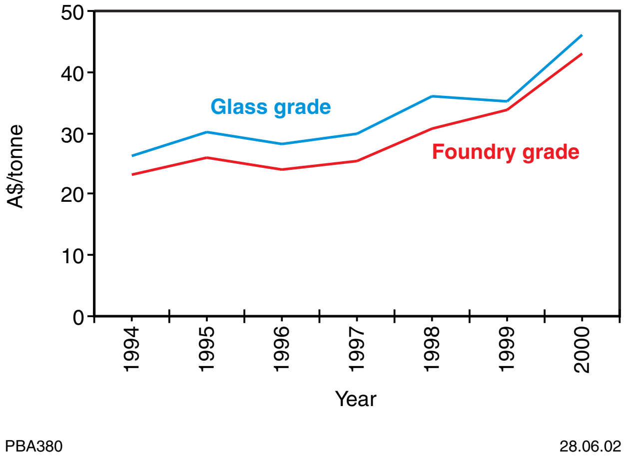

Figure 3. Prices of glass-grade and foundry-grade silica sand (adjusted to year 2000 dollars) (after Industrial Minerals, 1994 to 2000)

Also, high-quality technical glass, and to a certain extent lead and crystal glass for household and tableware, show an increase in demand in Europe. Nevertheless, raw material suppliers in Europe have been put under increasing pressure to meet customer specifications (Saller, 1999; González-Barros and Sanz, 2000).

Two other factors that may have an adverse influence on the glass sand supply industry are the use of recycled glass and alternative container products. The introduction of bottle banks in Europe twenty years ago has led to a rapid increase in the volume of collected glass for recycling, and the use of cullet (waste glass) in glass-making has also grown. Over 50% of the European container glass consumption is now recycled. In 1980, the amount of glass recycled in Europe totalled less than 2 Mt, but this has grown to more than 7.6 Mt in 1997. The largest proportion of glass recycling in Europe is still in the container-glass industry, which currently amounts for 5–10% of total sales in the European packaging markets. The fierce competition from other packaging materials, including aluminium cans, plastic bottles, and paper and card containers has also led to some concern for sand suppliers to the container-glass sector.

In South America, a surge in investment in the glass industry began in the late 1990s owing to an unprecedented expansion of the automobile industry, with production capacity expected to exceed two million cars per annum by the start of the new millenium. Also, the use of glass in the construction industry in South America is increasing with an expanding number of new office buildings changing over to glass as the primary cladding material, rather than concrete or stone (Kendall, 1996).

As for any other industrial mineral, the world prices of silica raw material vary depending on quality and end-use, with a price range around $10–45/t. Although silica raw material prices are generally low, the prices of value-added products can be very high. For example, the price of silicon metal can be as high as $2130–3180/t, and that of colloidal silica as high as $11–14/kg.

The positive trends in global prices during the last six years for some grades of silica sand suggest a steady growth in the silica sand industry. For example, prices of foundry- and glass-grade silica sand have doubled from around $21–23/t (dollar value of the day) in 1994, to around $43–46/t in 2000 (Fig. 3).

The current trend in diversity of applications of silica-based products, as well as a strengthening of Asian economies, has resulted in positive growth forecasts for many sectors. In addition to standard industries such as glass, foundry, and chemical industries for silica raw materials, there are new advances in the applications in silica-based products, which show very positive trends. For example, the global specialty silica industry, which involves products such as precipitated, fumed, and colloidal silica, used in diverse applications, is currently estimated to be worth globally about $3800 million, and is developing at a steady rate. Also, the electronic epoxy moulding compound markets show positive future trends for the fused-silica industry, and in the high-purity fused-quartz sector, huge investments in semiconductor manufacturing have ensured a ready market (O’Driscoll, 1997; Kendall, 2000).

Chapter 4

Silica sand resources of Western Australia

Sandplains in Western Australia

Sandplains are the main source of silica sand in Western Australia and are widespread in the regolith of coastal regions as well as in inland Western Australia. Geoscientists have drawn a distinction between sandplains that are found in coastal margins and those found farther inland, but because of a lack of detailed sedimentological studies the evolutionary characteristics of both coastal and inland deposits are poorly understood in detail. Most of the theories of sandplain evolution in Western Australia are centred around three models; formation in situ, eolian formation, and a combination of the two with local remobilization by wind or colluvial transport (Brewer and Bettenay, 1973; Lowry, 1977; Kendrick et al., 1991; Glassford and Semeniuk, 1995; Newsome, 2000). Newsome (2000) suggested that Western Australian sandplains are mostly the product of weathering in situ. A brief summary of Western Australian sandplain deposits and proposed origins follows.

Carroll (1939) stated that sandplains in the Southern Cross area generally occupy the higher part of the landscape, overlying a laterite horizon. The sand here is poorly sorted and contains some clay material in comparison with the dune and beach sand. She concluded that the sandplains in the Southern Cross area are residual pre-weathered soils and preserved because of low relief and the relatively low rainfall of the region. Her study was based on a study of heavy minerals in the sand and underlying rock formations. Prider (1966) stated that a characteristic feature of the landscape in the regions east of Meckering (132 km east of Perth), extending to the Eastern Goldfields and beyond, is the monotonous sandplains, which overlie lateritic material. The lateritic material, consisting of pisolitic ironstone gravels and cavernous iron-enriched crusts, is exposed along the sandplain margins where sand cover has been eroded. The lateritic material is underlain by weathered granitic and metamorphic rocks. Sandplains have deep deposits of yellow sand, which in places may be as much as 15 m thick. Prider (1966) endorsed Carroll's (1939) view stating that sandy surface soils constitute the upper part of the laterite profile and, for the most part, have formed in situ with the ferruginous zone lying below the sandplain. Baxter and Lipple (1985) stated that the residual soils in the Perth Basin are commonly yellow sand and that their particle shape and grain size reflects the nature of the bedrock. Hocking et al. (1987) also suggested a residual origin for the sand overlying sedimentary rocks of the Carnarvon Basin.

Mulcahy (1959, 1960) and Mulcahy and Hingston (1961), who based their findings on studies of soil–landscape relationships in the York–Quairading area (100–160 km east of Perth), considered that sandplains are not entirely residual in origin, but colluvially transported erosional products of the surface laterite. They suggested that long-term weathering of the ferruginous horizon of the laterite profile would provide a source of deep and extensive sandy deposits and proposed this as a general mode of formation of the Western Australian sandplains. Soil-survey work in the Merredin (260 km east of Perth) area has revealed surface soils that have developed from both transported materials and those in situ (Bettenay and Hingston, 1964). According to Bettenay and Hingston (1964), sand derived from weathering in situ of surface laterite has been transported downslope. Brewer and Bettenay (1973) suggested that yellow sand is derived by the physical disintegration of the mottled-pallid zone of the laterite and shows features of colluvial transport over relatively short distances.

Based on studies of laterite development on sedimentary rocks on the Dandaragan Plateau (166 km north of Perth), Churchward (1970) concluded that sand and gravel in upland areas are locally derived by colluvial transport of pre-weathered lateritic materials. However, based on the close relationship of grain size and shape of sandplain materials with the quartz fraction in underlying sedimentary rocks, Lowry (1974, 1977) considered that these sandplains are essentially residual sands with very minor local reworking.

Glassford and Semeniuk (1995) claimed that Western Australian sandplains are neither in situ nor local colluvial deposits but eolian sedimentary deposits that were formed in a desert environment. Newsome (2000) suggested that ideas presented by Glassford and Semeniuk (1995) are intended to explain the nature and origin of sandplains occurring on the fringe of the current arid zone through to the Swan Coastal Plain fringing the west coast. On the northern Perth and southern Carnarvon Basins there is widespread evidence of eolian activity and dune formation during Pleistocene time (Newsome, 2000). Newsome (2000) carried out a comprehensive study of the Victoria Plateau in the area northeast of Geraldton in order to find evidence for an in situ/local origin versus an eolian/far-travelled origin (Fig. 4). His work involved studies of grainsize, microtextures of quartz grains, magnetic

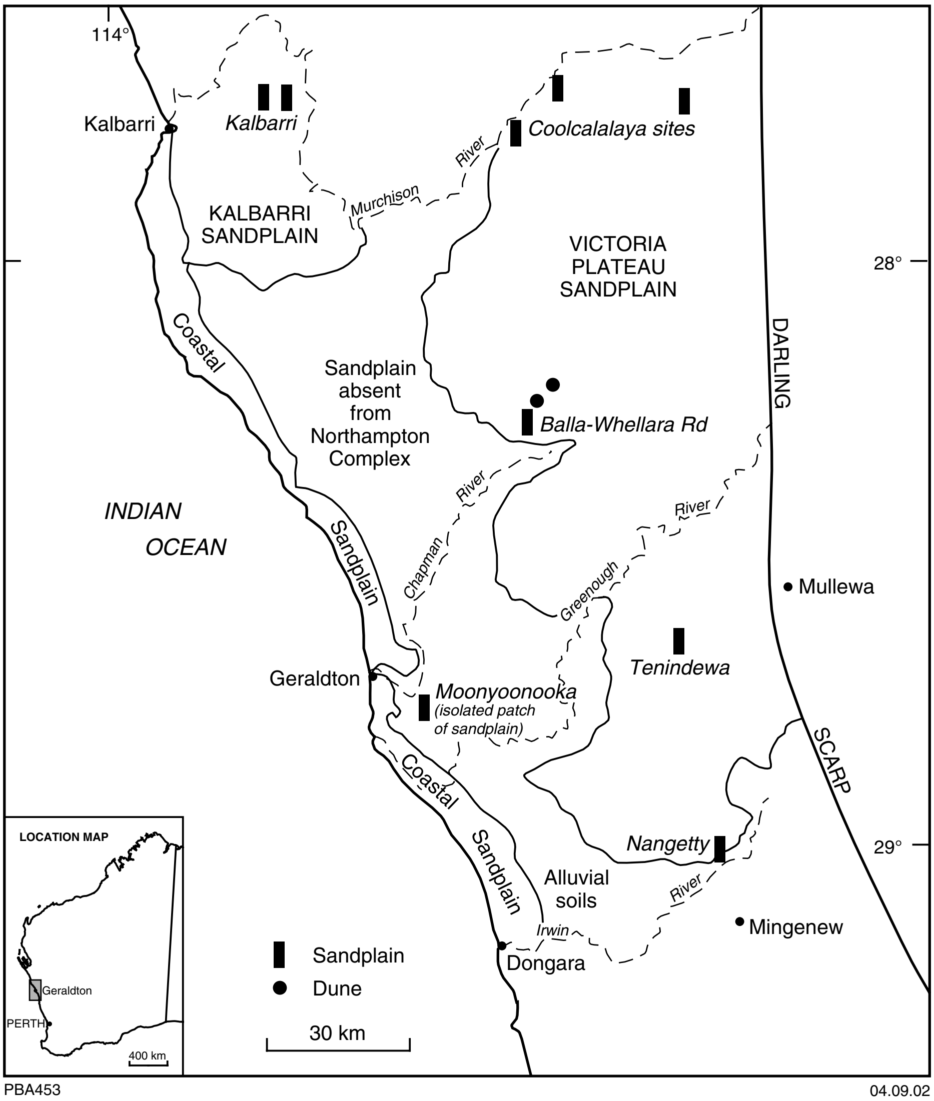

Figure 4. Sandplains in the areas north and northeast of Geraldton (after Newsome, 2000)

properties of minerals, and heavy minerals. The results of these studies mostly supported an origin in situ, with only localized eolian mobilization in some areas.

Other important sandplains in Western Australia are those in the Great Victoria Desert and the Gibson Desert. Sand ridges approximately 3–20 m high and up to several tens of kilometres long characterize the Great Victoria Desert of Western Australia (Daniels, 1969), which covers an area of approximately 240 000 km^2 in western South Australia and southeastern Western Australia. Most of the desert is underlain by Phanerozoic sedimentary rocks of the Gunbarrel Basin, which is bounded to the north by the Musgrave Complex and to the west, south, and southeast by the Archaean Yilgarn Craton. In the region underlain by the Gunbarrel Basin, the Great Victoria Desert is characterized by longitudinal dunes, relict palaeodrainage channels and playas (Pell et al., 1999). Farther to the west, where the Great Victoria Desert overlies the Yilgarn Craton, the landform is a complex interaction of lateritic breakaways, mesas, and palaeodrainage channels with only a few scattered dunes along small valleys. The dunes in the Great Victoria Desert are oriented approximately east–west, average 10 m in height, and range in length from 1 to 15 km. Dunes in the centre of the desert are more closely spaced and shorter than those farther to the west and have steeper southern flanks and closely spaced Y-junctions. Small areas of randomly oriented network dunes in the far northwest (approximately 26°S) mark the poorly defined boundary between the Great Victoria and Gibson Deserts. On the western margin of the desert and over the Yilgarn Craton, lunette dunes are common on the downwind margins of salt lakes.

Pell et al. (1999) carried out studies of the Great Victoria Desert (Fig. 4), covering regions of Western and South Australia. The study aimed to establish the provenance and sedimentary histories of the sand in the desert. The methodology used included the study of sand characteristics such as colour, grain size and heavy minerals, and also zircon U–Pb ages and oxygen isotopes of samples representing major sand groups. The results of these studies suggested derivation of the sand from local bedrock with very little subsequent eolian transport.

Zircon age dating indicated that ultimate protosources for the sands of western Great Victoria Desert are the Eastern Goldfields Terrane, Albany–Fraser Orogen, and Musgrave Complex, contributing about 50, 25, and 25% of the zircon respectively. The term 'protosource' is used to describe the parent igneous/metamorphic rock in which the precursor sand originally formed. The transport of the sediments from the Yilgarn Craton, approximately 90 km to the west, could have been by wind or water. Eolian transport from the Yilgarn Craton was possible after the region became arid in the Late Tertiary, and the transport of major fluvial sand deposits from the Yilgarn Craton to the Gunbarrel Basin was possible both during the Late Carboniferous to Permian glaciation and following Late Cretaceous uplift (Pell et al., 1999). Sand transport from the Musgrave Complex, 300 km northeast of the Gunbarrel Basin, has taken place during a number of geological periods: the Petermann Orogeny Ranges (575 Ma), uplift in the Ordovician, Late Carboniferous to Permian glaciation, and Early to mid-Cretaceous erosion. Most of the sand in the central Great Victoria Desert has derived ultimately from the Musgrave Complex by fluvial means during several episodes of Neoproterozoic to Late Paleozoic tectonics (Pell et al., 1999).

The main source of commercially exploited silica sand in Western Australia is sandplains located close to towns and coastal regions. For the purposes of description, known silica sand resources in the State are grouped into the following tectonic units (Fig. 5a,b):

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

Resources in coastal regions

Most economically significant silica sand deposits in Western Australia are found in the coastal regions of the Perth Basin (Fig. 5a,b). The resources in this basin are widespread in the sandplains of the Pleistocene Bassendean Sand, which extends from about 23 km north of Jurien to some 15 km southwest of Busselton (Fig. 6). Sand from this unit, in many localities, is suitable for high-grade applications such as glass and chemical industries. Most commercially active deposits in the Perth Basin are found in the Gnangara and Jandakot suburbs in the Perth Metropolitan Area, and at Kemerton, about 25 km north-northeast of Bunbury. Since sand resources in the Perth Basin are located close to consuming markets and port facilities, these have attracted the most attention from developers.

The next commercially significant area, after the Perth region, for high-grade silica sand deposits in Western Australia is the Albany region (Fig. 5a,b). In this area silica sand deposits overlie units of the Proterozoic Albany–Fraser Orogen, and Plantagenet Group. In these tectonic units, high-grade silica sand is found as infillings of topographic lows, as leeside accumulations on east and southeast flanks of topographic highs, and also in sand formations overlying laterite. High-grade silica sand deposits are distributed north and northeast of Albany, and along the coastal regions from Walpole to east of Esperance. Currently, a high-grade silica sand deposit is mined at Mindijup, 35 km northeast of Albany. In general, silica sand deposits along the south coast have a substantially finer grain-size range compared with that of similar deposits from the Bassendean Sand along the west coast. However, in both regions the silica sand is of very high chemical purity, generally exceeding 99% SiO_2.

Other prospective regions for silica sand in Western Australia include Lake Don and other areas around Albany, and also regions east of Esperance, such as Merivale and Condingup. Sand from the Kalgoorlie region, derived from the mottled–pallid zone of laterite, is generally found to be inferior in chemical quality compared with the sand in the Perth and Albany regions.

Resources on Yilgarn Craton

Inland silica sand formations are found on the Eastern Goldfields Granite–Greenstone Terrane of the Yilgarn Craton. On this terrane, reasonably high-grade silica sand, used as a flux for nickel smelting in the Kalgoorlie region, is produced from the deposits northwest of Mount Burges, about 45 km west of Kalgoorlie (Fig. 5a,b). This sand is of a lower grade than that found in the Perth and Albany regions. Inland silica sand formations are also found on the northern part of the Albany–Fraser Orogen and on the southern regions of the South West Terrane of the Yilgarn Craton. In these regions, there are widespread Tertiary to Quaternary inland sandplains, derived from Archaean to Palaeoproterozoic granite and gneiss.

Resources in desert sandplains

Vast inland sandplains are found in the Great Sandy Desert, Gibson Desert, and Great Victoria Desert (Fig. 7). Although these sandplains are likely to carry large deposits of silica sand of high quality, their remoteness from markets has to date discouraged their investigation as a source of high-grade silica.

Perth Basin

Regional geology

The Perth Basin is a polycyclic basin, and consists of Ordovician, Devonian, Upper Carboniferous–Permian, Triassic, Jurassic, Cretaceous, and Cainozoic sequences. The Perth Basin extends for about 1000 km along the southwestern coastal belt of Western Australia, has a width of some 80–175 km onshore, and covers an area of approximately 45 000 km^2 on land. It is bounded to the east by the Darling Fault, and extends west and south to the continental–oceanic crust boundary. The northern part is bounded to the northwest by the Ajana Ridge, which consists of shallow basement rocks. Deposition in the Perth Basin was continuous over the northern boundary into the Carnarvon Basin. The basement rocks underlying the Perth Basin consist of Proterozoic rocks of the Pinjarra Orogen. These are exposed in the Northampton Complex, the Leeuwin Complex, and the Mullingarra Inlier (Fig. 8)

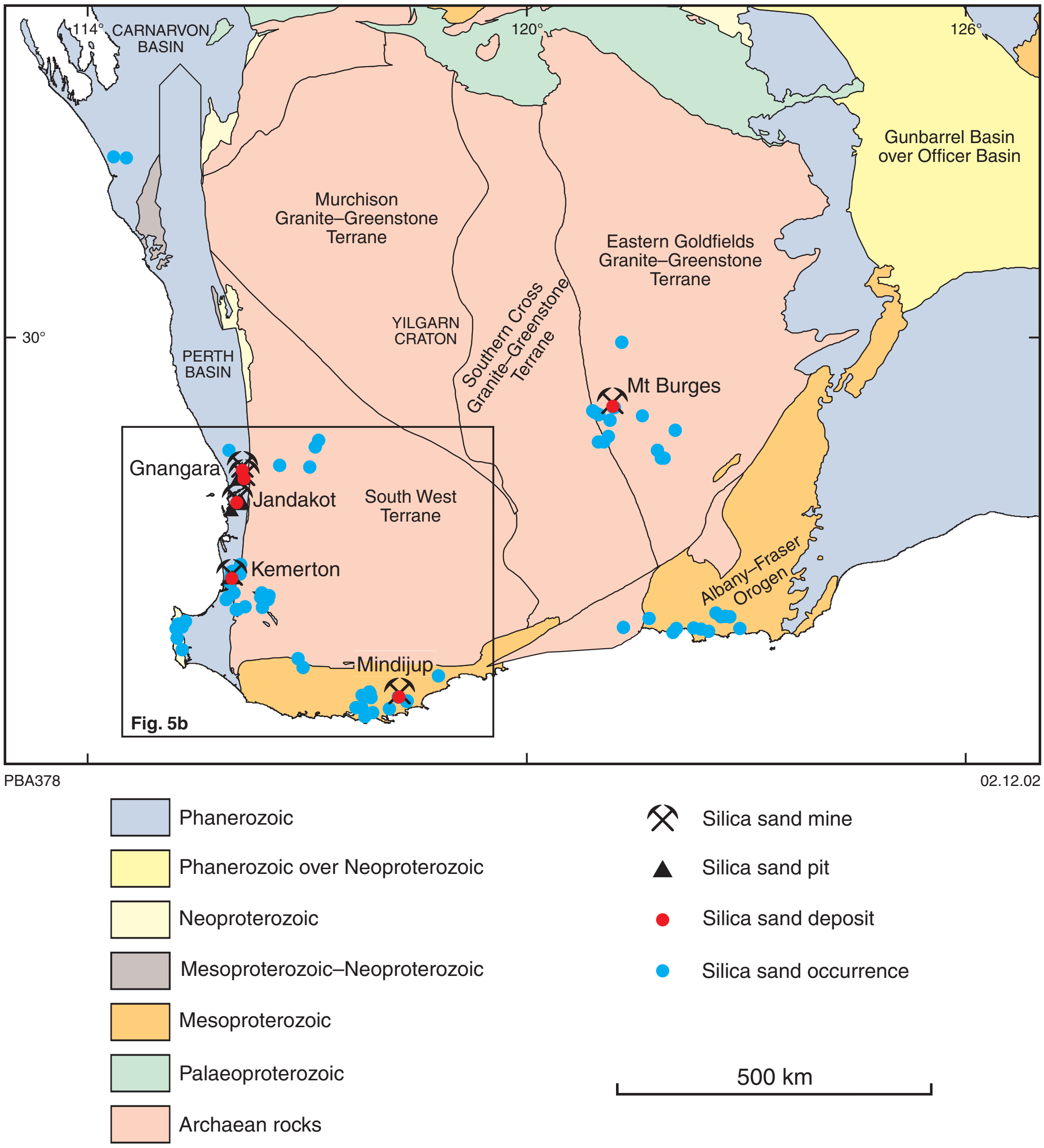

Figure 5a. Silica sand deposits and occurrences of Western Australia

(Playford et al., 1976; Cockbain, 1990; Hocking, 1994; Mory et al., 1998; Sircombe and Freeman (1999); Cawood and Nemchin (2000).

The following summary of the geology of the Perth Basin is based extensively on Playford et al. (1976), Cockbain (1990), Mory and Iasky (1996), and Mory et al. (1998).

In the Perth Basin, the Ordovician Tumblagooda Sandstone, exposed in the valley of the Murchison River, has a thickness exceeding 3000 m. The colour of the sandstone varies through red, yellow, brown, and white. The sandstone is very fine to coarse grained, and commonly conglomeratic. Devonian and Carboniferous rocks are poorly developed, but are known at the northern part of the basin east of the Northampton Complex (Fig. 8). The rocks consist of unnamed units of fine- to medium-grained quartz sandstone (Cockbain, 1990). The total thickness of the Upper Carboniferous and Permian rocks probably exceeds 2600 m, and the rocks consist of marine and continental sequences at the northern part of the basin and a continental sequence in the southern part. These rocks are known to outcrop only in the northern part of the Perth Basin. The outcrops of Triassic rocks are confined to the Geraldton and Hill River districts, but occur in the subsurface throughout most of the basin. The Triassic rocks may exceed 2500 m in thickness and consist of marine and continental sequences in the northern parts and a continental sequence in the southern parts. The Jurassic sequence is mainly continental with a thickness of at least 4200 m and is widespread throughout the basin, with the better exposures in the Geraldton and Hill River Districts. The main exposures of Cretaceous formations are in the Gingin–Dandaragan area, and the total thickness of Cretaceous rocks is thought to be around 12 000 m.

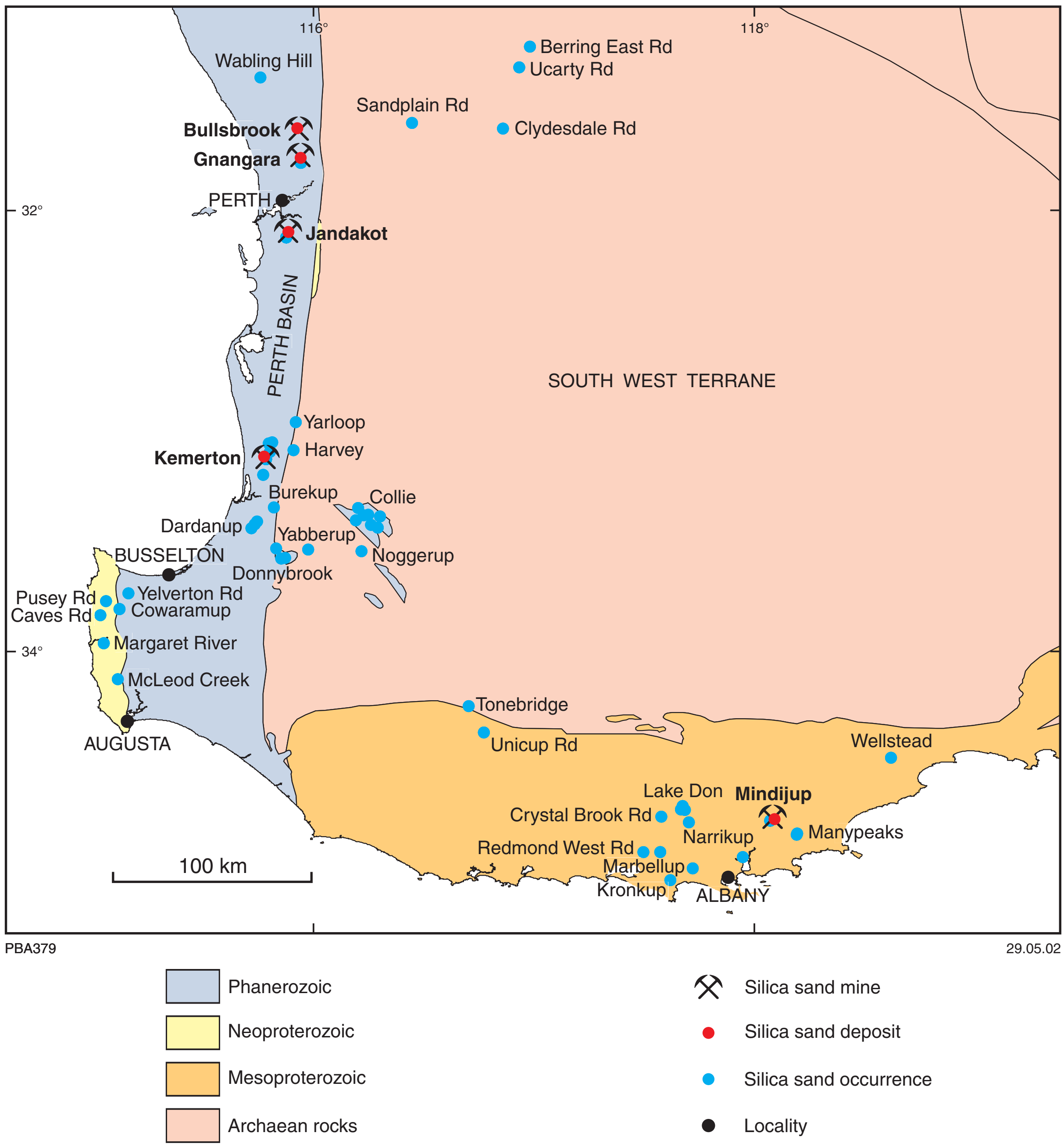

Figure 5b. Silica sand deposits and occurrences in the southwest region of Western Australia (bottom left corner of Fig. 5a)

The Paleocene and early Eocene rocks consist of predominantly carbonate rocks, which are best known in the central part of the basin and adjacent offshore region. The Quaternary rocks are distributed in many areas of the Perth Basin and comprise a suite of rocks of the Kwinana Group, which consists of Ridge Hill Sandstone, Yoganup Formation, Guildford Formation, Tamala Limestone (and other minor units, the Muchea, Rottnest, Peppermint Grove, and Herschell Limestones), Safety Bay Sand, and Bassendean Sand (and other minor units, the Cooloongup and Rockingham Sands). Ridge Hill Sandstone is a unit consisting of ferruginous sandstone with a thin basal conglomerate overlying Precambrian crystalline rocks and capped by laterite. It is found discontinuously along the Red Hill Shelf to elevations 76–91 m above sea level, and probably developed as a shoreline deposit during early Pleistocene or late Tertiary times. The Yoganup Formation occurs in a manner similar to Ridge Hill Sandstone, but its base lies 35–45 m above sea level. This shoreline deposit consists of a basal conglomerate and a foredune containing discontinuous concentrations of heavy minerals together with leached quartz sand. The formation is best developed in front of the Whicher Scarp, along the Yoganup Shoreline, and is also discontinuously exposed at the foot of the Darling Scarp for nearly 200 km (Playford et al., 1976; Wilde and Low, 1978; Harrison, 1990). The Guildford Formation consists of lenticular interbeds of sand, clay, and

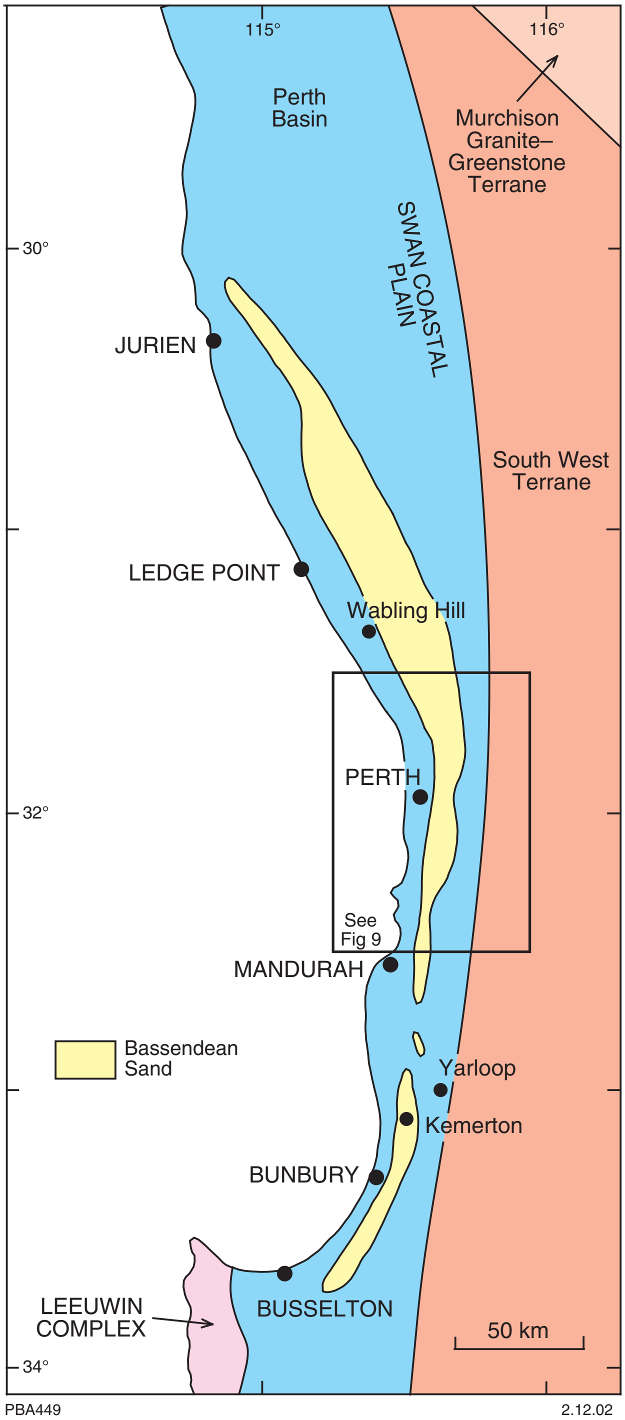

Figure 6. Distribution of Bassendean Sand

conglomerate, and is partly calcareous. It underlies the coastal plain and is overlain by the Bassendean Sand. The Guildford Formation extends from Busselton in the south to about 25 km north of Gingin in the north of the Perth Basin. The formation unconformably overlies the Kings Park Shale, and either the Osborne Formation or the Leederville Formation. The Tamala Limestone consists of coarse- to medium-grained calcarenite, composed of largely skeletal fragments, and contains variable amounts of quartz sand. This limestone is generally well bedded, commonly exhibits large-scale cross bedding, and contains soil horizons and calcified structures. It occurs in several belts of dunes representing successive shorelines during the late Pleistocene. The thickest developments in the Perth Basin are in the Cape Naturaliste region and along the coast south of the Hutt River (north of Geraldton), and probably exceed 150 m in both areas. The Holocene Safety Bay Sand is a unit consisting of calcareous sand dunes commonly consisting of shell fragments such as foraminifers and molluscs, variable quartz, and minor feldspar. It is widespread along the coastal stretch throughout the Perth Basin and overlies the Tamala Limestone and other Quaternary units. Some of the older parts of these dunes are lithified, and in some areas such as The Pinnacles there are rubbly heaps of friable limestone that have been left behind after the bulk of the dune has blown away.

Bassendean Sand

The Bassendean Sand, which extends over large areas of the Swan and Scott Coastal Plains of the Perth Basin, is the most important source of high-grade silica sand in Western Australia (Fig. 6). The name Bassendean Sand was introduced by Playford and Low (1972) for the widespread unit of quartz sand extending over large areas of the Swan Coastal Plain and equivalent units over the Scott Coastal Plain (Figs 6 and 8). It extends from about 23 km north of Jurien in the north, to about 15 km southwest of Busselton in the south (Fig. 6). The type area is Bassendean, a suburb of Perth, but owing to the lack of a good vertical section, a formal type section has not been designated. Its maximum thickness is thought to be about 45 m, and the unit is found as a strip parallel to the coast, having a width of about 10–20 km, and with its western edge about 5–10 km inland.

Quartz grains of the Bassendean Sand have been derived from granitic rocks in the Darling Range and have accumulated as shoreline and dune sands during two or more periods of relatively stable sea level, ranging from about 8 to 25 m above present sea level. Marine fossils have been found at Capel and at outcrops 8–11 km southwest of Busselton. The fossils are thought to be of early to middle, or possibly late Pleistocene in age. Westward, towards the coast, Bassendean Sand passes into Tamala Limestone, which comprises variably lithified limestone and associated leached quartz sand (Playford et al., 1976; Brown, 1986).

Bassendean Sand is typically clean, well rounded and well sorted. At depth, it is usually high in iron and consequently yellow to brown, but closer to the surface the amount of iron decreases and the sand is white. The physical, chemical, and mineralogical characteristics of the Bassendean Sand can vary considerably resulting in variation in the quality of the sand regionally as well as locally. In general, Bassendean Sand is covered with very little or no overburden. Within Bassendean Sand, there is a discontinuous layer of a relatively hard ferruginous material (generally less than a metre thick), known as ‘coffee rock’, at a depth ranging from less than a metre to about 15 m below the surface. The coffee rock

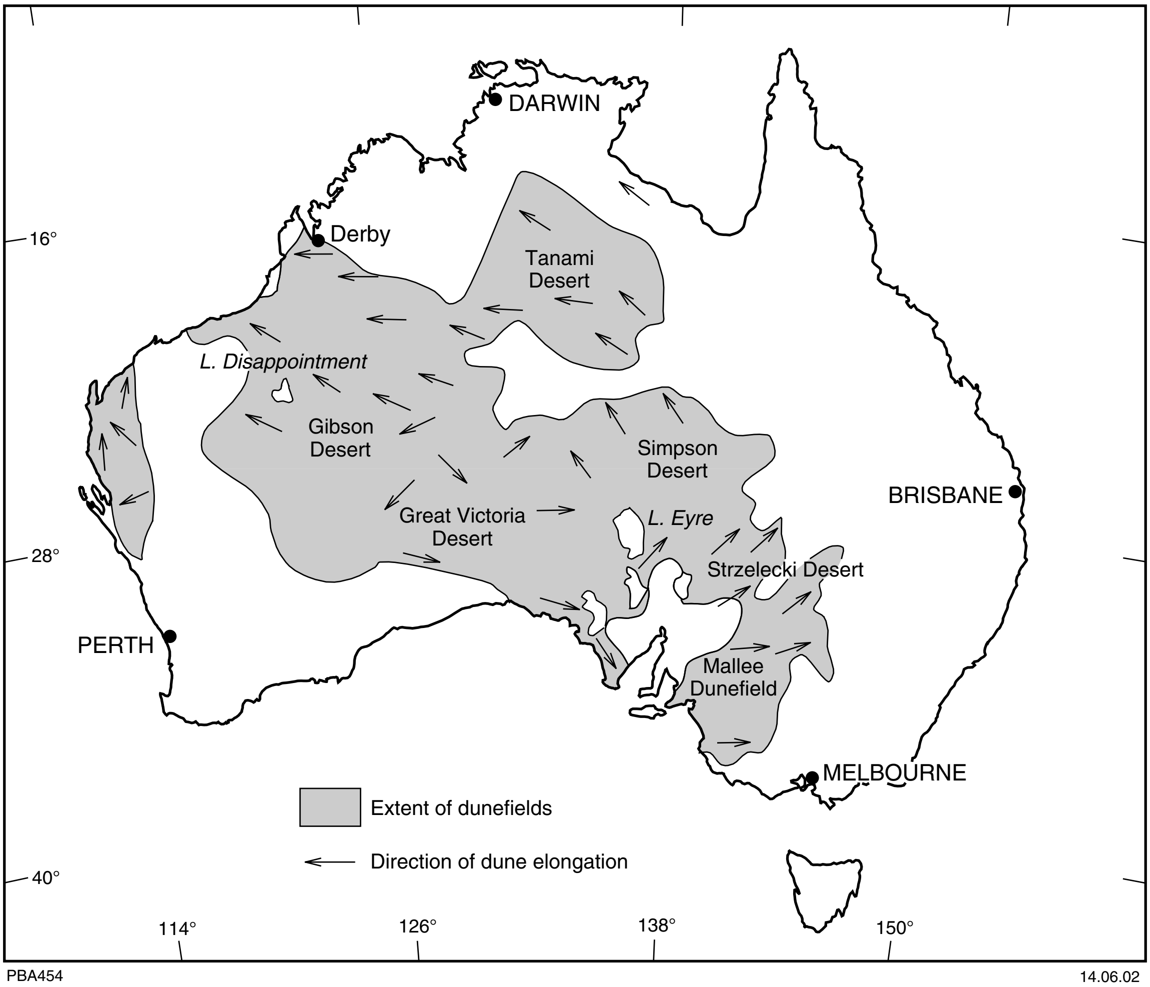

Figure 7. Major Australian desert regions (after Pell et al., 1999)

layer has apparently formed as a result of precipitation of oxides and hydroxides of iron from circulating iron-rich groundwater. Below this layer, the high-grade sand can be quite thick, extending to a maximum of about 15 m.

Geological units potentially hosting deposits of silica sand

The Pleistocene Bassendean Sand, which extends for a few hundred kilometres north and south of the Perth metropolitan region, is the most important unit for commercial deposits of silica sand in the Perth Basin.

In addition, there are extensive and continuous sandplain areas closely associated with the arenites of the northern Perth Basin. The formation that contains white quartz sand in appreciable quantities is the Jurassic Yarragadee Formation. The Pleistocene Yoganup Formation in the Perth Basin also contains leached and ferruginous sand. The quartz sand from these formations is generally found as reworked material in topographically low-lying areas such as valleys and depressions, but large deposits of high-grade silica sand deposits are unknown. Furthermore, these sands commonly carry heavy minerals in commercial quantities and are thus unsuitable for use as high-grade silica sand, unless beneficiated first.

Apart from the above geological formations, none of the Perth Basin sandstones described in the previous section is sufficiently pure to be considered as primary sources of high-grade silica for various industrial applications. However, reworked (and therefore of potentially higher quality) silica sand units derived from some of the sandstones are likely to be found in Cainozoic topographical depressions close to the parent rocks in the northern areas of the Perth Basin. Specific examples are as follows:

- Permian Wicherina Member, which is a white sandstone with minor conglomerate-filled channels and carbonaceous stringers;
- Permian Wagina Sandstone, exposed in a series of synclines adjoining the Darling Fault along a belt extending from Woolaga Creek to the south branch of the Irwin River;
- Triassic Lesueur Sandstone, widely distributed in the subsurface north of Dongara, and consisting for the most part of fine- to very coarse grained cross-bedded quartz sandstone;

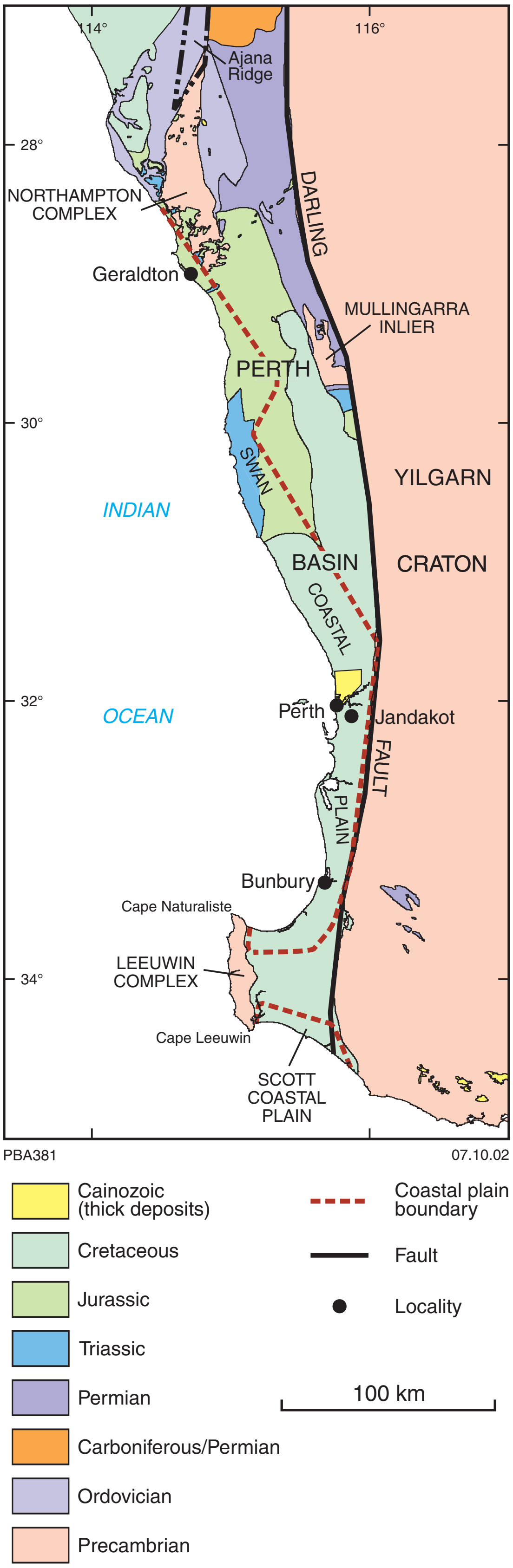

Figure 8. Solid geology of the Perth Basin (geology from GSWA database; coastal plains after Playford et al., 1976)

- Jurassic Parmelia Formation, found in the Dandaragan Trough (Playford et al., 1976; Cockbain, 1990).

At present, commercial silica sand deposits are unknown in any of the above Jurassic to Permian geological units.

Deposits of the Perth Metropolitan Area

A number of areas of Bassendean Sand are well-known high-grade silica sand deposits — in particular, Gnangara (20 km north of Perth), Jandakot (12 km south of Perth), and Kemerton (25 km north-northeast of Bunbury). In the Perth metropolitan region, the Bassendean Sand has been explored by a number of companies and many deposits have been identified (Fig. 9). During a regional sampling program in the Perth Metropolitan Area, Gozzard (1987a,b) carried out size analyses (and some partial chemical analyses) of the Bassendean Sand. These localities are given in Appendix 2.

The following section contains more-detailed descriptions of silica sand deposits found in Bassendean Sand of the Perth Basin.

Gnangara

The Gnangara region, about 20 km north of Perth, is well known for large deposits of silica sand within Bassendean Sand (Fig. 10). The sand from this area has been mined for several decades for use in the glass industry and other high-grade uses. Low-grade sand from this unit is used in the construction industry as concrete sand. The main companies operating in the area are Rocla Quarry Products, ACI Operations Pty Ltd, and Boral Resources.

The Bassendean Sand in the Gnangara area is typically well rounded and well sorted, with a very thin (less than about 30 cm) overburden consisting of grey to dark organic-rich soil. Below this is the high-grade sand, varying in thickness from about 3 to 15 m. Coffee rock is found discontinuously at variable depths as a thin layer (generally less than a metre thick), which can be seen in the quarries of the area. Below the high-quality silica sand is a layer of low-quality brown sand, which is mined for use in the construction industry mainly as concrete and filling sand.

In the Gnangara region, the area that has been explored most for high-grade silica sand is in and around the pine plantation close to the Gnangara Water Reserve (Fig. 10). The companies that have carried out most exploration work in this area are Silica Sales Pty Ltd, Rocla Quarry Products, and Sorensen Short and Associates (for West Australian Silica Sand).

Silica Sales Pty Ltd has undertaken detailed exploration work in the area around Gaskell Road, extending north close to Warbrook Road. This area is currently held by Rocla Quarry Products (Fig. 11). Sorensen Short and Associates has carried out detailed exploration work in Bentley, Dugite, and Saint Patrick Ridges, which are

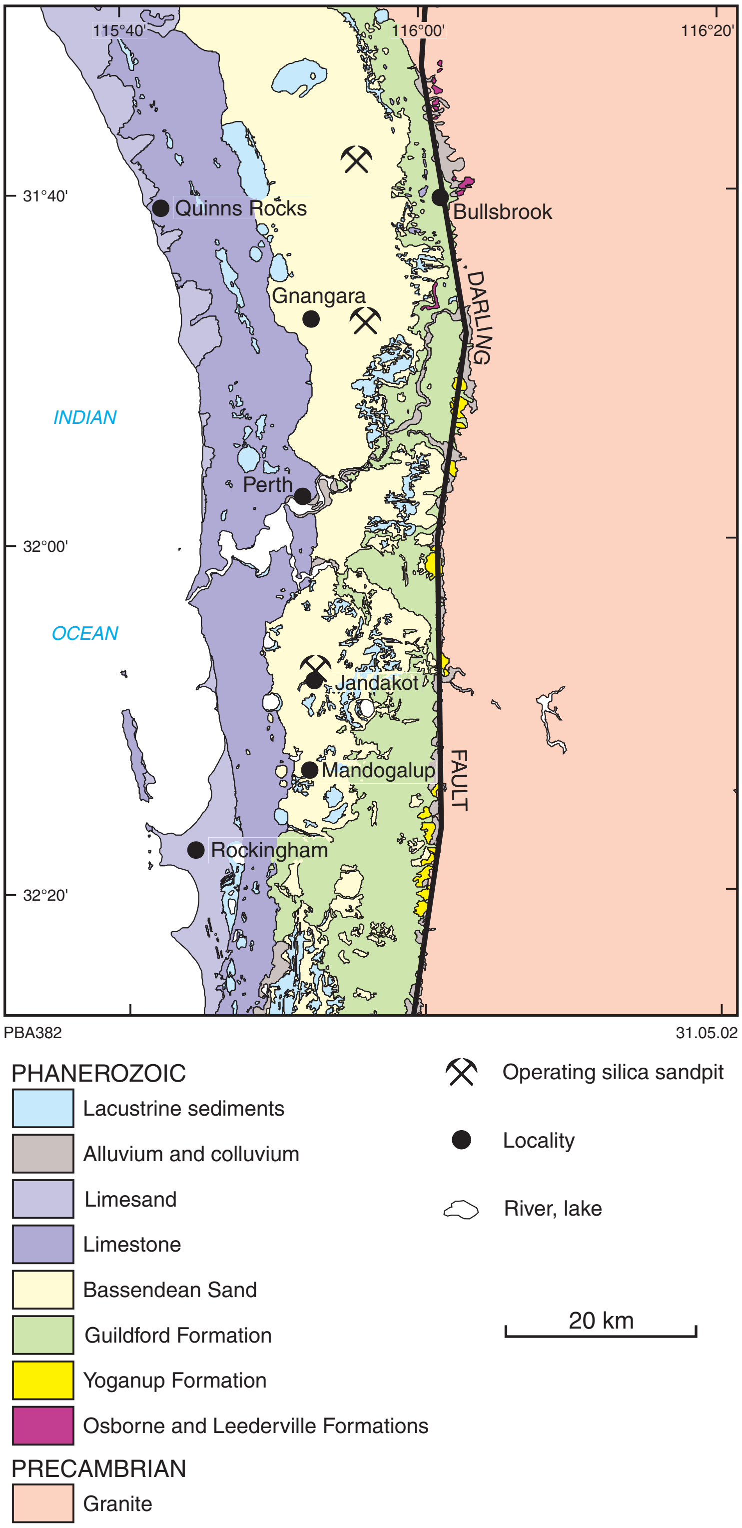

Figure 9. Regional geology around the Perth Metropolitan Area (after Low et al., 1978, 1980)

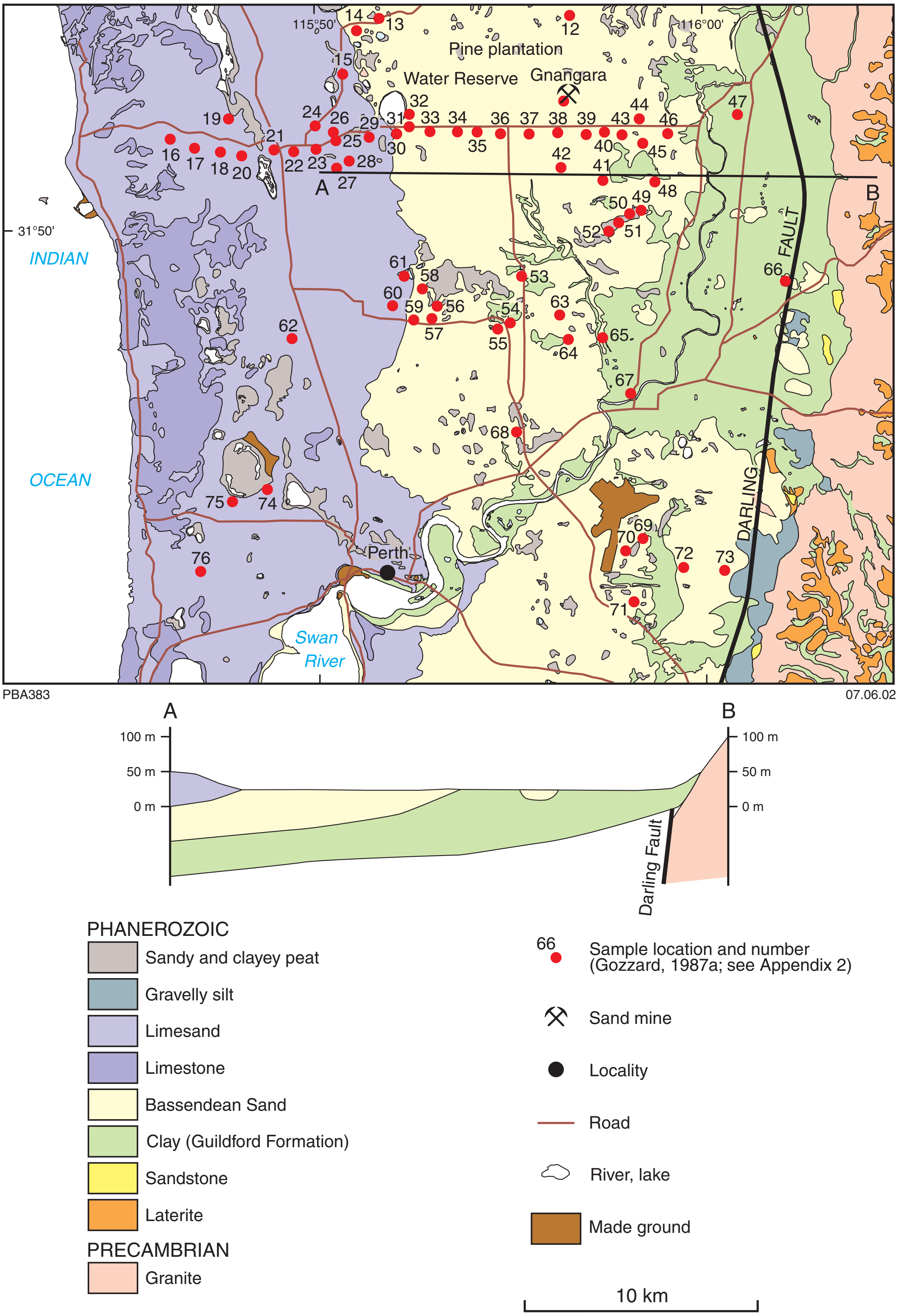

Figure 10. Bassendean Sand in the Gnangara area (after Gozzard, 1986)

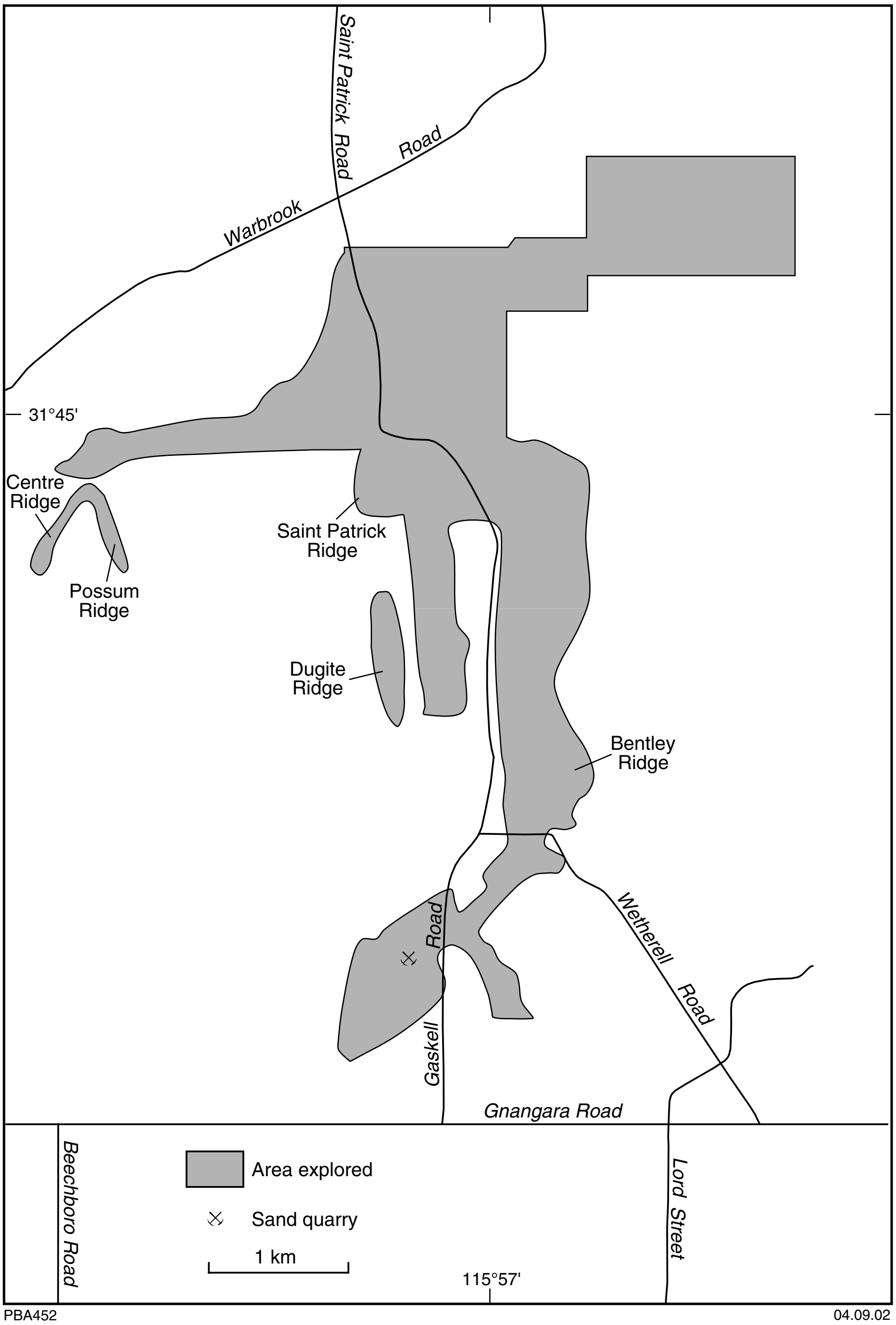

Figure 11. Area of silica sand exploration in Gnangara area

localities close to the area investigated by Silica Sales Pty Ltd (Fig. 11).

Rocla Quarry Products operation

In the early 1980s, Silica Sales Pty Ltd conducted detailed exploration in the area currently held by Rocla Quarry Products. This area is located north of Gnangara Road, and extends along Gaskell Road to south of Warbrook Road (Fig. 11).

Geology

The exploration work by Silica Sales Pty Ltd involved more than 2700 m of vacuum drilling, with more than 600 samples chemically analysed and tested for particle-size distribution. The drilling indicated that raw silica sand is clean and well sorted, medium grained, with almost no gravel, silt, or clay. The average overburden is about a metre thick and the high-grade silica sand layer averaged about 7 m in thickness.

Quality

The high-grade silica sand consists of almost pure quartz with only traces or no impurities of heavy minerals such as rutile and ilmenite.

The SiO_2 contents of the 600 samples ranged from 99.3 to 99.9% with an average of 99.76%. More than 60% of the samples had silica contents in excess of 99.8%. The Fe_2O_3 content of the samples ranged from <0.001 to 0.071%. More than 80% of the samples had <0.02% Fe_2O_3, with around 30% containing <0.01%. The Al_2O_3 content ranged from 0.001 to 0.154%, with an average of approximately 0.017%. The CaO levels were typically between 0.001 and 0.002% and rarely exceeded 0.003%. The TiO_2 values were typically between 0.025 and 0.060%.

The natural size of silica sand in the area lies mostly between 350 and 500 µm (Fig. 12). The sand can be processed to sizes ranging from under AFS20 to above AFS55. The AFS20 sand has about 90% in the >600 µm fraction, whereas the AFS55 sand has more than 90% in the <425 µm fraction.

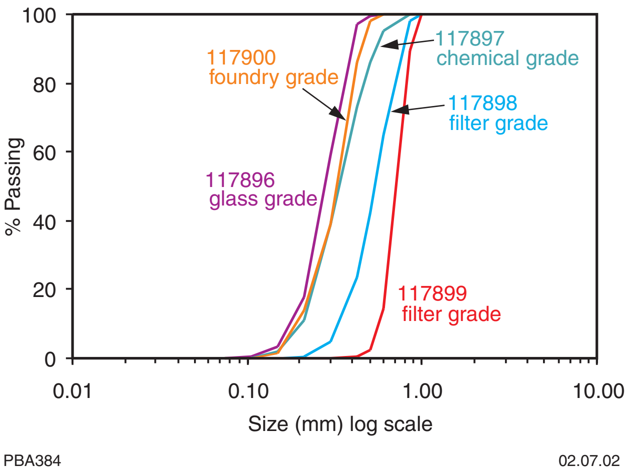

Figure 12. Particle-size distribution of silica sand — Gnangara (117896–900 are GSWA sample nos)

The sand is found to be suitable for high-grade applications that include crystal glass, optical lenses, fibre, and silicon crucible manufacture. At present, the high-grade silica sand from Rocla Quarry Products is used in the manufacture of chemicals and glass, and also as foundry and filtration sands.

Five samples (GSWA117896–900) collected by the author from various-grade stockpiles of Rocla Quarry deposit averaged 99.8% SiO_2, 0.03% Al_2O_3, 0.004% Fe_2O_3, <0.01% CaO, <0.01% MgO, and 0.009% P_2O_5 (Table 17). In general, sands used for various high-grade applications have very low impurities. For example, a glass-grade sand sample (GSWA117896) has 99.8% SiO_2, 0.02% Al_2O_3, 0.01% Fe_2O_3, a chemical-grade sand sample (GSWA117897) assays 99.7% SiO_2, 0.02% Al_2O_3, <0.01% FeO_3, and a filter-grade sand sample (GSWA117899) contains 99.8% SiO_2, 0.05% Al_2O_3, 0.01% Fe_2O_3.

Silica sand in the Gnangara deposit is well sorted and a plot of particle-size distribution of five samples (GSWA117896–900) collected from stockpiles of various grades shows that the majority of the sand grains are within the size range 0.15–0.6 mm (Fig. 12). Typically, glass-grade sand (GSWA117896) has around 97% in the <500 µm fraction, chemical grade sand (GSWA117897) has about 73% in the <500 µm, and filter-grade sand (GSWA117899) is much coarser and has over 58% in the >600 µm fraction (Table 18).

Resource

Sand reserves in Rocla's deposit are estimated at 61 Mt grading >99.7% SiO_2, <0.03% Fe_2O_3, <0.02% Al_2O_3, and <0.003% CaO (Dundon et al., 1984). The sand is amenable to beneficiation without requiring scrubbing, acid leaching, or magnetic separation and could be easily beneficiated to 99.94% SiO_2, 0.006% Fe_2O_3, <0.03% TiO_2, and <0.0001% Cr_2O_3. There is also an additional inferred resource of around 75 Mt, suitable for use as concrete sand in the construction industry (Industrial Minerals, 1989).

Mining and processing

Sand is selectively mined by developing shallow openpits (Fig. 13), with high-grade sand first washed and screened to remove any organic waste material such as plant material, and lumps of coffee rock. The relatively low-grade yellow-brown sand is directly transported for use in the construction industry. The washed high-grade sand is then sized and passed through purpose-built spiral separators, which remove any impurities such as traces of heavy minerals. In 1996, Rocla Quarry Products built and commissioned a new processing plant at Gnangara to meet production demands (Figs 14 and 15).

The plant is designed to produce a number of different size fractions for diverse applications. Typical sand grades produced by Rocla Quarry Products range from AFS20 to AFS55, the percentage size fractions of these grades are shown in Table 19.

Tables 17. Chemical analyses of silica sand from operating mines in Bassendean Sand

GSWA no.	*117896*	*117897*	*117898*	*117899*	*117900*	*117891*	*117892*	*117893*	*117894*	*117895*	*164506*	*164507*	*164508*	*164509*	*A*
								Percentage							
Al_2O_3	0.02	0.02	0.03	0.05	0.03	0.05	0.04	0.05	0.13	0.04	1.70	2.51	2.40	2.14	2.40
SiO_2	99.80	99.70	99.90	99.80	99.80	99.80	99.70	99.70	99.40	99.90	96.50	95.20	94.20	95.40	95.00
Fe_2O_3	0.01	<0.01	<0.01	0.01	<0.01	0.03	0.01	0.01	0.10	0.02	0.02	0.02	0.29	0.15	0.025
MgO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.005
CaO	0.01	0.01	0.01	<0.01	<0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.04	0.05	0.04	0.03
Na_2O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.09	0.12	0.12	0.10	0.125
K_2O	0.02	0.01	0.02	<0.01	<0.01	0.01	0.03	0.03	0.04	<0.01	1.29	1.93	1.91	1.66	1.9
TiO_2	0.04	0.03	0.03	0.02	0.03	0.07	0.03	0.03	0.11	0.04	0.06	0.04	0.60	0.31	0.025
MnO	0.01	<0.01	<0.01	0.01	0.01	0.01	<0.01	0.01	0.01	<0.01	0.01	<0.01	0.01	0.01	na
P_2O_5	0.004	0.008	0.015	0.008	0.008	0.013	0.013	0.009	0.009	0.005	0.01	0.01	0.012	0.01	na
BaO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.04	0.06	0.05	0.05	na
SO_3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.02	na
LOI	0.01	0.04	0.03	0.01	0.03	0.02	0.03	0.01	0.09	0.03	0.08	0.08	0.14	0.12	na
Total	**99.92**	**99.82**	**100.04**	**99.91**	**99.91**	**100.01**	**99.86**	**99.87**	**99.90**	**100.05**	**99.83**	**100.01**	**99.80**	**100.01**	**99.51**
H_2O	0.01	<0.01	<0.01	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	0.06	0.39	0.07	0.03	0.04	

NOTES: 117896–900: Gnangara silica sand deposit
117891–95: Jandakot silica sand deposit
164506–09: Kemerton silica sand deposit
117896: glass grade
117897: chemical grade
117898–99: filter grade
117900: foundry grade
164506: sheet-glass grade
164507: container-glass grade
164508: dredged, washed, head-feed sand
164509: dredged, washed sand
A: typical container-glass grade silica sand of Kemerton Silica Sand Pty Ltd
na: not available

Table 18. Size analyses (µm) of silica sand from operating mines in Bassendean Sand

GSWA no.	*117896*	*117897*	*117898*	*117899*	*117900*	*117891*	*117892*	*117893*	*117894*	*117895*	*164506*	*164507*	*164508*	*164509*
							Percentage							
>850	0.01	0.02	1.84	10.82	0.00	0.44	2.49	3.90	1.03	0.70	0.00	0.00	0.64	0.83
600–850	0.08	4.56	33.43	74.93	0.03	13.17	26.49	36.46	6.05	8.51	0.02	0.00	3.52	4.05
500–600	0.33	9.34	22.53	11.69	2.13	9.69	20.38	25.48	5.87	11.55	1.06	0.01	4.95	1.51
425–500	2.39	12.80	18.46	1.89	11.61	14.72	20.30	19.60	11.35	18.75	6.79	1.80	7.56	8.22
300–425	37.99	34.31	19.03	0.65	47.12	39.39	23.90	13.62	39.45	45.58	39.20	24.13	25.35	21.64
212–300	41.64	27.75	4.18	0.01	25.07	19.81	5.81	0.85	27.31	14.05	34.07	41.72	29.69	31.46
150–212	14.28	9.24	0.51	0.00	12.41	2.78	0.61	0.08	7.44	0.81	16.67	26.79	22.89	23.99
106–150	3.04	1.86	0.03	0.00	1.60	0.01	0.00	0.00	1.10	0.02	2.00	5.16	4.26	6.66
75–106	0.20	0.11	0.00	0.00	0.03	0.00	0.00	0.00	0.05	0.00	0.15	0.32	0.87	1.15
<75	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.02	0.05	0.06	0.28	0.49

NOTES: 117896–900: Gnangara silica sand deposit
117891–95: Jandakot silica sand deposit
164506–09: Kemerton silica sand deposit
117896: glass grade
117897: chemical grade
117898–99: filter grade
117900: foundry grade
164506: sheet-glass grade
164507: container-glass grade
164508: dredged, washed, head-feed sand
164509: dredged, washed sand

PBA458

Figure 13. Rocla Quarry Products silica sand openpit at Gnangara

PBA460

Figure 14. Rocla Quarry Products silica sand processing plant at Gnangara

PBA459

Figure 15. Stockpiles of silica sand at Rocla Quarry Products quarry at Gnangara

Production, uses, and markets

Rocla Quarry Products is one of the largest producers and suppliers of high-grade sand in Australia, and has operations in five states close to capital cities. Rocla's Gnangara minesite covers an area of about 540 ha and has the capacity to produce in excess of 500 000 tpa. The reported production by Rocla Quarry Products in 1999 amounted to 260 106 t.

The mine produces silica sand for high-grade applications in the chemical, glass, foundry, and filtration industries for export and local markets. Lower grade sand from the mine is used in other applications such as in the shaping of golf courses and in the construction industry.

The main export destinations are Japan and Korea. The majority of sales are in the form of bulk shiploads. However, depending on the markets, the company can also provide sand in container loads, or dry graded sand in bulker bags, or milled products. Bulk shipments up to 40 000 t are handled through a loading facility in Kwinana (near the Fremantle port) with a maximum daily loading rate of 11 000 t. The sand is delivered to the ship-loading facility in Kwinana by road train.

Table 19. Typical AFS (American Foundrymen's Society) values and sizes (μm) of silica sand from Rocla Quarry Products openpit

AFS value	*AFS20*	*AFS25*	*AFS30*	*AFS35–38*	*AFS42*	*AFS46–48*	*AFS50–55*
				Percentage			
>850	9.6	5.0	3.4	3.0	0.1	<0.1	<0.1
600–850	80.0	51.0	28.5	26.0	5.0	1.3	<0.1
500–600	8.7	23.9	28.1	15.7	14.9	5.2	0.2
425–500	0.6	9.3	17.3	9.6	14.5	10.1	1.4
300–425	0.1	8.6	18.2	24.3	32.6	39.9	36.9
212–300	<0.1	1.7	3.5	14.3	22.2	28.7	39.7
150–212	<0.1	0.4	0.7	5.2	8.6	11.3	16.5
106–150	<0.1	0.1	0.2	1.3	1.8	3.0	4.5
75–106	<0.1	<0.1	<0.1	0.3	0.1	0.4	0.1
<75	<0.1	<0.1	<0.1	0.1	<0.1	0.1	0.1
<53	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Table 20. Chemical composition of silica sand samples from Bentley Ridge at Gnangara

Drillhole	*Depth of drillhole (m)*	*Average of m sampled over (depths) shown*	*SiO_2*	*Fe_2O_3*	*Al_2O_3*	*CaO*	*MgO*	*Na_2O*	*K_2O*	*TiO_2*
						Percentage				
BR1	6	5 m (0–3 m and 4–6 m)	99.58	0.032	0.057	0.003	0.005	0.003	0.004	0.065
BR2	7	6 m (1–7 m)	99.59	0.016	0.030	0.002	0.005	0.004	0.003	0.035
BR3	6	6 m (0–6 m)	99.62	0.016	0.037	0.002	0.004	0.003	0.003	0.037
BR4	7	4 m (1–4 m and 5–6 m)	99.51	0.096	0.080	0.002	0.003	0.003	0.004	0.046
BR5	4	2 m (1–3 m)	99.43	0.026	0.027	0.002	0.003	0.002	0.002	0.073
BR6	6	2 m (0–2 m)	99.66	0.023	0.036	0.003	0.004	0.003	0.005	0.040
BR7	18	4 m (0–2 m and 16–18 m)	99.33	0.028	0.072	0.046	0.005	0.006	0.005	0.062
BR8	5.5	4 m (0–4 m)	99.27	0.020	0.039	0.008	0.006	0.007	0.002	0.062
BR9	8	4 m (0–3 m and 6–7 m)	99.51	0.028	0.039	0.010	0.005	0.008	0.004	0.067
BR10	12.5	5 m (0–2 m and 8–11 m)	99.55	0.043	0.080	0.008	0.004	0.007	0.006	0.066
BR11	9	6 m (0–4 m and 6–8 m)	99.44	0.031	0.070	0.008	0.005	0.006	0.003	0.060
BR12	9	4 m (1–2 m and 7–9 m)	99.61	0.040	0.099	0.007	0.005	0.004	0.004	0.064
BR13	14	7 m (1–5 m, 6–7 m, and 12–14 m)	99.41	0.053	0.143	0.005	0.007	0.004	0.006	0.106
BR14	11	8 m (0–8 m)	99.08	0.074	0.180	0.064	0.008	0.007	0.010	0.070
BR15	4	2 m (1–3 m)	99.54	0.026	0.013	0.005	0.009	0.004	0.002	0.054
BR16	4	3 m (0–3 m)	99.17	0.016	0.010	0.005	0.008	0.005	0.001	0.053
BR17	9	7 m (0–6 m and 7–8 m)	99.38	0.035	0.030	0.006	0.006	0.006	0.003	0.050
BR18	13	7 m (0–4 m and 10–13 m)	99.46	0.033	0.093	0.013	0.007	0.003	0.004	0.060
BR19	10	6 m (0–2 m and 5–9 m)	99.51	0.040	0.084	0.009	0.003	0.006	0.004	0.065
BR20	9	6 m (0–3 m and 5–8 m)	99.09	0.065	0.102	0.011	0.006	0.006	0.004	0.061
BR21	8	5 m (0–2 m and 4–7 m)	99.26	0.029	0.122	0.021	0.005	0.003	0.008	0.078
BR22	14.5	5 m (0–3 m and 11–13 m)	99.28	0.051	0.100	0.088	0.008	0.007	0.007	0.059
BR23	9	6 m (1–5 m and 7–9 m)	99.52	0.033	0.072	0.005	0.005	0.004	0.004	0.038
BR24	12	8 m (1–7 m and 10–12 m)	99.27	0.047	0.108	0.006	0.005	0.004	0.003	0.044
BR25	17	12 m (1–6 m, 8–11 m, and 12–16)	99.24	0.053	0.179	0.004	0.004	0.004	0.004	0.049
BR26	15	12 m (0–10 m and 13–15 m)	99.50	0.016	0.040	0.008	0.004	0.012	0.002	0.032
BR27	20	13 m (0–1 m and 8–20 m)	99.32	0.040	0.104	0.003	0.003	0.003	0.003	0.033
BR28	5	4 m (1–5 m)	99.59	0.018	0.013	0.004	0.003	0.005	0.002	0.038
BR29	4	3 m (1–4 m)	99.37	0.018	0.009	0.003	0.004	0.005	0.002	0.051
BR30	5	1 m (0–1) m	95.74	0.026	0.061	0.055	0.02	0.007	0.005	0.044
BR31	6.5	5 m (0–2 m and 4–6 m)	99.36	0.031	0.110	0.004	0.002	0.007	0.006	0.073
BR32	6	3 m (0–1 m and 4–6 m)	99.46	0.053	0.117	0.019	0.005	0.006	0.006	0.065
BR34	11	4 m (0–3 m and 10–11 m)	99.41	0.029	0.054	0.006	0.004	0.006	0.004	0.053
BR35	14	2 m (0–2 m)	99.42	0.027	0.034	0.006	0.005	0.004	0.004	0.083
BR36	7	2 m (0–2 m)	99.44	0.017	0.034	0.003	0.002	0.006	0.002	0.044
BR37	4	3 m (0–3 m)	99.48	0.010	0.029	0.004	0.002	0.007	0.001	0.041
BR38	6.5	2 m (0–2 m)	99.55	0.035	0.061	0.003	0.002	0.007	0.005	0.081
BR39	5	5 m (0–5 m)	99.48	0.019	0.038	0.005	0.002	0.007	0.002	0.061
BR40	8.5	5 m (0–5 m)	99.47	0.020	0.035	0.004	0.003	0.008	0.002	0.058
BR41	10	5 m (0–2 m, 3–4 m, and 7–9 m)	99.39	0.041	0.062	0.010	0.004	0.006	0.004	0.068
BR42	12	5 m (0–3 m and 10–12 m)	99.44	0.039	0.041	0.012	0.006	0.004	0.003	0.044
BR43	6	6 m (0–6 m)	99.43	0.026	0.019	0.011	0.008	0.004	0.002	0.029

Table 20. (continued)

Drillhole	*Depth of drillhole (m)*	*Average of m sampled over (depths) shown*	SiO_2	Fe_2O_3	Al_2O_3	*CaO*	*MgO*	Na_2O	K_2O	TiO_2
						Percentage				
BR44	8	7 m (0–7 m)	99.28	0.016	0.025	0.014	0.006	0.005	0.001	0.033
BR45	8	3 m (0–2 m and 5–6 m)	99.42	0.023	0.051	0.003	0.004	0.005	0.005	0.066
BR46	5	4 m (0–4 m)	99.59	0.016	0.028	0.003	0.004	0.002	0.002	0.048
BR47	6	3 m (0–1 m and 4–6 m)	99.31	0.039	0.131	0.003	0.003	0.002	0.001	0.067
BR48	11	3 m (0–2 m and 3–4 m)	99.33	0.033	0.064	0.005	0.003	0.003	0.002	0.045
BR49	5	4 m (0–4 m)	99.32	0.023	0.028	0.009	0.006	0.004	0.001	0.043
BR50	8	7 m (1–8 m)	99.39	0.038	0.035	0.008	0.004	0.008	0.001	0.030
BR51	6	5 m (0–5 m)	99.56	0.023	0.025	0.004	0.003	0.007	0.001	0.017
BR52	5.5	3 m (0–2 m and 3–4 m)	99.12	0.031	0.064	0.005	0.003	0.006	0.003	0.048
BR54	13	6 m (0–4 m and 11–13 m)	99.47	0.029	0.044	0.006	0.003	0.007	0.002	0.025
BR55	4	3 m (0–3 m)	99.33	0.025	0.016	0.005	0.003	0.007	0.001	0.036
BR56	10	7 m (0–3 m, 5–6 m, and 7–10 m)	99.48	0.040	0.048	0.002	0.002	0.004	0.003	0.052
BR57	14	4 m (0–4 m)	99.50	0.027	0.021	0.006	0.002	0.004	0.001	0.050
BR60	8	8 m (0–8 m)	99.40	0.030	0.027	0.004	0.002	0.004	0.001	0.056
BR61	12	8 m (1–4 m, 6–8 m, and 9–12 m)	99.31	0.050	0.079	0.005	0.002	0.004	0.002	0.059
BR62	10	6 m (1–3 m and 6–10 m)	99.25	0.043	0.064	0.024	0.003	0.007	0.004	0.092
Average			**99.35**	**0.033**	**0.061**	**0.011**	**0.005**	**0.005**	**0.003**	**0.054**

SOURCE: after Sorensen and Buonaiuto (1991)

Table 21. Chemical composition of silica sand samples from Dugite Ridge at Gnangara

Drillhole	*Depth of drillhole (m)*	*Average of m sampled over (depths) shown*	*SiO_2*	*Fe_2O_3*	*Al_2O_3*	*CaO*	*MgO*	*Na_2O*	*K_2O*	*TiO_2*
						Percentage				
DR1	10	8 m (0–5 m and 6–9 m)	99.56	0.023	0.037	0.004	0.002	0.008	0.002	0.064
DR2	5.5	3 m (1–4 m)	99.67	0.025	0.011	0.006	0.002	0.004	0.002	0.062
DR3	9.5	7 m (1–8 m)	99.60	0.038	0.048	0.003	0.002	0.005	0.003	0.089
DR4	5.5	4 m (0–4 m)	99.03	0.066	0.450	0.005	0.008	0.009	0.019	0.130
DR5	3	3 m (0–3 m)	99.19	0.030	0.123	0.013	0.006	0.009	0.010	0.076
DR6	7	6 m (1–7 m)	99.67	0.025	0.033	0.004	0.003	0.004	0.002	0.071
DR7	4.5	4 m (0–4 m)	99.45	0.015	0.022	0.005	0.004	0.004	0.001	0.036
DR8	7	7 m (0–7 m)	99.52	0.046	0.053	0.004	0.004	0.004	0.002	0.100
DR9	3.5	1 m (1–2) m	99.46	0.021	0.045	0.003	0.003	0.004	0.002	0.116
DR10	6	6 m (0–6 m)	99.69	0.024	0.044	0.003	0.004	0.003	0.002	0.091
DR11	6	6 m (0–6 m)	99.15	0.015	0.024	0.004	0.004	0.003	0.002	0.083
DR12	5	4 m (1–5 m)	99.34	0.034	0.051	0.003	0.002	0.002	0.002	0.084
DR13	2.5	2 m (0–2 m)	98.64	0.023	0.091	0.004	0.003	0.006	0.002	0.125
DR14	8	3 m (0–3 m)	99.24	0.034	0.050	0.004	0.002	0.004	0.002	0.087
DR15	5	5 m (0–5 m)	99.42	0.014	0.021	0.004	0.002	0.003	0.001	0.059
DR16	3.5	2 m (1–3 m)	99.14	0.024	0.026	0.004	0.002	0.003	0.001	0.067
DR17	5.5	5 m (0–5 m)	99.47	0.025	0.028	0.003	0.002	0.003	0.001	0.067
DR19	6	5 m (1–6 m)	99.52	0.040	0.023	0.002	0.003	0.004	0.002	0.099
DR20	3	1 m (0–1) m	99.76	0.023	0.021	0.004	0.003	0.004	0.002	0.094
DR21	2	2 m (0–2 m)	99.69	0.018	0.010	0.004	0.003	0.004	0.001	0.068
DR22	7	4 m (0–4 m)	99.61	0.041	0.037	0.005	0.004	0.004	0.003	0.107
DR23	3.5	1 m (0–1) m	99.05	0.019	0.013	0.005	0.006	0.004	0.003	0.081
DR24	3	1 m (1–2) m	99.00	0.026	0.053	0.004	0.005	0.005	0.002	0.100
DR25	5.5	4 m (0–4 m)	99.36	0.038	2.785	0.004	0.005	0.005	0.001	0.109
DR26	3	1 m (0–1) m	99.15	0.026	0.027	0.004	0.006	0.004	0.001	0.112
DR27	5	4 m (0–3 m and 4–5 m)	98.97	0.024	0.078	0.004	0.005	0.004	0.001	0.087
DR28	7.5	3 m (1–3 m and 6–7 m)	99.65	0.031	0.053	0.005	0.005	0.004	0.001	0.093
DR29	4.5	3 m (0–3 m)	96.20	0.017	0.031	0.005	0.004	0.005	0.001	0.090
DR30	4.5	2 m (0–2 m)	99.01	0.024	0.024	0.005	0.003	0.006	0.001	0.108
DR31	4	3 m (0–3 m)	99.50	0.015	0.028	0.005	0.003	0.006	0.001	0.046
DR32	4	2 m (0–2 m)	99.36	0.015	0.032	0.006	0.006	0.007	0.001	0.033
Average			**99.26**	**0.027**	**0.141**	**0.004**	**0.004**	**0.005**	**0.002**	**0.085**

SOURCE: after Sorensen and Buonaiuto (1991)

Bentley, Dugite, and Saint Patrick Ridges near Gnangara pine plantation

In 1991, Sorensen Short and Associates carried out a drilling program for West Australian Silica Sand to assess silica sand resources at Bentley Ridge, Dugite Ridge, and Saint Patrick Ridge (Fig. 11). The program of exploration involved drilling and assaying of silica sand from 93 holes (totalling 710 m) at the three sites (Sorensen and Buonaiuto, 1991); however, the program was not completed owing to various landuse constraints.

Geology

The silica sand deposit is in a complex Quaternary dune system of the Bassendean Sand. In general, the area consists of a topsoil cover (approximately 50 cm thick) underlain by a leached zone containing whitish sand of variable thickness (1–7 m), which is underlain in turn by a limonitized zone containing some dark yellowish sand. The limonitized zone is underlain by a zone of 'root moulds' followed by a faintly bedded zone of variable thickness containing yellowish orange sand horizons. The silica sand horizons extend to a maximum depth of around 18 m.

The drillholes at Bentley Ridge intersected silica sand layers to a depth of around 18 m, with individual silica sand horizons ranging from 1 to 13 m in thickness. Thin limonite-rich layers are sandwiched between the sandy layers.

Quality

The best silica sand intersections were in holes BR27 and BR26 with 13 and 12 m-thick sand horizons containing an average of 99.32 and 99.59% SiO_2 respectively. The average thickness of silica sand at Bentley Ridge is around 5 m. The average chemical composition of silica sand at the Bentley Ridge deposit is 99.35% SiO_2, 0.033%Fe_2O_3, 0.061% Al_2O_3, and 0.054% TiO_2 (Sorensen and Buonaiuto, 1991) (Table 20).

At Dugite Ridge, the silica sand layers are 1–8 m in thickness, with an average thickness of 3.6 m. The silica sand of this deposit averages 99.26% SiO_2, 0.027% Fe_2O_3, 0.141% Al_2O_3, and 0.085% TiO_2 (Table 21). The four drillholes at Saint Patrick Ridge intersected silica sand layers ranging in thickness from 6 to 8 m, with an average of 7.3 m. The silica sand averages 99.36% SiO_2, 0.028%Fe_2O_3, 0.041% Al_2O_3, and 0.045% TiO_2 (Table 22).

The above analyses indicate that the quality of silica sand is high and would be suitable for use in glass, chemical, and foundry industries.

Jandakot

Jandakot, approximately 15 km south of Perth, is an area of active silica sand mining, as well as of sand extraction for the construction industry. The operations in the area are located between the Jandakot airport and Armadale Road (Fig. 16). The main operator in the area for high-grade silica sand is the Readymix Group, with other operators mostly involved in the extraction of sand for the construction industry. However, the area has a considerable high-grade silica sand resource, comparable to that in the Gnangara region, although figures have not yet been released by Readymix.

Readymix operation

Geology

Bassendean Sand in the Jandakot area has characteristics similar to that in the Gnangara area. The high-grade white silica sand at Jandakot is found at a depth of about 30 cm below an overburden material containing grey to black soil rich in organic material. In the area mined by Readymix, the brown to dark-brown coffee rock layer is typically found at a depth of 1–3 m from the surface (Fig. 17). This layer here is generally continuous, and has a variable thickness of about 1–2 m. Below this, the high-grade white sand layer continues to deeper levels, and is 3–5 m thick (Fig. 18). White sand above and below the coffee rock is suitable for high-grade applications such as those in the glass or chemical industries. Below the second high-grade sand layer is yellow-brown, relatively low-grade sand, which is mined for construction applications.

Quality

The high-grade white sand is almost 99% quartz with only traces of heavy minerals, mostly rutile and ilmenite. Such purity is reflected in the chemical analyses, with typical high-grade silica sand (GSWA117891) from a stockpile of Readymix assaying 99.8% SiO_2, 0.05% Al_2O_3, and 0.03% Fe_2O_3 (Table 17). This is similar to high-grade sand from the Gnangara deposit. A raw sample (GSWA117893) of white silica sand from the quarry face of Readymix assayed 99.7% SiO_2, 0.05% Al_2O_3, and 0.01% Fe_2O_3, whereas a relatively impure brown to yellowish sand below the high-grade sand assayed 99.4% SiO_2, 0.13% Al_2O_3, and 0.10% Fe_2O_3 (GSWA117894).

A typical raw high-grade silica sand sample (GSWA117893) from the Jandakot deposit is well sorted and medium grained, with more than 95% within the 300–850 µm range (Fig. 19, Table 18). The sand in this deposit can be processed to obtain size fractions of AFS20 to over AFS55, again similar to that of Gnangara, and suitable for diverse applications.

Mining and processing

The Readymix operation at Jandakot is limited to simple quarrying, washing, and minor sizing. Since the sand is well sorted and found as loose material, the extraction can be done simply with the use of a front-end loader. The relatively low-grade, brown to yellow sand is directly trucked for use in the construction industry, whereas the high-grade sand is transported to the washing and processing plant at the site. At the washing and processing plant, the fines and small percentage of heavy minerals (rutile and ilmenite) are washed off and different size fractions (generally within the range AFS35–40) are produced.

Production, uses, and markets

The mine produces approximately 100 000–120 000 tpa of mostly high-grade silica sand, with a smaller tonnage for

Table 22. Average chemical composition of silica sand samples from Saint Patrick Ridge at Gnangara

Drillhole	*Depth of drillhole (m)*	*Average of m sampled over (depths) shown*	*SiO_2*	*Fe_2O_3*	*Al_2O_3*	*CaO*	*MgO*	*Na_2O*	*K_2O*	*TiO_2*
						Percentage				
SPR1	11.5	8 m (0–8 m)	99.40	0.033	0.024	0.005	0.004	0.008	0.001	0.055
SPR7	10	6 m (0–4 m and 8–10 m)	99.45	0.030	0.023	0.004	0.004	0.006	0.001	0.036
SPR11	8	7 m (0–6 m and 7–8 m)	99.23	0.022	0.044	0.003	0.003	0.007	0.001	0.044
SPR13	8	8 m (0–8 m)	99.35	0.028	0.071	0.003	0.003	0.007	0.001	0.046
Average			**99.36**	**0.028**	**0.041**	**0.004**	**0.004**	**0.007**	**0.001**	**0.045**

SOURCE: after Sorensen and Buonaiuto (1991)

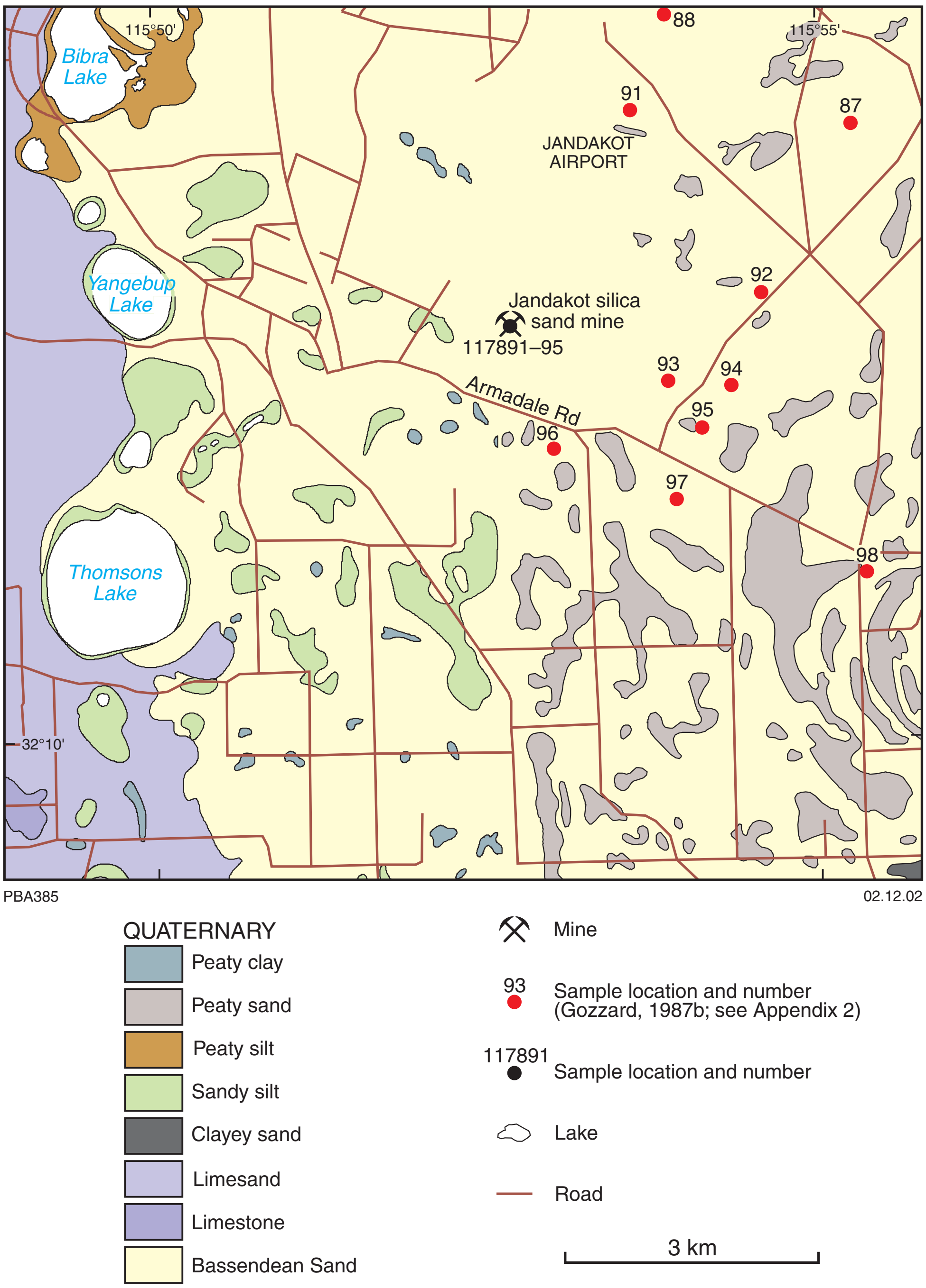

Figure 16. Geology around Jandakot silica sand mine (after Gozzard 1983; Jordan, 1986)

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Figure 17. Coffee rock layer of the silica sand formation at Readymix Group Jandakot mine

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Figure 18. A quarry face at Readymix Group silica sand mine at Jandakot

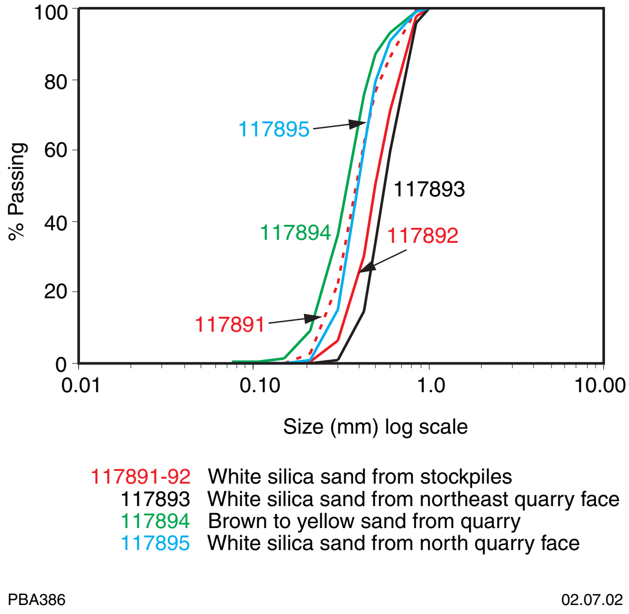

Figure 19. Particle-size distribution of silica sand — Jandakot (117891–95 are GSWA samples nos)

the construction industry. A significant proportion of the production is exported to Japan and other Asian destinations. Some of the uses are in high-grade applications such as in the glass and foundry industries. Other less common applications in Japan include the construction of artificial white sand beaches and golf courses. The main domestic markets are in the foundry, concrete, and filler sands.

Bullsbrook

ACI Operations Pty Ltd, now owned by Unimin Australia Ltd, extracts silica sand from a quarry approximately 9 km west of Bullsbrook (Fig. 9). The deposit is estimated to contain an indicated resource of 2.6 Mt. Sand extracted from this deposit is low in iron content and is used in the manufacture of clear glass containers, such as soft drink bottles, and coloured glass containers such as beer and wine bottles. These products are used locally as well as interstate. The plant, at Canning Vale (in the Perth metropolitan region) has the capacity to produce 60 000–65 000 tpa of glass products (Department of Resources Development, 1999).

Mandogalup

The topsoil profile at Mandogalup (Fig. 9), approximately 10 km east of Kwinana, contains 1–3 m silica sand of the Bassendean Sand. The white sand at the top of the profile is probably suitable for high-grade applications such as in the glass industry. The total sand resource in the deposit is estimated at 1.3 Mt, of which 30–40% is likely to be high-grade silica sand (Harrington, 1993). Silicon Quarries Pty Ltd has plans to mine high-grade silica sand for export.

Wabling Hill

In 1971, General Mining Corp Ltd investigated an area about 4 km northeast of Wabling Hill, approximately 60 km north-northwest of Perth, for silica sand (Fig. 6). The area consists of dunes of Pleistocene Bassendean Sand rising from 40 to 70 m above sea level. The dunes are covered with banksia and gum trees with medium-density undergrowth.

The investigation included the drilling of 28 auger holes, each to a depth of 5 m. The quartz sand below the 55 m contour (above sea level) in the western half of the area, was contaminated with lateritic material. Composite samples of 5 m sections from each of five auger holes yielded silica values ranging from 99.5 to 99.8%. Two of the five samples had a maximum of 0.3% impurities, which included 0.028% Al_2O_3 and 0.036% Fe_2O_3. The resource, likely to be in the inferred category, was estimated at 15×10^6 m^3 (approximately 26 Mt) of high-grade silica sand (Linden, 1971).

In 1992, from the Prospecting Licence 70/651 located south of the Mineral Claim 70/12655, three bulk samples were tested for their heavy mineral content. Results indicated 0.03–0.40 wt% heavy mineral fraction in TBE (tetrabromoethane). One of these samples had 99.8% pure silica residue after the heavy fraction was removed. The major impurities were TiO_2 (0.048%) and Al_2O_3 (0.031%). Particle-size analysis of one sample indicated more than 90% of the material was in the 212–850 µm fraction, and of this, 36.5% was in the 425–600 µm fraction (Western Silicates Pty Ltd, 1992).

Canning Vale

In 1993, Rocla Quarry Products carried out a drilling program near Canning Vale Prison to assess the potential for high-grade silica sand. The area investigated is bounded by Nicholson Road to the west, Warton Road to the southeast, and Canning Vale Prison to the north (Fig. 20). Eighty drillholes (totalling around 415 m) spaced at about 50 m, were drilled along ten lines, separated by 100 m (Rocla Quarry Products, 1994).

The most predominant geological unit in the locality explored is Pleistocene Bassendean Sand. Drilling results indicate that the sand unit has a topsoil cover varying in thickness from 0 to 4 m, and averaging 0.9 m. Underlying the topsoil cover is a white sand layer, having a thickness varying from 0 to 5.5 m and with an average of around 2 m. A cream-coloured sand layer, varying in thickness from 0 to 8.5 m and averaging about 3 m, underlies the white sand layer. The depth of the watertable varies from 1 to 13 m, averaging around 5.5 m (Table 23).

The resource of white sand in the deposit, which is likely to be of indicated status, is estimated at about 1.3 Mt (736 000 m^3), of which approximately 0.9 Mt (527 000 m^3) is more than 2 m above the watertable. Tests of silica sand samples indicate an average AFS value of 45.6, which is considered to be suitable for export grade. Partial chemical analyses of silica sand samples from the

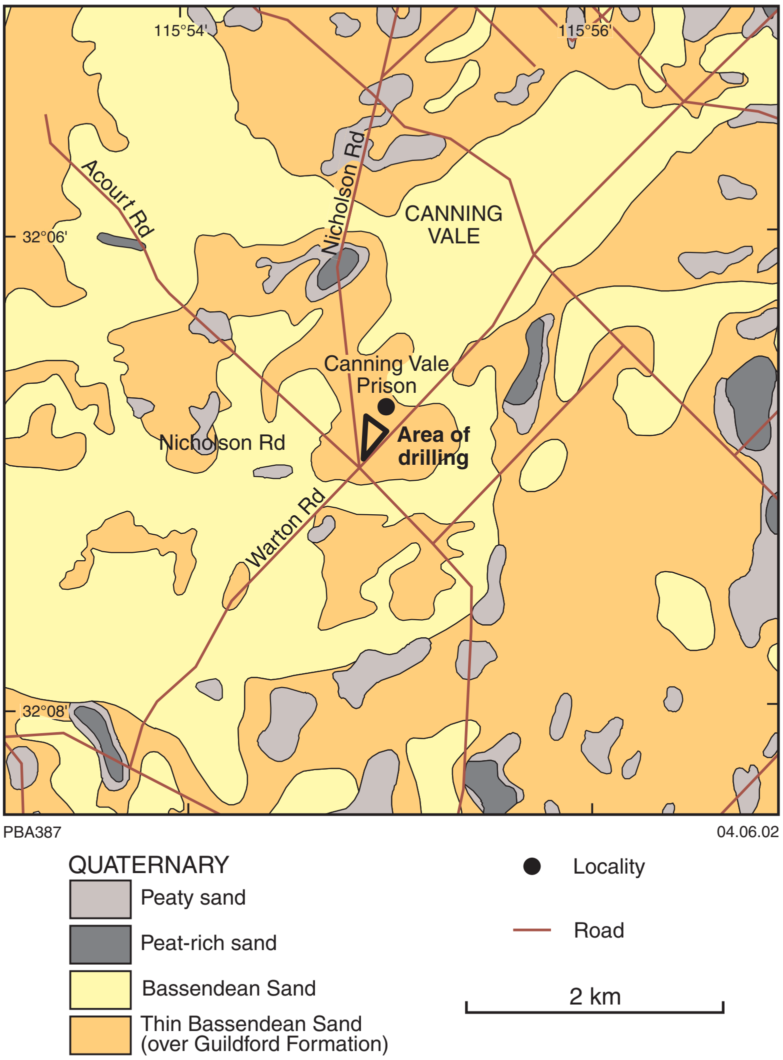

Figure 20. Geology around Canning Vale silica sand deposit (after Jordan, 1986)

deposit indicate averages of 0.144% Fe_2O_3, 0.045% Al_2O_3, and 0.429% TiO_2 (Table 24) (Rocla Quarry Products, 1994).

Deposits south of the Perth Metropolitan Area

The Bassendean Sand extends almost continuously to near Busselton, and in many localities exposures of white sand are conspicuous. The biggest producing silica sand mine in Western Australia is found at Kemerton (Fig. 6), in Bassendean Sand. In numerous other localities, Bassendean Sand has been quarried to extract sand for the construction industry, regardless of its quality. Towards the southern end of the Bassendean Sand, particularly around the Busselton and Capel regions, the sand is found to be richer in heavy minerals, compared with the sand in regions north of Bunbury.

Kemerton

In the Kemerton region, about 25 km north-northeast of Bunbury, there are large areas of high-grade silica sand deposits in the Bassendean Sand (Fig. 21). The high-grade silica sand is found at shallow depths, below an overburden (ranging in thickness from a few centimetres to approximately 2 m) consisting of grey to dark grey organic-rich soil. Commercial mining of this high-grade resource began with the opening of the Kemerton Silica Sand Pty Ltd mine in 1996.

Kemerton silica sand mine

The Kemerton silica sand mine is operated by Kemerton Silica Sand Pty Ltd, a joint venture project between Itochu Corporation (50%) and Tochu Co Ltd (50%). In early 2002, Sons of Gwalia Ltd sold its 70% interest to the above two companies. Itochu is a major Japanese trading house, whilst Tochu is a supplier and processor of sand

Table 23. Canning Vale Prison Reserve — drillhole data

Drillhole	*Overburden*	*White sand*	*Cream sand*	*Impure material*	*Watertable*
			Depth (m)		
A1	1.0	1–1.5	1.5–5.0	5.0–5.5	5.5
A2	1.0	1.0–2.0	2.0–8.0	0.0	8.0
A3	0.5	0.5–3.0	3.0–6.5	6.5–10	10.0
A4	2.0	2.0–3.0	3.0–11.0	0.0	11.0
A5	4.0	0.0	4.0–10.0	0.0	10.0
A6	2.0	2.0–3.5	3.5–6.5	6.5–10	10.0
A7	2.0	2.0–6.5	0.0	6.5–8.0	8.0
A8	2.0	2–4.5	0.0	4.5–7.0	7.0
A9	1.0	0.0	0.0	1.0–7.0	7.0
A10	0.5	0.5–3.5	3.5–5.0	5.0–6.0	6.0
A11	1.0	1.0–5.0	0.0	0.0	5.0
A12	0.5	0.5–4.5	4.5	4.5–5.0	5.0
A13	0.5	0.5–4.5	0.0	0.0	4.5
A14	0.5	0.5–2.5	0.0	2.5–3.0	3.0
A15	1.0	1.0–3.0	0.0	0.0	3.0
B1	1.0	1.0–4.5	0.0	4.5–5.0	5.0
B2	0.5	0.5–2.5	2.5–7.0	0.0	7.0
B3	0.0	0.0–3.5	3.5–7.0	7.0–9.0	7.0
B4	0.5	0.5–2.5	11.0	0.0	10.0
C1	1.0	1.0–3.5	0.0	3.5–4.0	4.0
C2	0.0	1.0–5.0	5.0–5.5	5.5–7.0	7.0
C3	0.5	0.5–2.5	2.5–9.0	0.0	9.0
C4	0.5	0.5–2.5	2.5–8.0	0.0	8.0
C5	1.0	1.0–2.5	2.5–8.0	0.0	8.0
C6	1.0	1.0–3.5	3.5–5.5	5.5–8.0	8.0
C7	0.0	0.0–2.5	2.5–8.0	0.0	8.0
C8	0.0	0.0–3.0	3.0–6.0	0.0	6.0
C9	0.5	0.5–5.0	0.0	0.0	5.0
C10	0.5	0.5–4.0	0.0	0.0	4.0
D1	2.0	0.0	0.0	0.0	2.0
D2	1.0	1.0–3.5	0.0	3.5–4.0	4.0
D3	0.5	0.5–1.5	1.5–7.0	0.0	7.0
D4	0.5	0.5–2.5	2.5–7.0	0.0	7.0
D5	0.5	0.5–3.0	3.0–5.5	5.5–7.0	7.0
D6	0.5	0.5–3.0	0.0	3.0–5.0	5.0
D7	1.0	1.0–4.5	0.0	4.5–6.0	6.0
D8	0.5	0.5–4.0	4.0–9.0	0.0	9.0
D9	0.5	0.5–5.5	0.0	5.5–6.0	6.0
D10	0.5	0.0	0.0	0.5–3.0	3.0
D11	1.0	0.0	0.0	1.0–2.0	2.0
D12	1.0	0.0	0.0	1.0–2.0	2.0
D13	1.0	0.0	0.0	1.0–2.0	2.0
D14	1.0	0.0	0.0	1.0–2.0	2.0
E1	0.5	0.0	0.0	0.5–1.0	1.0
E2	1.0	0.0	0.0	0.0	1.0
E3	1.0	0.0	0.0	0.0	1.0
E4	0.5	0.5–4.0	0.0	0.0	4.0
E5	0.5	0.5–4.5	0.0	4.5–7.0	7.0
E6	1.5	1.5–3.0	3.0–6.5	0.0	6.0
E7	1.0	1.0–2.5	0.0	2.5–4.0	4.0
E8	0.5	0.5–4.0	0.0	0.0	4.0
E9	1.0	0.0	0.0	1.0–3.0	3.0
E10	2.0	0.0	0.0	0.0	2.0
E11	2.0	0.0	0.0	0.0	2.0
E12	2.0	0.0	0.0	0.0	2.0
F1	2.0	0.0	End of hole	–	nr
F2	1.5	1.5–2.0	End of hole	–	nr
F3	0.5	0.5–3.0	End of hole	–	nr
F4	0.5	0.5–3.5	End of hole	–	nr
F5	1.0	1.0–4.0	End of hole	–	nr
F6	1.0	1.0–3.5	End of hole	–	nr
F7	0.5	0.5–2.0	2.0–5.0	0.0	nr
F8	0.5	0.5–5.0	End of hole	–	nr
F9	1.5	1.5–2.0	End of hole	–	nr
F10	2.0	End of hole	–	–	nr
G1	2.0	End of hole	–	–	nr
G2	1.5	1.5–4.5	End of hole	4.5–5.0	5.0

Table 23. (continued)

Drillhole	*Overburden*	*White sand*	*Cream sand*	*Impure material*	*Watertable*
			Depth (m)		
G3	0.5	0.5–6.0	End of hole	0.0	6.0
G4	1.0	1.0–4.0	4.0–9.0	9.0–10.0	10.0
G5	0.5	0.5–3.5	3.5–11.0	0.0	11.0
G6	0.5	0.5–3.0	3.0–10.0	10.0–11.0	11.0
G7	1.0	1.0–5.0	End of hole	5.0–7.0	7.0
G8	0.5	0.5–4.0	End of hole	0.0	4.0
H1	0.5	0.5–3.0	End of hole	0.0	3.0
H2	0.5	0.5–4.0	4.0–8.0	0.0	8.0
H3	0.5	0.5–5.0	5.0–11.0	11.0–13.0	13.0
H4	0.5	0.5–5.5	5.5–9.0	9.0–11.0	11.0
H5	0.5	0.5–2.5	2.5–10.0	0.0	10.0
H6	0.5	0.5–2.0	2.0–9.0	0.0	9.0
I1	0.5	0.5–1.0	End of hole	0.0	–

NOTE: nr = watertable not reached
SOURCE: after Rocla Quarry Products (1994)

to the glass and foundry industries. Operations at Kemerton began in May 1996 with the commissioning of a processing plant.

Geology

A vertical profile of the mine area indicates the presence of high-grade white silica sand of the Bassendean Sand beneath 1–2 m of overburden material consisting of grey to dark grey soil containing organic material. The thickness of the white silica sand horizon varies from about 3 to 5 m, and within this at variable depth (about 1–1.5 m) is found a thin (few centimetres) dark brown coffee rock layer (Fig. 22). Below the white silica sand is a 5–10 m-thick horizon of white, slightly clayey sand, which is relatively richer in alumina (but <2%) than the upper white sand. Below this alumina-rich layer the sand becomes richer in calcium due to the presence of shell material.

Although the sand at the upper levels is richer in silica, the sand with slightly elevated alumina below is the more important resource for this operation. This sand is sought out by some consumers because of its inherent alumina content (approximately 2%), which imparts unique properties making it preferable for use in the container-glass industry. This layer of sand is mostly found below the watertable and therefore sand is dredged using a suction cutter dredge. This is the State's only project where wet-mining operation is carried out for silica sand.

Quality

The silica sand mined at the Kemerton deposit consists predominantly of quartz with accessory amounts of heavy minerals (rutile and ilmenite), but the heavy mineral content is generally less than 3%. At the processing stages, the heavy minerals are removed through a spiral classifier. The most important aspect of quality of this sand is that the alumina content varies from about 1% near the surface to 3% at the bottom of the deposit. The deposit is mined to produce a tailored alumina content of around 2.4%, specified by the markets.

Raw sand from the Kemerton deposit (samples GSWA164508–09) indicates 94.2–95.4% SiO_2, 2.14–2.40% Al_2O_3, 0.15–0.29% Fe_2O_3, and 1.66–1.91% K_2O (Table 17). The processed sand (samples GSWA 164506–07) for sheet and container glass indicates 95.2–96.5% SiO_2, 1.70–2.51% Al_2O_3, 0.02% Fe_2O_3, and 1.29–1.93% K_2O.

Particle-size analyses of washed raw samples indicate that more than 75% of the sand lies within the size range 150–425 µm (Table 18; Fig. 23). The sand mined in the Kemerton deposit has a higher proportion of smaller size sand than that at the Jandakot deposit (Fig. 23).

Table 24. Partial chemical analyses of drillhole samples at Canning Vale

Drillhole	*Depth (m)*	Fe_2O_3	Al_2O_3	TiO_2
			Percentage	
F5	0–1	0.180	0.038	0.510
G2	0–1.5	0.050	0.026	0.240
G3	0–0.5	0.040	0.019	0.170
H2	0–0.5	0.220	0.040	0.470
H3	0–0.5	0.145	0.036	0.320
H4	0–0.5	0.140	0.027	0.250
H5	0–0.5	0.213	0.049	0.550
F6	1–2	0.077	0.033	0.283
G2	3–4	0.061	0.031	0.200
H2	1–2	0.238	0.050	0.734
H2	2–3	0.235	0.060	0.683
H3	1–2	0.190	0.047	0.583
H3	2–3	0.117	0.044	0.450
H4	1–2	0.207	0.047	0.680
H4	2–3	0.144	0.043	0.433
H4	3–4	0.084	0.036	0.300
H4	4–5	0.097	0.042	0.350
H4	5–6	0.075	0.044	0.234
H5	1–2	0.146	0.058	0.533
H6	1–2	0.262	0.120	0.683
H3	4–5	0.107	0.052	0.350

SOURCE: after Rocla Quarry Products (1994)

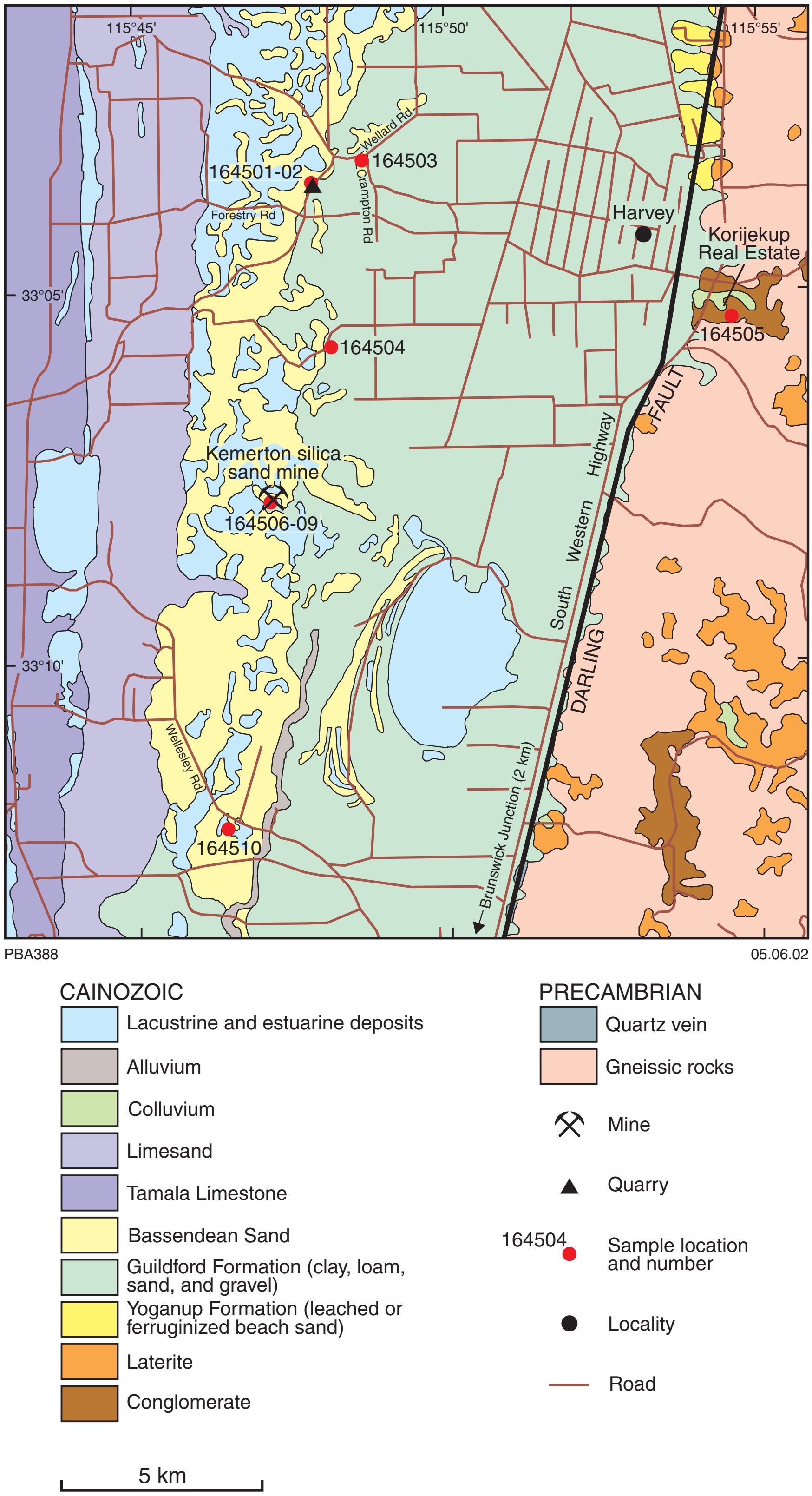

Figure 21. Regional geology around Kemerton silica sand deposit (after Lowry et al., 1983)

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Figure 22. Layer of coffee rock within the silica sand formation at Kemerton deposit

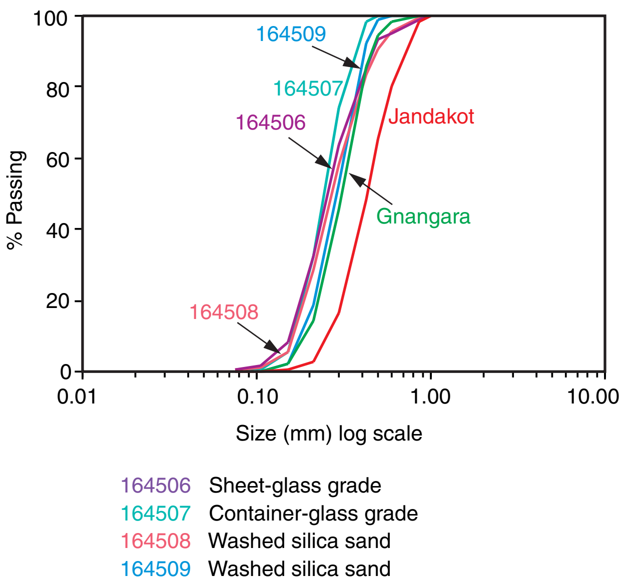

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Figure 23. Particle-size distribution of silica sand — Kemerton (164506–9 are GSWA sample nos)

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Figure 24. Washing plant for removing clay and organic material from the dredged silica sand at Kemerton silica sand mine

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Figure 25. Silica sand processing plant at Kemerton silica sand mine

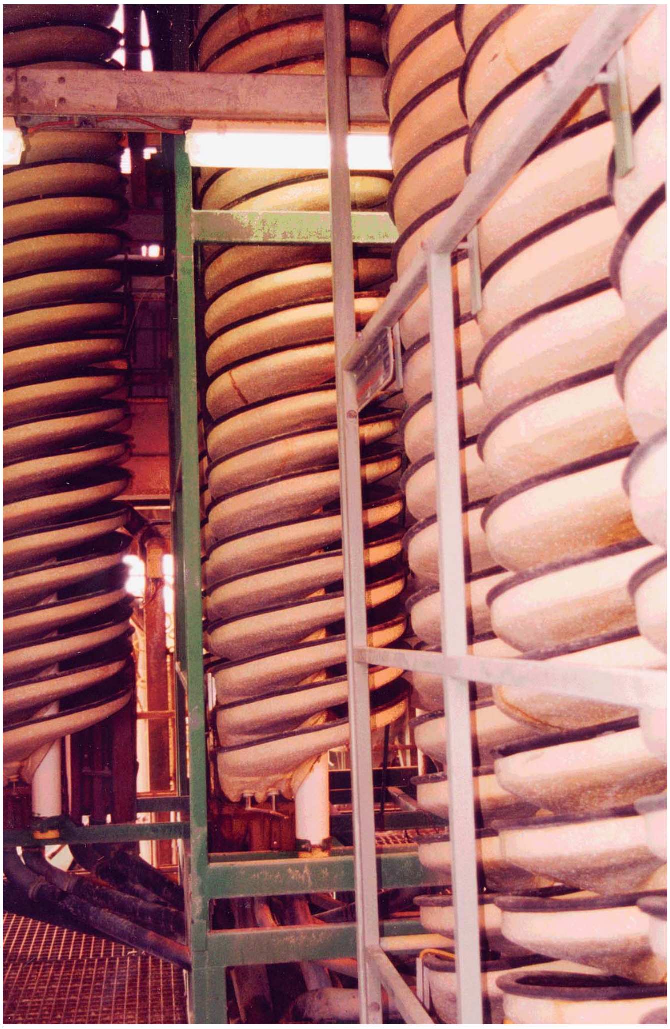

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Figure 26. Spiral classifier for separating heavy minerals at Kemerton silica sand mine

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Figure 27. Stockpiles of sized silica sand at Kemerton silica sand mine

Figure 28. Abandoned sandpit — 8 km west of Harvey (location of samples GSWA164501–02)

Resource

The silica sand resource of the Kemerton mine is very large and estimated at more than 200 Mt by Kemerton Silica Sand Pty Ltd (Department of Resources Development, 1999).

Mining and processing

Mining is carried out by a suction cutter dredge, which is capable of mining at a rate of 350 t per hour. The dredge can mine to a vertical depth of 15 m, which is the approximate maximum depth of the ore-grade sand.

The dredged sand is directly fed through a pipe line into a washing plant (Fig. 24) that is designed to remove organic debris and a significant amount of clay material. The slurry is then dewatered with cyclones, and the sand discharged onto stockpiles ready to feed into the processing plant. The sand is fed into the processing plant (Fig. 25) on a variable speed conveyor belt and passes over a coarse screen, which removes wood and oversize rocks from the sand. The sand then passes over another set of Derrick screens, which remove the majority of the oversize particles from the sand. The oversize fraction is rejected. After the Derrick screens, the sand is deslimed and dewatered (using a cyclone) and then passed to the attritioning cells, which clean the particle surfaces by strongly agitating the thick slurry. The sand is then delivered to the submerged trommels, which carry out the final sizing by removing any grains over 425 µm size. The sized sand is then passed through a spiral classifier to remove heavy minerals (Fig. 26), and again through a wet high-intensity magnetic separator (WHIMS) to remove any remaining iron. The sand is then pumped to cyclones, which dewater the sand, and stackers finally place it in sized stockpiles (Fig. 27). The sand drains naturally on these stockpiles to a moisture content of less than 5%.

The final product is then loaded into trucks and carted to the port of Bunbury, where sand is stored in a 45 000 t capacity shed for loading into 40 000 t vessels.

Production, uses, and markets

During 2000, the production of silica sand from the Kemerton mine was 405 828 t. Expansion is being planned to increase the plant capacity to 700 000 tpa.

Almost all the production of silica sand from the Kemerton deposit is exported to Japan for use in the container-glass industry and television picture tubes. This market requires a special high-quality sand containing alumina and very tight control of the size of grains and the level of impurities. The silica sand should typically contain 95% SiO_2 and 2.4% Al_2O_3 (Table 17), and should contain fewer than 10 grains (per 5 kg) coarser than 600 µm, less than 2% of size coarser than 425–600 µm, and less than 12% finer than 106 µm (information from Kemerton Silica Sand Pty Ltd).

As a step towards diversifying its markets, Kemerton Silica Sand Pty Ltd has produced about 10 000 t of sheet-glass grade silica sand in recent times. The company also sells a small quantity of its products to local markets, such as Unimin Australia Ltd (formerly ACI), for glass manufacture.

Table 25. Chemical analyses of silica sand from the Harvey region, Yarloop, Brunswick Junction, Burekup, and Dardanup

GSWA no.	*164501*	*164502*	*164503*	*164504*	*164505*	*164510*	*164511*	*164512*	*164513*	*164514*	*164515*
						Percentage					
SiO_2	99.50	99.10	98.70	98.60	98.30	98.60	98.50	96.20	98.60	98.80	99.20
Al_2O_3	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.08	0.03	<0.01
Fe_2O_3	0.05	0.08	0.13	0.19	0.14	0.35	0.25	0.34	0.25	0.18	0.12
MgO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CaO	<0.01	0.01	0.01	0.01	0.01	0.01	<0.01	0.01	0.01	0.02	0.01
Na_2O	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.01	<0.01	<0.01
K_2O	0.01	0.04	0.01	0.01	0.01	0.05	0.01	0.02	0.07	0.04	0.02
TiO_2	0.20	0.29	0.70	0.81	1.19	0.83	1.10	2.74	0.72	0.50	0.36
MnO	<0.01	<0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01
P_2O_5	0.013	0.01	0.008	0.009	0.020	0.007	0.012	0.017	0.011	0.011	0.013
BaO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
SO_3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	0.23	0.40	0.42	0.16	0.11	0.08	0.04	0.12	0.15	0.44	0.04
Total	**100.00**	**99.96**	**99.99**	**99.80**	**99.79**	**99.96**	**99.92**	**99.47**	**99.91**	**100.03**	**99.77**
H_2O	8.95	3.17	5.07	2.63	3.25	3.26	2.74	2.99	2.68	2.13	3.77

NOTES: 164501–05: Harvey region
164510: Brunswick Junction
164511: Yarloop
164512: Burekup
164513: Garvey Road, Dardanup
164514: Dardanup Road West, Dardanup
164515: South West Highway, north of Boyanup

Table 26. Size analyses (μm) of silica sand from the Harvey region, Yarloop, Brunswick Junction, Burekup, and Dardanup

GSWA no.	*164501*	*164502*	*164503*	*164504*	*164505*	*164510*	*164511*	*164512*	*164513*	*164514*	*164515*
						Percentage					
>850	0.65	0.32	0.53	0.33	2.03	1.00	0.83	18.38	1.91	0.96	2.84
600–850	5.28	2.47	6.26	8.81	11.70	7.74	12.51	12.62	15.09	11.68	12.82
500–600	5.76	5.43	5.80	15.66	4.35	12.48	7.21	3.57	5.66	12.72	4.65
425–500	14.54	9.13	23.82	18.06	16.68	14.39	16.22	6.58	19.97	18.36	12.60
300–425	37.58	36.89	27.89	31.68	33.24	42.00	30.86	21.97	29.66	33.24	24.67
212–300	25.90	32.60	20.28	14.92	18.25	19.21	19.82	17.95	16.39	13.20	24.68
150–212	8.06	11.02	11.03	7.84	6.50	2.88	7.15	8.57	6.27	6.29	11.53
106–150	1.56	1.34	3.34	2.01	3.53	0.19	2.52	3.62	2.86	2.16	4.08
75–106	0.25	0.27	0.41	0.37	1.76	0.02	1.22	2.80	1.01	0.78	1.29
<75	0.42	0.51	0.62	0.32	1.95	0.09	1.65	3.93	1.17	0.61	0.84

NOTES: 164501–05: Harvey region
164510: Brunswick Junction
164511: Yarloop
164512: Burekup
164513: Garvey Road, Dardanup
164514: Dardanup Road, West Dardanup
164515: South West Highway, north of Boyanup

Harvey

Bassendean Sand, as well as other reworked sand derived from the weathered Archaean granitic and gneissic rocks in the regions 6–8 km east and 3–4 km southeast of Harvey, has been locally mined for the construction industry. Some localities of Bassendean Sand in the area appear to contain high-grade silica sand. Following are descriptions of some samples collected from some of localities around Harvey (Fig. 21).

An abandoned sandpit (Fig. 28) (now a rubbish tip) on the north side of Forestry Road, and approximately 8 km west of Harvey, contains an appreciable quantity of sand. This is fine-grained Bassendean Sand and, as seen from the pitwall, is about 3 m or more deep. The top 0.5–1.0 m of the white sand contains organic material and roots of thin vegetation. The upper 2 m or so of the sand bed is white and below this turns gradually to light brown. Two samples (GSWA164501–02) of mixed white and brown sand from this pit had 99.1–99.5% SiO_2, <0.01–0.03%

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Figure 29. Abandoned sandpit — 8 km southwest of Harvey (location of sample GSWA164504)

Al_2O_3, and 0.05–0.08% Fe_2O_3, indicating high-grade silica sand (Table 25). Particle-size analyses of the washed raw sample show that more than 75% of the sand lies within the size range 150–500 µm, indicating the possibility that the sand is suitable for some high-grade applications (Table 26).

Greyish white to brown, fine- to coarse-grained Bassendean Sand is exposed in the area at the corner of Crampton and Wellard Roads bordering a nature reserve, approximately 7 km west-northwest of Harvey (Fig. 21). Sand is locally developed in relatively low-lying flat areas. The sand is greyish white at the surface (where oxidized) but brown within the first metre (less or partially oxidized). The sand unit appears to continue to deeper levels. The resource of possible high-grade sand in the area is uncertain, but could be significant. A sample (GSWA164503) had 98.7% SiO_2, <0.01% Al_2O_3, and 0.13% Fe_2O_3, indicating generally high-grade silica sand (Table 25). Particle-size analysis of the washed raw sample indicates more than 70% of the sand is within the size range 212–500 µm, suggesting that the sand would be suitable for high-grade applications (Table 26).

Approximately 8 km southwest of Harvey, and bordering a track north of Harvey River Diversion Drain, there are small abandoned pits of white Bassendean Sand. The resource of sand in this locality may not be very large. The sand is white and medium grained, and is more than 3 m deep as seen from the pitwall (Fig. 29). A sample (GSWA164504) of medium-grained, white sand from a pit approximately 8 × 3 × 3 m (deep) indicates 98.6% SiO_2, <0.01% Al_2O_3, and 0.19% Fe_2O_3, suggesting the sand is probably suitable for high-grade applications (Table 25). Particle-size analyses of the washed raw sample further support this interpretation, with more than 65% of the sand within the size range 212–500 µm (Table 26).

A relatively small occurrence of white to cream fine- to medium-grained sand, probably of the Pleistocene Yoganup Formation, is found at the eastern side and outside the Korijekup Real Estate Development, which is at the eastern side of the South Western Highway near Harvey. The occurrence is in a narrow and linear (approximately east–west elongated) depression on a gentle hill slope. The upper regions of the hill, at the northern side of this occurrence, are covered with gravelly lateritic material. The depth of the sand unit is more than one metre, with a thin (few centimetres) carbonaceous layer at the surface. The quantity of sand available from this location is small. A sample (GSWA164505) of medium-grained, white sand indicates 98.3% SiO_2, <0.01% Al_2O_3, and 0.14% Fe_2O_3, suggesting the sand is high grade (Table 25). Particle-size analyses of the washed raw sample indicate that more than 65% of the sand is within the size range 212–500 µm, supporting the suitability of this sand for high-grade applications (Table 26).

Yarloop

White and brown sand, probably of the Pleistocene Yoganup Formation, is exposed at an abandoned rubbish tip at the east side of the South West Highway (Fig. 6). The proportion of the brown sand containing accessory ilmenite and rutile appears to be high. However, there are localized pockets of white silica sand extending to a depth of about 3 m, and below this, the sand tends to be brown. The Yoganup Formation is a shoreline deposit consisting of a basal conglomerate and foredune containing discontinuous concentrations of heavy minerals as well as leached quartz sand (Playford et al., 1976; Wilde and Low, 1978; Harrison, 1990). The area sampled is located just north of Cable Sands (WA) Pty Ltd's heavy mineral sand leases, and is likely to become part of Cable Sands' leases. A raw sample (GSWA164511) of fine-grained white sand had 98.5% SiO_2, <0.01% Al_2O_3, 0.25% Fe_2O_3, and 1.10% TiO_2, suggesting that the sand is reasonably high grade (Table 25), but has relatively high levels of the undesirable impurities Fe_2O_3 and TiO_2. The presence of minerals such as ilmenite and rutile has resulted in relatively higher percentages of TiO_2 and Fe_2O_3 than in the Bassendean Sand. Particle-size analyses of the washed raw sample indicates more than 65% of the sand is within the size range 212–500 µm (Table 26).

Brunswick Junction

Approximately 8 km south of the Kemerton silica sand mine and 9 km northwest of Brunswick Junction, on the southwest side of Wellesley Road, white to creamy, fine- to coarse-grained Bassendean Sand is found on a gentle hillock (Fig. 21). The sand unit is more than 2 m deep and appears to spread in an area extending a few hundred metres to the paddock in the southwest. The upper 0.25 m of the sand consists of dark to grey clayey sand and below this is fine- to coarse-grained white to creamy silica sand. A sample (GSWA164510) of medium-grained, white sand had 98.6% SiO_2, <0.01% Al_2O_3, and 0.35% Fe_2O_3, suggesting the sand is high grade (Table 25). The particle-size analyses of the washed raw sample indicate that more than 75% of the sand is within the size range 212–500 µm, suggesting the possibility that the sand is suitable for high-grade applications (Table 26).

Burekup

Approximately 5 km south-southeast of Burekup, at the south side of the easterly end of Edwards Road, white and brown sand, probably derived from Yoganup Formation, is found in an abandoned quarry (Fig. 30). The quarry, about 30 m long and 20 m wide, has a vertical sand profile extending to at least 4 m. The sand is medium grained, contains accessory ilmenite and rutile, and has a high proportion of brown sand. A raw sample (GSWA164512) of medium-grained white sand indicated only 96.20% SiO_2, and had 0.34% Fe_2O_3 and 2.74% TiO_2, indicating the presence of heavy minerals (Table 25). Particle-size analyses of the washed raw sample indicate that more than 30% of the sand exceeds 600 µm in size and about 45% is within the size range 212–500 µm, indicating a bimodal spread in the sizes (Table 26). The bimodal distribution of sand endorses the view that the Yoganup Formation (from which this sand is derived) is a shoreline deposit.

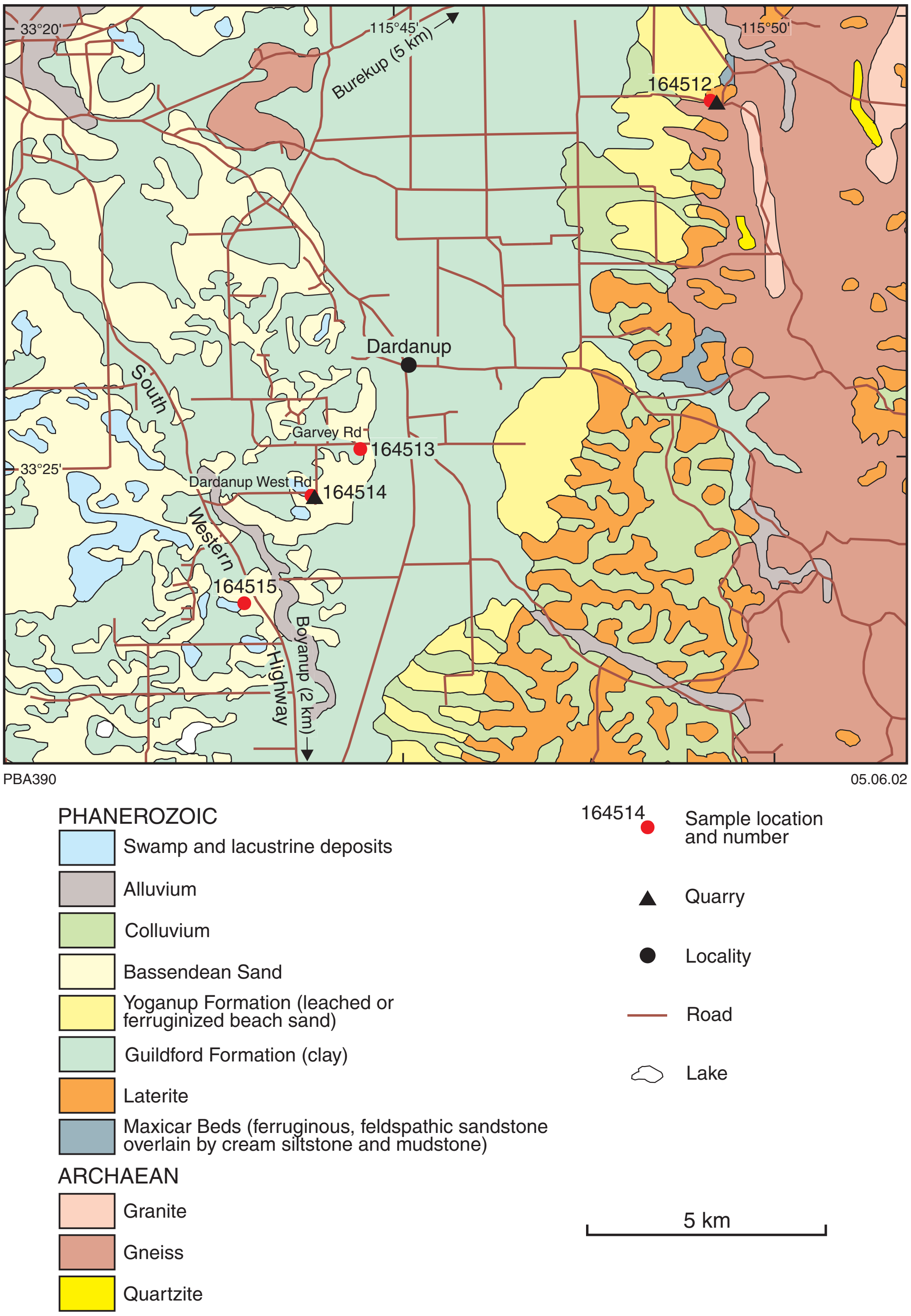


Figure 30. Regional geology around Dardanup (after Lowry et al., 1983)

Dardanup–Boyanup

In the area west of Dardanup to Boyanup, Pleistocene Bassendean Sand is exposed in a number of localities. The sand in this region is typically white and fine to medium grained. Sand has been mined from several localities, possibly for use in the construction industry. Samples were collected from locations at Garvey Road, Dardanup Road West, and the west side of the South Western Highway (Fig. 30).

Sand exposed at Garvey Road near the Dardanup cemetery is white, medium grained, and extends to a depth of more than one metre. A sample (GSWA164513) assayed 98.6% SiO_2, 0.08% Al_2O_3, 0.25% Fe_2O_3, and 0.72% TiO_2, indicating that the sand is moderately high grade (Table 25). Particle-size analyses of the washed raw sample indicate that about 65% of sand grains are within the size range 212–500 µm with about 16% of sand in the >600 µm fraction, indicating a bimodal spread (Table 26). The surface distribution of sand at this location is not very extensive, and the quantity of sand available may not be substantial.

The area surrounding an abandoned pit off Dardanup Road West has a substantial white sand resource. As seen from the pit walls, the thickness of the sand profile is at least 4 m, and the sand unit extends about 300 m in a north–south direction. The sand is white and medium grained, has an overburden about 0.5 m thick, and contains carbonaceous and other plant material (Fig. 31). A raw sample (GSWA164514) of medium-grained sand had 98.80% SiO_2, 0.03% Al_2O_3, 0.18% Fe_2O_3, and 0.50% TiO_2, suggesting possible use in high-grade applications (Table 25). Particle-size analyses of the washed raw sample (GSWA164514) indicate about 65% of the grains lie within the range 212–500 µm and about 12% are coarser than 600 µm (Table 26).

There is a prominent silica sand bed exposed on the west side of the South Western Highway, approximately 5 km north of Boyanup. The sand is medium grained and white and is exposed in a large area capping a gentle hill (Fig. 32). The thickness of the sand bed is at least 4 m. Chemical analysis of a raw sample (GSWA164515) of medium-grained sand indicates 99.20% SiO_2, <0.01% Al_2O_3, 0.12% Fe_2O_3, and 0.36% TiO_2 (Table 25), suggesting its suitability for high-grade applications. Particle-size analysis of the washed raw sample shows that more than 70% lies within the range 150–500 µm, indicating a suitability for high-grade applications (Table 26).

During exploration for heavy mineral sands in the early 1970s, Westralian Sands reported the presence of silica sand deposits along the coastal plain of the Boyanup and Capel regions.

Naturaliste region

The Naturaliste region is the coastal belt (extending approximately 15 km inland) between Cape Naturaliste in the north to Cape Leeuwin in the south, a distance of about

PBA470

Figure 31. Abandoned sandpit at Dardanup Road West (location of sample GSWA164514)

PBA471

Figure 32. White silica sand bed exposed at the west side of South Western Highway (location of sample GSWA164515)

95 km (Fig. 33). The region is relatively rugged (elevations ≤220 m), consisting predominantly of Precambrian crystalline rocks, mostly capped by laterite, with Pleistocene Tamala Limestone, and Holocene coastal sand units. The Holocene sand units closer to the coastline and west of the Cape Naturaliste and Cape Leeuwin ridge are limesand units and are high in calcium carbonate (≥70%). Quartz sand units are found in dunes, associated with lateritic units, and in valleys towards more easterly areas of the Cape Naturaliste and Cape Leeuwin ridge (Lowry, 1967; Playford et al., 1976; Abeysinghe, 1998).

Podzolized sand dunes of Pleistocene age are found 1.5–15 km inland in belts parallel to the coast of Flinders Bay and Geographe Bay, and also in a small area 8 km northwest of Augusta, parallel to the coast. These dunes consist of well-rounded quartz sand overlying ferruginous laterite developed close to the present watertable. These quartz-sand dunes are older than the current limesand dunes found at the coastal region, but are believed to have been formed by the leaching of old limesand dunes resembling the current limesand dunes (Lowry, 1967).

Laterite and associated quartz sand are widely developed in areas farther than 5 km inland from the coast line (Fig. 33). The sand that once covered the limonitic laterite, which itself covers hills underlain by Mesozoic and Precambrian rocks, has been washed into present-day Holocene valleys. The original profile of the area is considered to be as follows:

- 0–3 m quartz sand;
- 3–5 m ferruginous laterite;
- 5–10 m weathered rock;
- unweathered bedrock at 10 m.

Quartz sand accumulated in valleys and on laterite is found in numerous localities around Cowaramup, Margaret River, and the McLeod Creek area close to the Bussell Highway (Fig. 33). The sand at localities farther inland (e.g. Margaret River and McLeod Creek area) is much coarser and more angular than that found near the coast or in Bassendean Sand. In addition, the grain-size variation of this coarse sand is very erratic; within the same deposit the size of sand grains can vary from less than 1 mm to more than 3 mm, suggesting that the sand is not well sorted and has probably been transported only very short distances from its source. It is possible that the coarse sands from this area would be suitable as filtration sands, particularly for waterbores, providing sufficient quantities of appropriately sized material were available. However, well-sorted and medium- to fine-grained sand, comparable to Bassendean Sand, is found closer to the coast; for example, around Caves Road and Pusey Road. The available quartz sand resource of both coarse- and medium-grained varieties in the Naturaliste region is very large. Following are descriptions of some deposits and occurrences where samples have been collected.

Yelverton Road

At the corner of Yelverton Road and Bussell Highway, there is an abandoned sandpit covering an area more

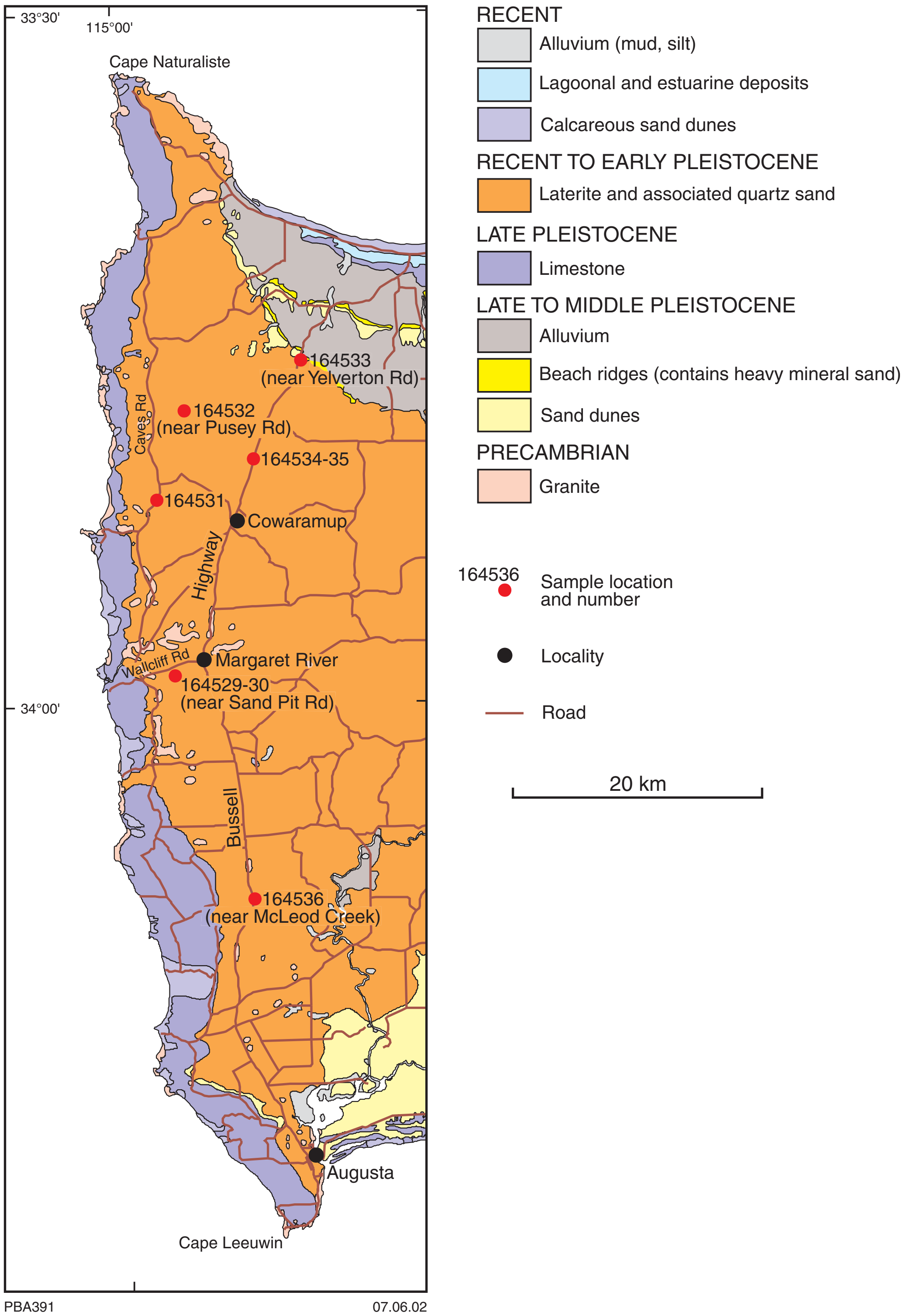


Figure 33. Regional geology around Cowaramup and Margaret River areas (after Lowry et al., 1967)

Table 27. Chemical analyses of silica sand from the Naturaliste region

GSWA no.	*164529*	*164530*	*164531*	*164532*	*164533*	*164534*	*164535*	*164536*
				Percentage				
SiO_2	99.30	99.50	98.90	99.20	99.50	97.50	97.50	98.90
Al_2O_3	0.06	<0.01	0.07	<0.01	<0.01	<0.01	<0.01	<0.01
Fe_2O_3	0.08	0.01	0.09	0.05	0.03	0.51	0.18	0.16
MgO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CaO	0.01	0.01	0.01	<0.01	<0.01	0.01	0.01	<0.01
Na_2O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
K_2O	0.01	<0.01	0.01	0.03	<0.01	<0.01	<0.01	0.01
TiO_2	0.23	0.19	0.67	0.38	0.38	1.53	1.72	0.59
MnO	<0.01	0.01	0.01	<0.01	<0.01	0.03	0.01	0.01
P_2O_5	0.010	0.009	0.015	0.013	0.01	0.017	0.012	0.004
BaO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
SO_3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	0.11	0.08	0.18	0.06	0.08	0.16	0.07	0.07
Total	**99.81**	**99.81**	**99.96**	**99.73**	**100.00**	**99.76**	**99.50**	**99.74**
H_2O	3.03	3.13	8.35	2.81	7.22	5.08	2.58	3.64

than 100 m long and 75 m wide (Fig. 33). The sand is found below a carbonaceous layer about 0.25–0.50 m thick. The pit at this location indicates the thickness of the sand profile to be at least 4 m. The sand is coarse (≤1.5 mm across), white, and angular to subrounded. Below about 4 m depth, a grey to dark-brown hard clayey layer resembles coffee rock seen in Bassendean Sand. A sample (GSWA164533) assayed 99.5% SiO_2, <0.01% Al_2O_3, 0.03% Fe_2O_3, and 0.38% TiO_2, indicating moderately high grade quartz sand (Table 27). Particle-size analyses show that more than 63% of the sample exceeds 850 µm with less than 5% passing through 106 µm, indicating that this sand has a considerably high proportion of coarser material than that found in operating silica sand mines in Western Australia (Table 28; Fig. 34).

Pusey Road

Immediately east of Pusey Road, within a Government reserve (Fig. 33), there is an abandoned sandpit (about 50 m long, 30 m wide, and 5 m deep). The area is covered with relatively thick vegetation. The sand formation is below a thin overburden of about 0.5 m thick carbonaceous-rich soil; the sand is medium to fine grained, white, and subrounded. The deposit is apparently open ended in all directions, suggesting the presence of a substantial resource. A sample (GSWA164532) assayed 99.2% SiO_2, <0.01% Al_2O_3, 0.05% Fe_2O_3, and 0.38% TiO_2, indicating moderately high grade quartz sand (Table 27). Particle-size analysis indicates that about 85% of the sample contains grains within the range 150–850 µm, with only about 10% of the sample above size 850 µm (Table 28). These values suggest that about 85% of the sample is of sizes comparable to those in Bassendean Sand from operating sand mines at Jandakot and Gnangara (Fig. 34).

Cowaramup

Approximately 6 km north of Cowaramup (Fig. 33), on the west side of the Bussell Highway and south of Harmans Road, there is an abandoned sandpit. The sand unit extends in an east–west direction for about 75 m and consists of

Table 28. Size analyses (µm) of silica sand from the Naturaliste region

GSWA no.	*164529*	*164530*	*164531*	*164532*	*164533*	*164534*	*164535*	*164536*
				Percentage				
>850	87.11	83.44	13.64	9.95	63.42	69.21	23.93	58.32
600–850	3.88	3.89	6.92	17.03	4.38	3.57	11.47	7.64
500–600	1.03	1.37	4.04	7.12	1.53	2.27	3.83	1.88
425–500	1.11	1.45	7.79	8.54	1.50	2.85	3.88	2.56
300–425	2.08	2.95	29.60	22.09	4.28	5.02	7.56	4.38
212–300	1.53	3.04	24.42	18.75	7.45	5.93	15.65	8.06
150–212	1.31	2.11	8.14	11.99	7.78	4.87	14.92	6.58
106–150	0.79	0.71	2.47	2.40	5.24	2.70	9.93	4.14
75–106	0.36	0.38	1.12	0.78	2.41	1.49	4.79	3.13
<75	0.81	0.66	1.86	1.35	2.01	2.08	4.05	3.30

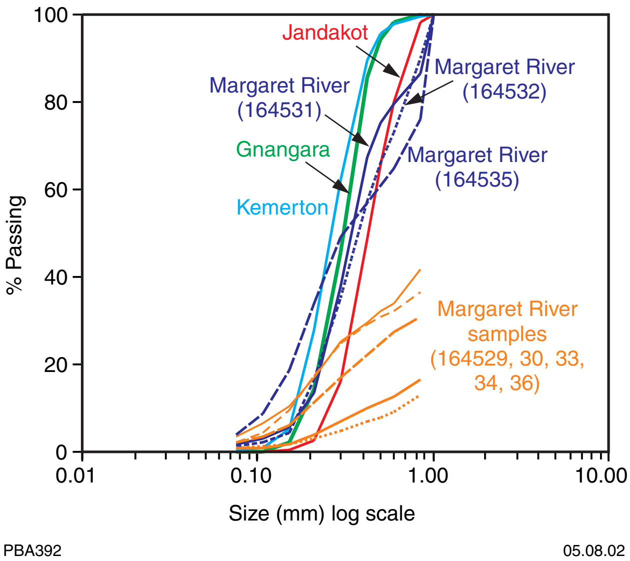


Figure 34. Particle-size distribution of sand from Margaret River region and some operating silica sand mines in Western Australia

white, subrounded sand of variable size with relatively coarse grained (1–3 mm) sand underlying medium- to fine-grained sand (<1 mm). The medium- to fine-grained sand unit is about 3 m thick, with the coarser unit below about 2 m thick. The sandpit is in a small valley. A sample (GSWA164534) of coarse sand has 97.50% SiO_2, <0.01% Al_2O_3, 0.51% Fe_2O_3, and 1.53% TiO_2. A sample (GSWA164535) of medium- to fine-grained sand also has similar composition with 97.50% SiO_2, <0.01% Al_2O_3, 0.18% Fe_2O_3, and 1.72% TiO_2 (Table 27). Both types of sand contain accessory amounts of ilmenite and/or rutile, which is reflected by high TiO_2 and Fe_2O_3 in the chemical composition. Particle-size analyses indicate that 69% of the coarse-grained sample (GSWA164534) has a grain size above 850 µm, a much higher percentage than sand from operating sand mines in Western Australia. In the medium- to fine-grained sample (GSWA164535) there is about 24% in the >850 µm fraction but with a significant proportion (~60%) within the size range of sand of the operating silica sand mines in Western Australia (Fig. 34; Table 28).

Caves Road

On the eastern side of Caves Road and south of Fifty Road there is an abandoned sandpit. The area covered by the sand formation around the pit is large and extends a few hundred metres in a north–south direction (Figs 33 and 35), and has an average width of about 50 m, as seen from the surface exposure. The sand is creamy white, medium grained and rounded, and has a vertical thickness of at least 3 m. At a depth of about 3 m, there is a hard grey to dark brown layer of uncertain thickness, similar to the coffee rock in Bassendean Sand. A sample (GSWA164531) assayed 98.90% SiO_2, <0.07% Al_2O_3, 0.09% Fe_2O_3, and 0.67% TiO_2, indicating moderately high grade quartz sand (Table 27). The particle-size analysis indicates that nearly 14% of the sample is above 850 µm, with about 53% in the 212–425 µm fraction (Table 28). The particle-size distribution shows close similarities to those from operating sand mines at Jandakot and Gnangara in Bassendean Sand (Fig. 34).

Margaret River

Approximately 2.5 km west of the Margaret River township, there is a sandpit at the eastern side of a track named Sand Pit Road, which runs off Wallcliffe Road (Fig. 33). The sand from this pit appears to be used in the construction industry. The pit extends to both sides of Sand Pit Road, with the bigger deposit on the eastern side, covering an area of about 125 × 100 m. The thickness of the sand unit is at least 3 m, and there is a fairly significant resource in the pit area and in the immediate vicinity. The sand on both sides of the track is coarse (most grains 1–3 mm in diameter) and angular, with a slightly dark colour due to a surface coating of carbonaceous material. Two samples (GSWA164529–30), from the east and west sides of the deposit, have 99.30–99.50% SiO_2, <0.01–0.06% Al_2O_3, 0.01–0.08% Fe_2O_3, and 0.19–0.23% TiO_2, indicating that the sand is chemically high grade (Table 27). As expected, the particle-size analyses show that more than 80% of the samples exceeds 850 µm (Table 28), which indicates that the proportion of coarser sand is considerably higher than that found in sands of operating silica sand mines at Jandakot, Gnangara, and Kemerton (Fig. 34).

McLeod Creek

On the western side of the Bussell Highway, just south of a rest area and north of McLeod Creek, a fairly large sandpit is in operation (Fig. 33). This sand unit forms a prominent hill, some 10 m above surrounding ground level (Fig. 36), and thickens towards the west. On the pitwall at the western side of the quarry there is a brown, relatively hard layer similar to the coffee rock in Bassendean Sand. Below this coffee rock, the white sand layer is at least 3–4 m thick. The quarry is about 150 m long and 70 m wide. The sand is creamy white, angular, and coarse (1–2 mm). A sample (GSWA 164536) assayed 98.90% SiO_2, <0.01% Al_2O_3, 0.16% Fe_2O_3, and 0.59% TiO_2, indicating moderately high grade quartz sand from a chemical perspective (Table 27). Particle-size analysis indicates that about 58% of the sample exceeds 850 µm, with the remainder nearly uniformly distributed into sizes between 850 µm and 75 µm (Table 28). The proportion of coarser sand (>850 µm) is considerably higher than that from operating silica sand mines of Western Australia (Fig. 34).

Albany–Fraser Orogen and Bremer Basin

The most important formations that contain significant deposits of quartz sand, within about 150 km of Albany and Esperance on the Albany–Fraser Orogen and in the Bremer Basin, are found in the Tertiary and Quaternary units that are shown in Figures 37, 38, 39, and 40.

PBA472

Figure 35. Extensive exposures of sand bed close to the abandoned sandpit near Caves Road (close to location of sample GSWA164515)

PBA473

Figure 36. Sand quarry at west side of Bussell Highway and north of McLeod Creek (location of sample GSWA164536)

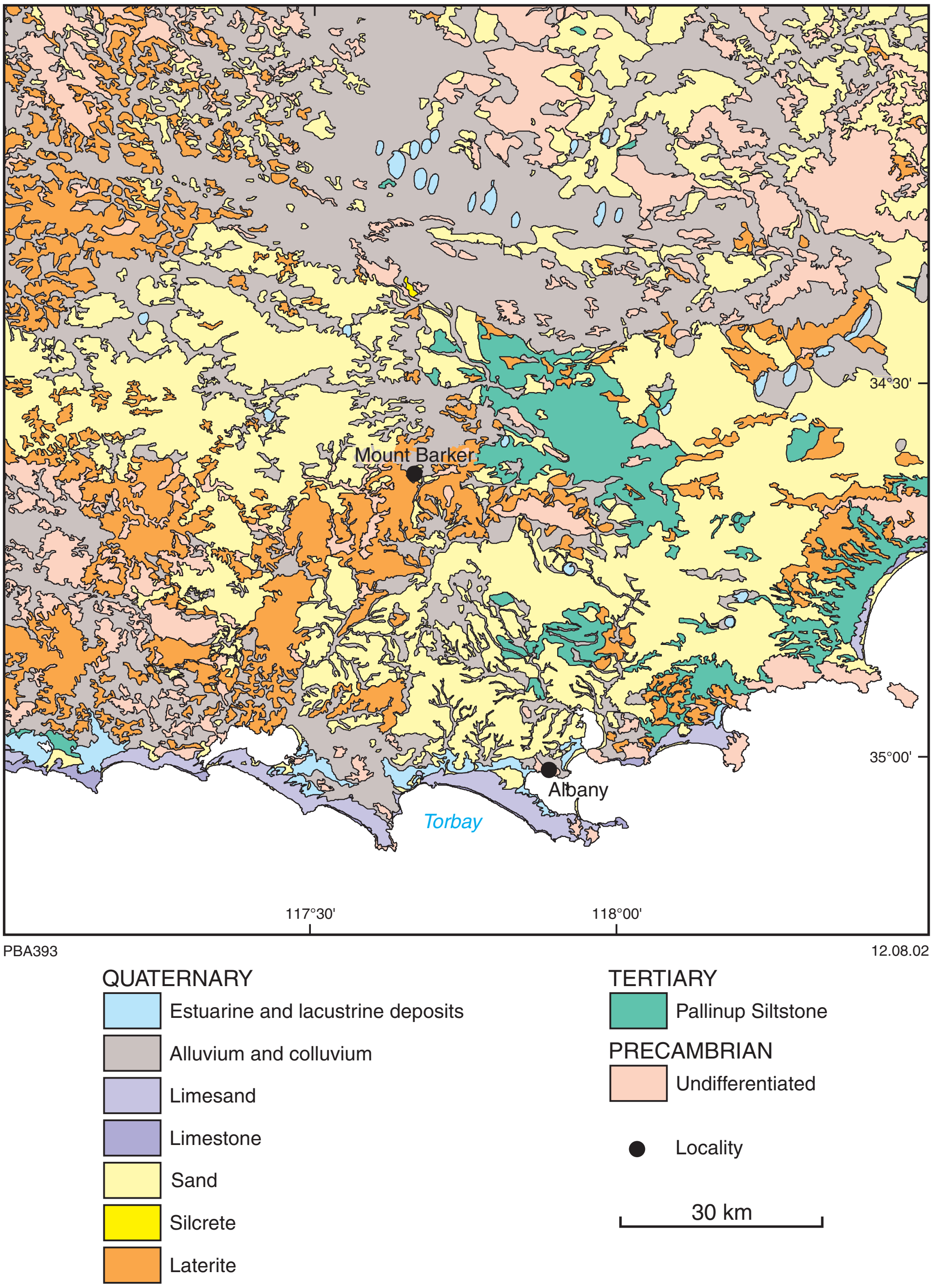


Figure 37. Sand formations in the Albany – Mount Barker area (after Muhling et al., 1984)

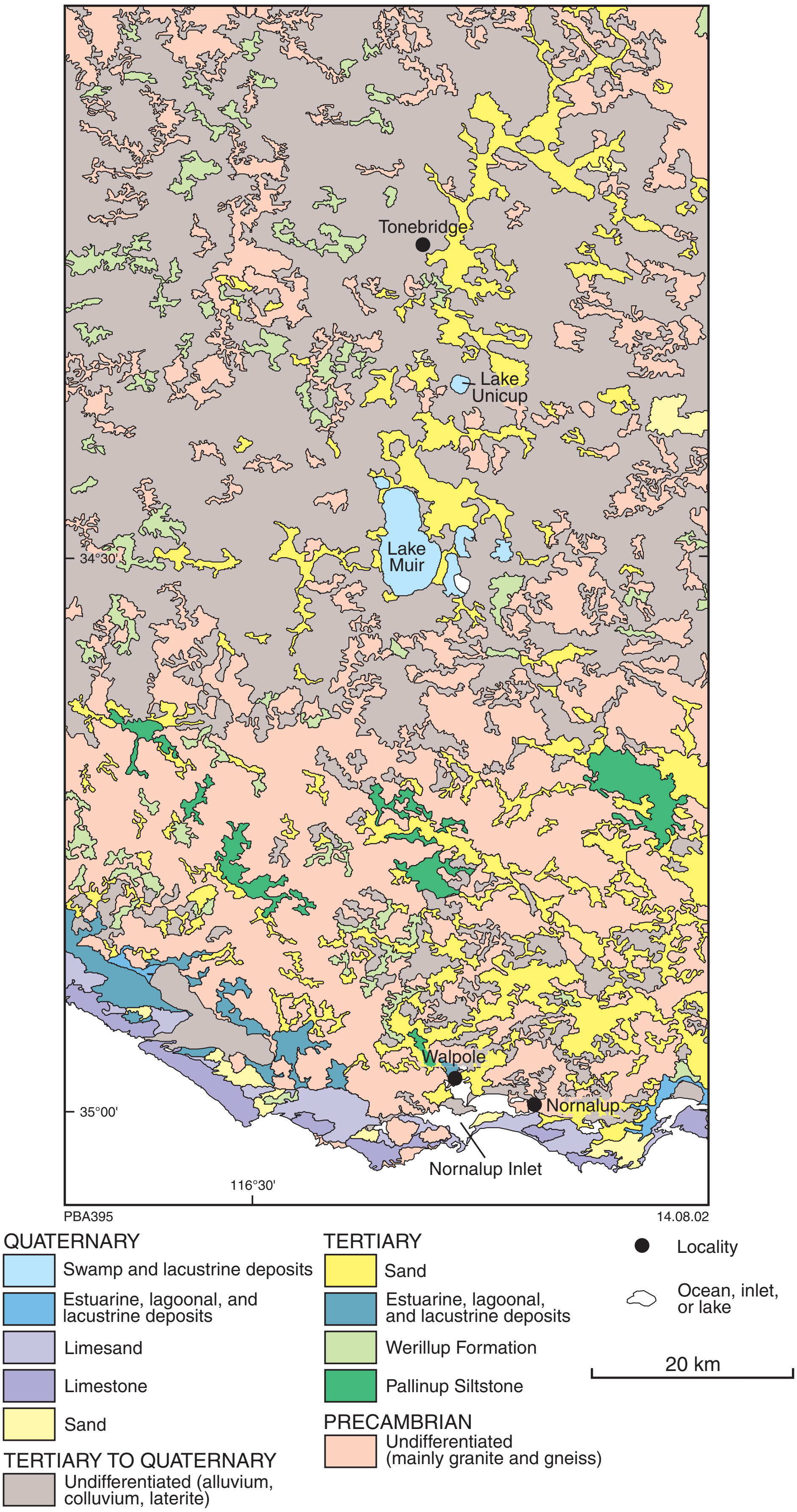


Figure 38. Simplified geology of the Walpole – Lake Muir area (after Wilde and Walker, 1984a)

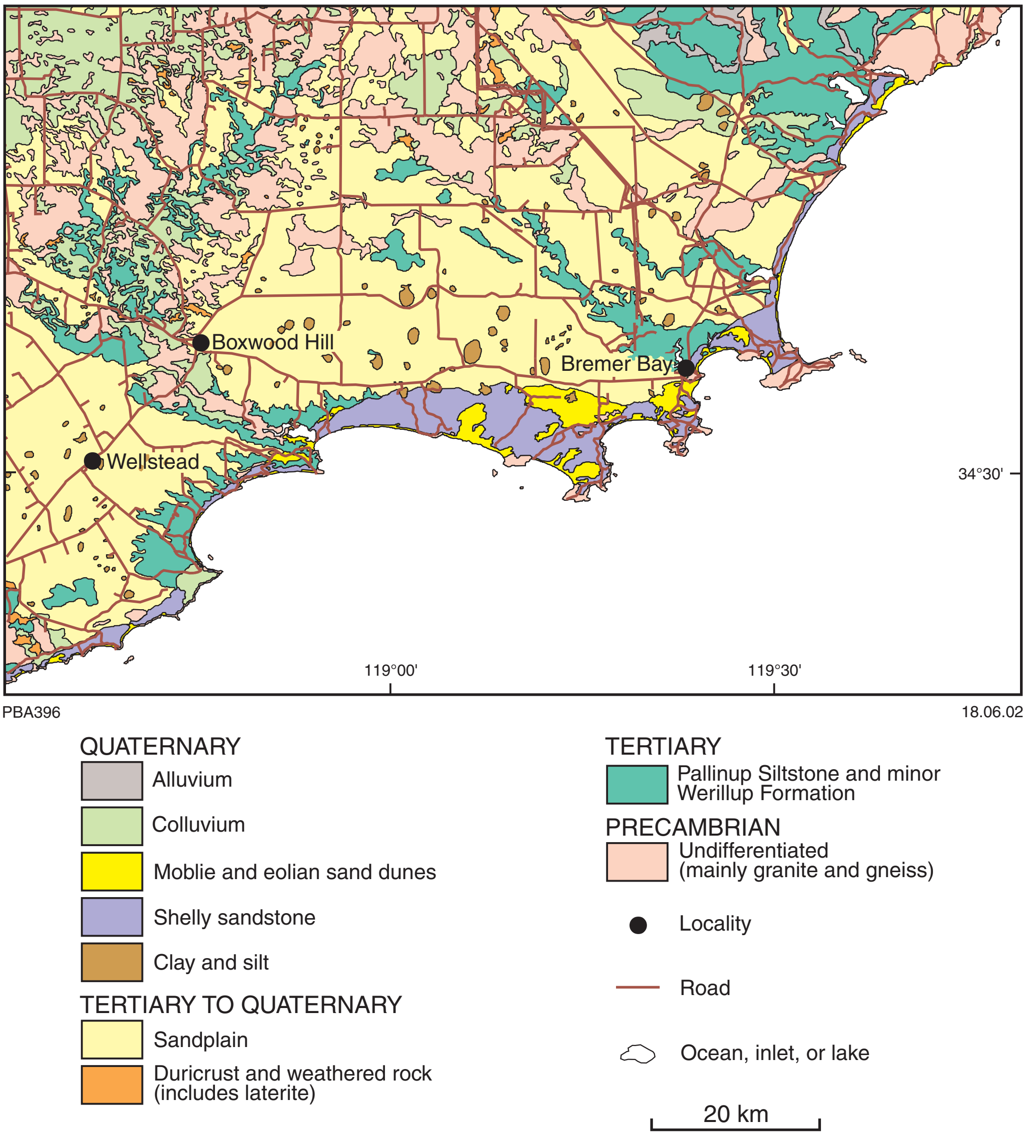


Figure 39. Simplified geology of the Bremer Bay area (after Thom and Chin, 1984)

Albany–Mount Barker region

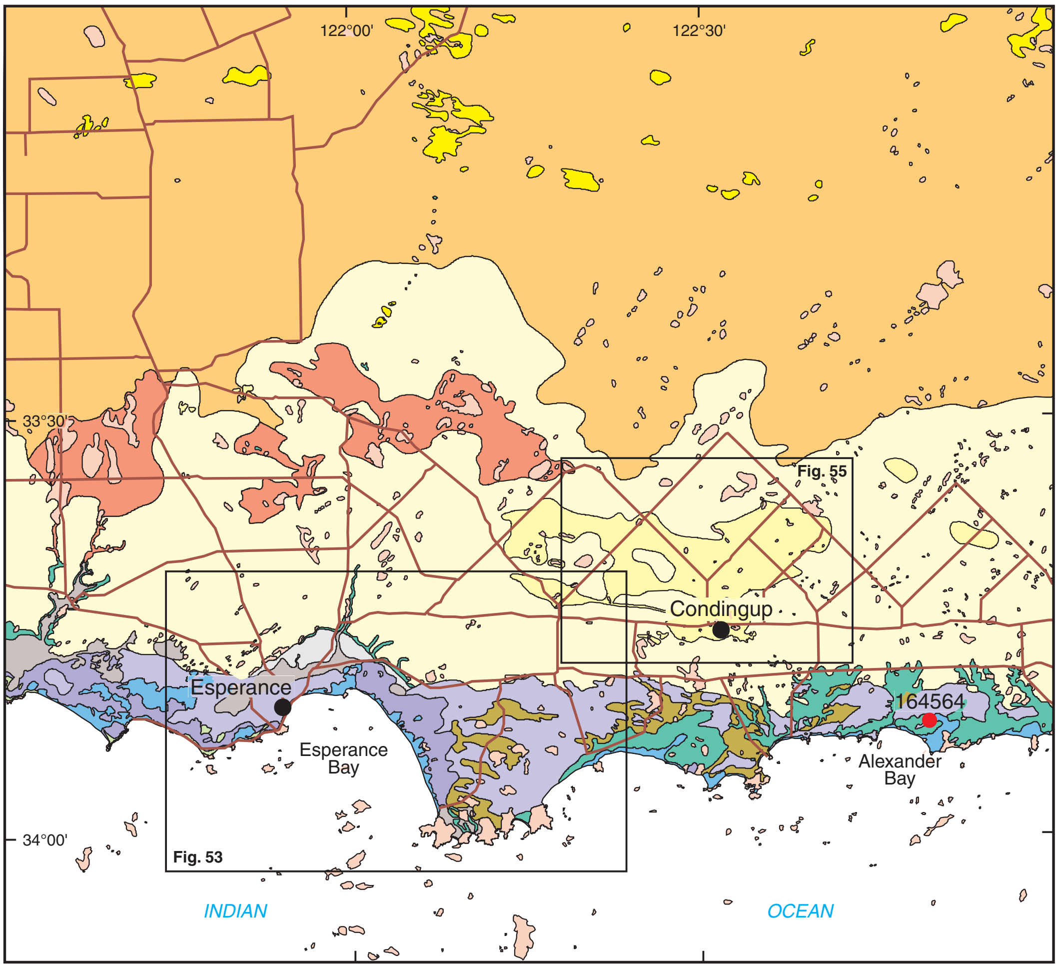
Tertiary and Quaternary sand units in the Albany–Mount Barker region contain extensive deposits of white silica sand (Fig. 37). Inland from the coast, these sands generally form sandplains overlying the Eocene Bremer Basin, Pallinup Siltstone, and the granitoid rocks of the Proterozoic Albany–Fraser Orogen. Despite the wide distribution of Quaternary sand in the southern half of the region, many sand units have not undergone sufficient reworking and sorting to form high-grade silica sand deposits.

Silica sand deposits of economic importance are known from a number of localities north and northeast of Albany. These deposits consist of reworked sand derived from the older units, which have been concentrated in ancient drainages and topographic depressions, and other geologically favorable environments such as ancient valleys. Resources identified in these deposits are vast and economically significant.

At present, a considerable tonnage of high-grade silica sand (all of which is exported to Japan) is mined from a deposit at Mindijup. There is potential for further development of silica sand-based projects in the region as there is a significant resource within economic distances of the port of Albany. Following are descriptions of mines, deposits, and other prospects within the region.

Mindijup

The only operating silica sand mine in the Albany region is located 2 km southeast of Mindijup, which is 35 km northeast of Albany.



QUATERNARY

- Alluvium *(Qra)*
- Mobile coastal sand *(Qrf)*
- Coastal parallel sand dune *(Qrd)*
- Coastal sand on coastal hills *(Qrc)*
- Dissected alluvium *(Qpa)*
- Dune sand (white, leached, fine grained) *(Qps)*
- Dune sand (red, loamy, fine grained) *(Qpf)*
- Eolianite (shelly) *(Qpl)*
- Red soil *(Qpr)*
- Lower sandplain deposit *(Qpp_2)*
- Sandplain deposit *(Qpp_1)*
- Red inland sandplain *(Qpi)*

TERTIARY

- Pallinup Siltstone (*Tep*)

PRECAMBRIAN

- Undifferentiated

164564 Sample location and number

Locality

Road

30 km

Figure 40. Simplified geology of the Esperance area (after Morgan, 1972)

Mindijup silica sand mine

The Mindijup mine is a large producer of silica sand in Western Australia. The mine is owned by TT Sand Pty Ltd (a joint venture between Tochu Co Ltd, 90% and Tomen Australia Ltd, 10%) and operated by AustSand Mining (an Australian company). Production of silica sand began in late 1995 and has been continuous since then.

Geology

The mine lies within a Tertiary sand unit that is widespread in the area (Fig. 41). The sand, covered with a thin (0.5–1.0 m) overburden of organic-rich dark-greyish sand, is white, rounded, and well sorted, and has a thickness averaging around 7 m. Below this the sand is clayey. The silica sand layer consists of nearly 100% quartz with very few impurities, indicating the sand is reworked material derived from older rocks and subsequently deposited in topographic depressions such as ancient valleys or drainages (TT Sand Pty Ltd, 1994).

Resources

Based on a drilling program involving some 40 reverse circulation holes within an area of about 2 km^2, the company has estimated a resource (likely to be in the indicated category) in excess of 20 Mt of silica sand. The deposit is open ended on all sides and the available resource in the area is likely to be much larger.

Quality

The sand is extremely rich in SiO_2, and impurities are scarce except for traces of clay and heavy minerals (predominantly rutile). Such purity is reflected in the chemical composition — a raw sample (GSWA164544) assayed 99.5% SiO_2, 0.02% Al_2O_3, <0.01% Fe_2O_3, and 0.17% TiO_2 (Table 29). Processed sand from the stockpiles is very high grade, averaging 99.90% SiO_2, 0.01% Al_2O_3, and 0.05% TiO_2 (GSWA164545–48).

The sand is finer grained than that found in Bassendean Sand in the Perth region. Approximately 60% of raw sand (Fig. 42a) lies within the size range 150–850 µm, allowing the company to process the sand for high-grade applications such as in the glass and foundry industries (Table 30). The rest of the sand is used in low-grade applications such as construction industries. The average size range of silica sand at the Mindijup mine is wider, and with a higher percentage of fine-grained sand, than the sand from Jandakot, Gnangara, and Kemerton operating mines (Fig. 42b).

Mining and processing

Because the sand is of high quality and the lack of need for any selective mining, the mining operation at Mindijup is relatively simple. The sand, which is found as loose material in the ground, is extracted with a front-end loader (Fig. 43) and then transported by truck to the washing and processing plant at the site. Processing includes primary screening, hydraulic classification, and cleaning over spirals. There is some secondary screening for special products. The size of the sand produced (Fig. 44) is intended to be free from >850 µm and <150 µm fractions, and aimed at obtaining a range of sizes: AFS25, AFS35, AFS48, and AFS90. The processed sand is transported to the Albany port for export.

Production uses and markets

In late 1997, the plant was upgraded to a capacity of 300 000 tpa to produce a range of silica grades for use in glass making, foundry casting, and in the construction industries. At present, the mine produces around 100 000 tpa of high-grade silica sand, which is exported to Japan for the foundry and glass industries. Other markets are currently being sought in South East Asia.

Spencer Road – Crystal Brook Road

The area around the intersection of Spencer and Crystal Brook Roads has numerous exposures of white sand. The area generally has a rolling topography, and the sand exposures are seen on slopes of gentle hills and valleys.

In 1984, Westralian Sands Ltd explored an area 8 km west of Narrikup, north of Crystal Brook Road and around Spencer Road, for silica sand (Fig. 45). The sand units are found on gently to moderately sloping ground and support a very characteristic plant association of banksia, casurina, widely spaced stunted eucalypts and a dense undergrowth of tea tree. The deposits contain subrounded, moderately sorted, reworked alluvial terrace sand, filling a fluvial channel. The sand in surface horizons is white and that in basal sections is stained yellow. Sand grades into sandy grits (derived from the underlying Precambrian granite) towards the basal horizons (Hochwimmer, 1982; Clayton, 1984).

The deposit has a width ranging from 200 to 375 m and a length of about 850 m. Approximately 50 shallow drillholes (1–8 m deep), totalling 250 m, and generally spaced at 150 m intervals were drilled using a Sonair reverse-cycle drill rig. The thickness of the silica sand horizon varies between 4 and 8 m (averaging 6.1 m) with an overburden of about 0.5 m that consists of black soil.

Samples were collected at 4 m intervals or less, depending on the depth to the Precambrian granite basement. Deslimed samples, after drying and weighing, were used for sizing, heavy mineral determination, and chemical analyses.

The sand averages 0.03% Fe_2O_3, 0.04% Al_2O_3, and 0.54% TiO_2, and has an average heavy mineral content of 0.44%. The size distribution shows that the sand is fine grained with only 4.2% exceeding 850 µm. The proportion of sand less than 425 µm size is 83.7% (Clayton, 1984) (Table 31).

A sample (GSWA164555) collected by the author, a few hundred metres west of the deposit along Spencer Road, assayed 99.20% SiO_2, 0.02% Al_2O_3, <0.01% Fe_2O_3, and 0.43% TiO_2 (Table 32). The sand at this location is more than one metre deep and the sample is a composite

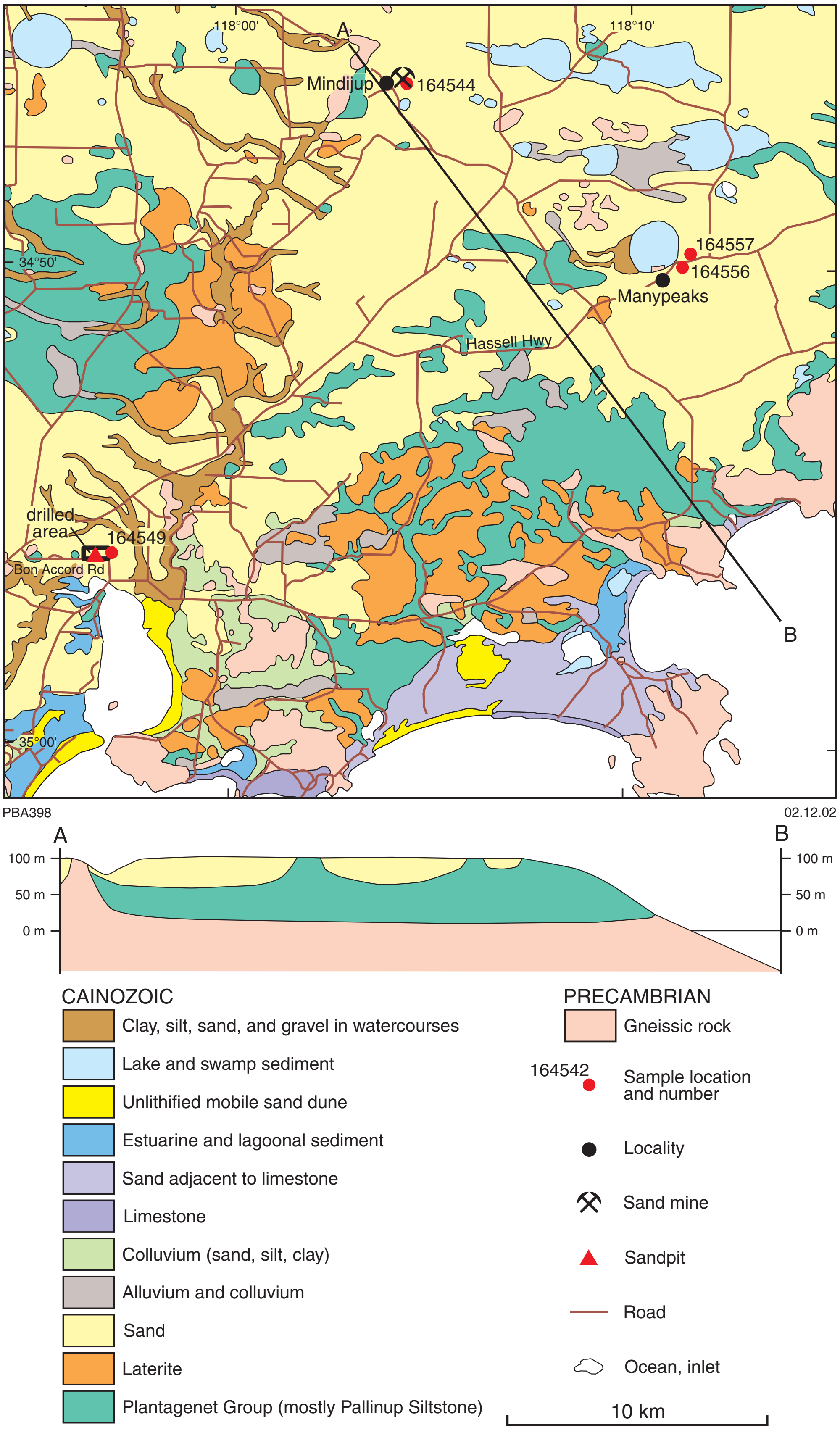


Figure 41. Geology around Mindijup and Manypeaks (after Muhling et al., 1984)

Table 29. Chemical analyses of silica sand from the Mindijup mine

GSWA no.	*164544*	*164545*	*164546*	*164547*	*164548*
			Percentage		
SiO_2	99.50	100.00	99.90	99.80	99.90
Al_2O_3	0.02	<0.01	0.02	<0.01	<0.01
Fe_2O_3	<0.01	0.01	<0.01	<0.01	<0.01
MgO	<0.01	<0.01	<0.01	<0.01	<0.01
CaO	<0.01	<0.01	<0.01	<0.01	<0.01
Na_2O	<0.01	<0.01	<0.01	<0.01	<0.01
K_2O	0.01	<0.01	<0.01	<0.01	<0.01
TiO_2	0.17	0.04	0.06	0.05	0.05
MnO	<0.01	<0.01	<0.01	<0.01	<0.01
P_2O_5	0.007	0.006	0.006	0.012	0.003
BaO	<0.01	<0.01	<0.01	<0.01	<0.01
SO_3	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	0.12	0.01	0.07	0.04	0.06
Total	**99.83**	**100.07**	**100.06**	**99.90**	**100.01**
H_2O	4.06	2.77	2.69	2.60	4.03

of material taken over the first metre from the surface. The particle-size analysis of this sample produced results comparable with those obtained by Westralian Sands, with 4.31% of sand in the >850 µm fraction and 84.13% in the <425 µm fraction, of which 45.06% is in the <150 µm fraction (Table 33).

Based on drilling by Westralian Sands, the deposit is estimated to contain an indicated resource of 1 137 000 t averaging 99% silica (Hochwimmer, 1982).

Bon Accord Road

Extensive areas of white Tertiary to Quaternary sand are found around Bon Accord Road, 14 km northeast of Albany, with some localities having been mined previously for construction sand that was used locally.

During 1981–82, Westralian Sands Ltd explored an area near Bon Accord Road (for silica sand) within the area containing prominent exposure of white sand in old sandpits (Figs 41 and 46). Twenty-one holes totalling 132 m were drilled by Westralian Sands Ltd as part of this program (Hochwimmer, 1982).

The drilling results indicated the deposit to be a saucer-shaped body having a length of approximately 570 m, width 100–270 m, and an average thickness of 5.7 m (3–10.5 m). The overburden, comprising black carbonaceous-rich sandy soil, is less than 0.5 m deep (Hochwimmer, 1982). The sand is very similar to that at the Mindijup deposit and appears to be reworked material derived from older rocks and subsequently deposited in topographic depressions, as indicated by the uneven bottom profile of the sand units.

The chemical composition of a bulk sample from the drillholes, before removal of heavy mineral sands, indicates 99.02% SiO_2, 0.04% Fe_2O_3, 0.05% Al_2O_3, and 0.48% TiO_2. The sand consists of 0.49% heavy minerals, and 2.08% slime. The chemical composition of ten drill samples from the deposit averaged 99.02% SiO_2, 0.05% Al_2O_3, 0.04% Fe_2O_3, and 0.48% TiO_2 (Table 34). The highest level of impurities tends to be in the western part of the deposit. As expected, the TiO_2 content shows a direct correlation with the heavy mineral content of the samples. A sample (GSWA164549) collected by the author from an abandoned pit in the area explored by Westralian Sands indicated comparable assays, with 99.30% SiO_2, <0.01% Al_2O_3, 0.02% Fe_2O_3, and 0.53% TiO_2 (Table 32).

The size fractions of the bulk sample of Westralian drillholes indicates only 1% above 850 µm and 88.8% less than 425 µm, of which 62.3% is less than 150 µm size (Hochwimmer, 1982; Clayton, 1984) (Table 35). The size fractions of sample GSWA164549, collected by the author, indicated results comparable with those of Westralian Sand in having 1.08% above 850 µm, and 88.62% of size less than 425 µm, of which 64.61% is less than 150 µm (Table 33).

The deposit is estimated to contain an indicated resource of 846 000 t of fine-grained silica sand. Of this, 88.2% is finer than 425 µm (Hochwimmer, 1982).

Kronkup

White Tertiary to Quaternary sand is found in the area south and west of Kronkup, 28 km west-southwest of Albany. The sand appears to be reworked material derived from older rocks and subsequently deposited in topographic depressions.

During 1981–82, Westralian Sands Ltd explored the area for silica sand. The localities explored are immediately north of Kronkup, bounded by Kronkup North Road to the north and Lower Denmark Road to the east. Some of the sand is found within the colluvial material in the area (Fig. 47). The exploratory drilling

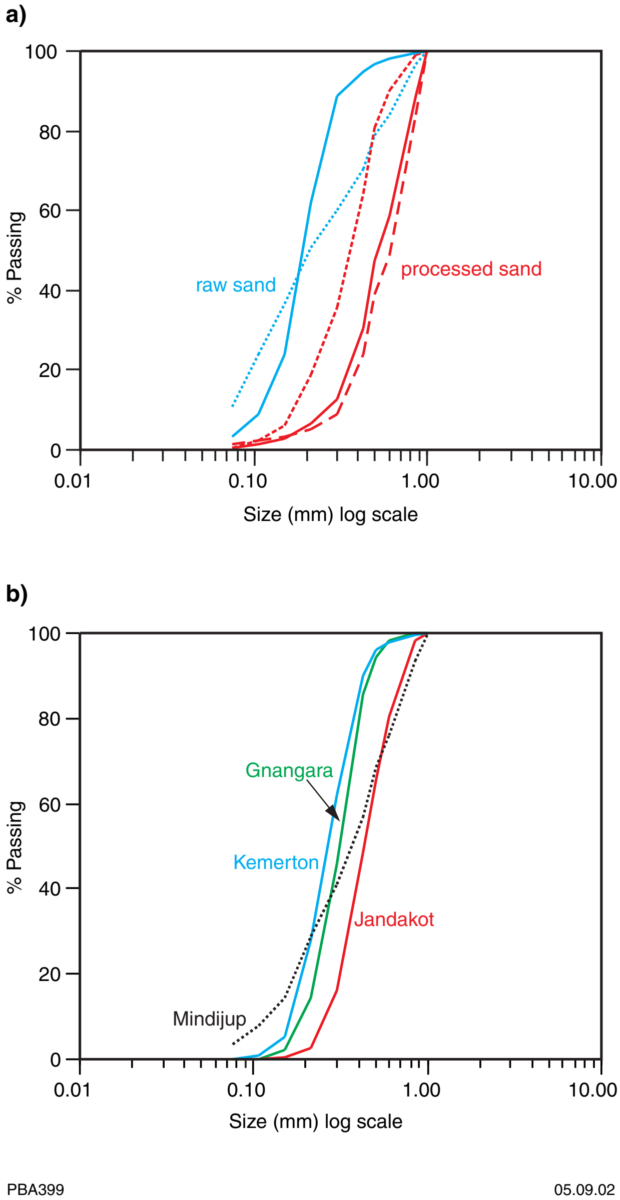


Figure 42 a) Particle-size distribution of silica sand from Mindijup mine; b) Particle-size distribution of silica sand from Mindijup mine and other operating silica sand mines of Western Australia

identified three prospects, designated as Areas A, B, and C. Within these three areas, 28 holes were drilled totalling 135.5 m and of 4.8 m average depth. Within Area A, 15 were drilled averaging 4.9 m, and within Area B 11 were drilled averaging 4.8 m. In Area C, two holes were drilled, each of 4 m depth. The results indicated that Areas A and B are 'lobe-shaped' and are connected by a thin body of sand 50 m wide. Area C is smaller than the other two. The lobe-shape suggests that the sand is found in a palaeodrainage system or alternatively has deposited as colluvial material.

The chemical composition of a bulk sample from the drillholes in Area A, before removal of heavy mineral sands, is 99.2% SiO_2, 0.05% Fe_2O_3, 0.06% Al_2O_3 and 0.25% TiO_2, with 0.34% heavy minerals and 0.8% slime. A bulk sample from Area B contained 99.2% SiO_2, 0.06% Fe_2O_3, 0.04% Al_2O_3 and 0.31% TiO_2, with 0.39% heavy minerals and 1.0% slime. Nine composite samples, from each of nine drillholes in Areas A and B of the Kronkup deposit, averaged 99.12% SiO_2, 0.06% Al_2O_3, 0.08% Fe_2O_3, and 0.33% TiO_2 (Table 36). Analysis of a raw white, fine-grained silica sand sample (GSWA164551), collected by the author from Area A explored by Westralian Sands, indicated comparable but slightly higher grade assays, in having 99.60% SiO_2, <0.01% Al_2O_3, 0.04% Fe_2O_3, and 0.20% TiO_2 (Table 32).

The size fractions of the bulk sample from Area A indicated that only 0.5% of the sand was coarser than 850 µm, with 88.8% less than 425 µm. The respective size fractions of the bulk sample from Area B were 0.8% and 86.8% (Table 37). Sample GSWA164551 had 0.23% above 850 µm and 92.42% less than 425 µm (Table 33).

Area A was estimated to contain an indicated resource of 261 000 t of white, fine-grained, well-sorted silica sand, of which 88.8% is less than 425 µm. Area B has an indicated resource estimated at 316 000 t of fine-grained, well-sorted, sand, of which 86.8% is less than 425 µm. In Area B, the highest levels of impurity southeast of drill lines 11 and 12 (Hochwimmer, 1982).

Marbellup

In the area around Marbelup, about 20 km west-northwest of Albany, Tertiary to Quaternary white, fine-grained silica

Table 30. Size analyses (µm) of silica sand from the Mindijup mine

GSWA no.	*164544*	*164545*	*164546*	*164547*	*164548*
			Percentage		
>850	3.28	1.03	0.39	11.13	16.17
600–850	12.56	8.85	1.46	30.40	35.06
500–600	5.44	9.32	1.46	11.13	10.03
425–500	8.29	16.54	1.85	16.73	14.89
300–425	10.50	28.46	6.15	17.82	14.87
212–300	9.07	16.83	26.65	6.15	4.03
150–212	14.33	12.71	38.27	3.87	1.85
106-150	12.54	4.07	14.72	1.29	0.91
75–106	13.39	1.52	5.57	0.79	1.00
<75	10.59	0.67	3.47	0.69	1.19

PBA474

Figure 43. Mining of silica sand at AustSand Mindijup mine

PBA475

Figure 44. Stockpiles of processed silica sand at AustSand Mindijup mine

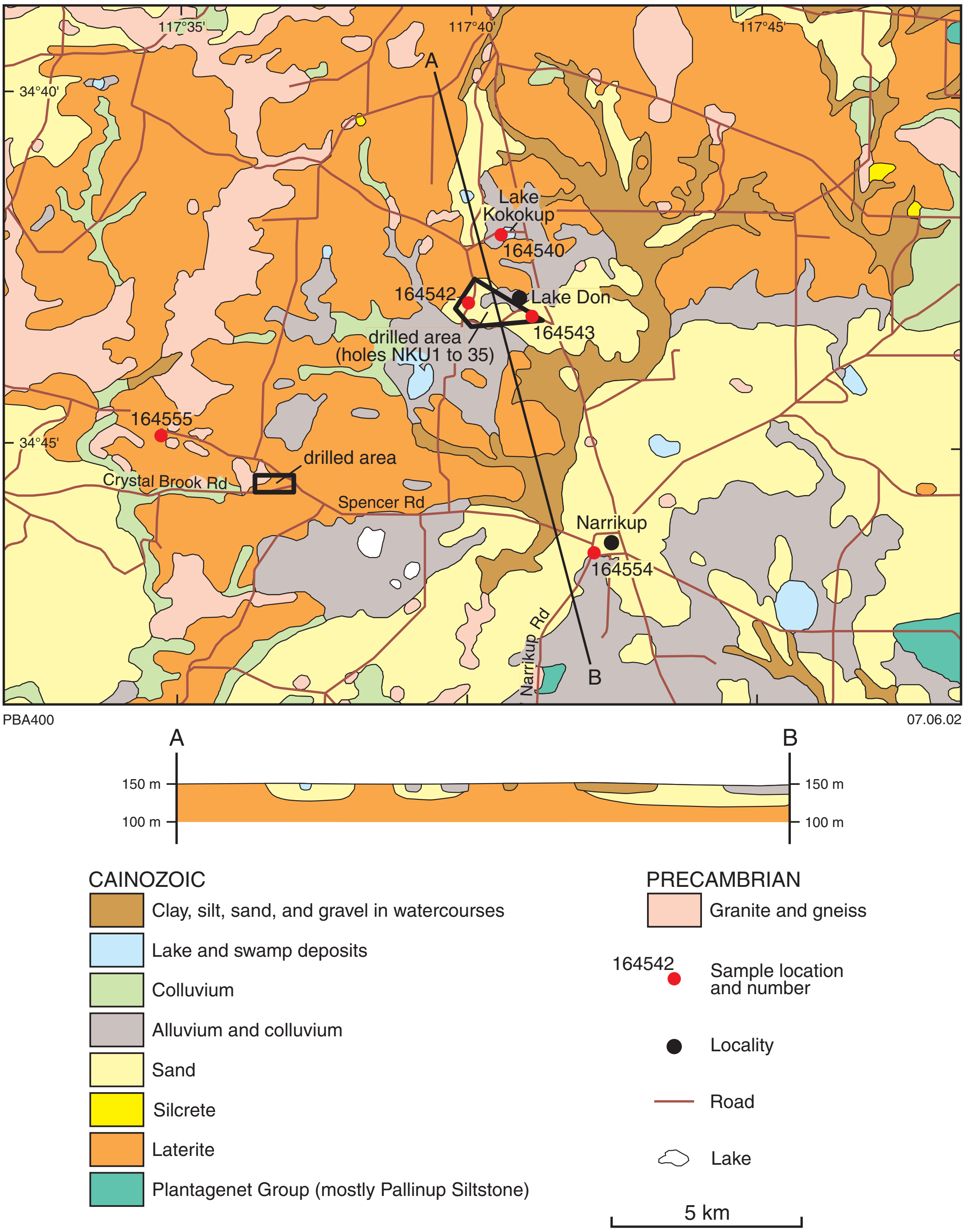


Figure 45. Geology around Crystal Brook Road, Lake Don, and Narrikup (after Muhling et al., 1984)

Table 31. Particle-size distribution of silica sand from the Crystal Brook deposit

Grain size (µm)	*Wt%*	*Wt% cumulative*
>1400	0.9	0.9
>850	3.3	4.2
>600	4.6	8.8
>500	3.4	12.2
>425	4.1	16.3
>355	4.3	20.6
>300	5.8	26.4
>250	6.6	33.0
>212	4.7	37.7
>180	5.9	43.6
>150	10.3	53.9
>125	11.3	65.2
>106	12.2	77.4
>75	17.1	94.5
<75	5.5	100.0

SOURCE: after Hochwimmer (1982)

sand is exposed at a few localities south of the South Coast Highway (Fig. 47). The sand appears to be reworked material derived from older rocks and deposited in Tertiary drainages. The regional distribution of these has been mapped by Muhling et al. (1984).

Mineral Claim 21217, some 17 km west of Albany and just west of Marbellup, was explored for silica sand by Westralian Sands Ltd during 1981–82. The explored area is bounded by the South Coast Highway to the north and Marbelup Road to the west (Fig. 47). Eight drillholes, totalling 44.5 m and averaging 5.6 m in depth, were drilled on this Mineral Claim. The drilling revealed a small and narrow silica sand deposit 50–150 m wide and 500 m long, with a thickness varying from 5.5 to 6.5 m. The thickest zone is of sand infilling an erosional channel within the lateritized basement, and with the deposit covered by a patch of cream coloured sand.

A bulk sample of the deposit indicated 99.2% SiO_2, 0.03% Fe_2O_3, 0.04% Al_2O_3, 0.28% TiO_2, 0.0.31% heavy minerals, and 1.8% slime. Five composite samples from each of five drillholes averaged 99.2% SiO_2, 0.04% Al_2O_3, 0.05% Fe_2O_3, and 0.33% TiO_2 (Table 38). Analysis of a raw, white, fine-grained silica sand sample (GSWA164550), collected by the author from the area explored by Westralian Sands, indicated comparable but slightly higher grade assays, with 99.40% SiO_2, <0.02% Al_2O_3, 0.02% Fe_2O_3, and 0.21% TiO_2 (Table 32).

The size fractions of the bulk sample from the area investigated indicated 0.4% coarser than 850 µm and 93.8% less than 425 µm, of which 78% was within the size range 106–425 µm (Table 39). Sample GSWA164550 had very similar results, with 0.33% coarser than 850 µm, 93.7% less than 425 µm, and 78.8% within the size range 106–425 µm (Table 33).

The deposit is estimated to contain a resource (likely to be inferred) of 153 000 t of white, fine-grained silica sand, of which 93.8% is within the <425 µm fraction. The estimated resource of silica sand is not higher because a portion of the deposit is covered by Marbellup Road (Hochwimmer, 1982).

Lake Don

The area around Lake Don, 7 km north-northwest of Narrikup (Fig. 45), contains abundant exposures of white, fine-grained silica sand. The sand is currently mined at Lake Kokokup, about 2 km north of Lake Don, presumably for local uses (construction sand and filling sand).

Basement to the sand deposits consists of a Precambrian suite of gneissic and high-grade metamorphic rocks intruded by granitoids. These basement rocks are overlain by a thin layer of late Eocene sedimentary rocks of the Plantagenet Group. Deposits of fine, white silica sand overlying the basement highs are considered to be Tertiary to Quaternary age (Monks, 1993).

In 1991, a reconnaissance survey by Sons of Gwalia Ltd in the area around Lake Don identified a number of deposits of fine-grained, white silica sand. A melt test of a sample of this sand, carried out through Itochu Corporation in Japan, produced acceptable results for use in Japanese glass manufacture (Monks, 1993).

In 1993, a program of hand augering, involving 35 holes totalling 70.1 m, was completed to define the resource and quality of the sand deposit (Fig. 45, Table 40). The holes were augered on a 200 × 200 m grid, and about 75% of the holes penetrated the full sand profile into the weathered basement, with the remainder terminating at the watertable, which was encountered before penetrating the full sand layer. A summary of the auger holes is given in Table 40.

Twenty-one samples representing sand profiles of 21 holes, which had significant white sand horizons, were collected for testing. The samples were attritioned and the heavy mineral component removed using heavy liquid, tetrabromoethane (Table 41). The float fraction of the 21 samples ranged from 99.3–99.7%, averaging 99.5%, indicating the heavy fraction of the sand to be less than 1%. The results also indicated that only 50–80% of the titanium minerals were removed by heavy-liquid separation using tetrabromoethane, and this was considered by the company to be inadequate for use of the sand in the glass industry.

Chemical analysis of the float fraction of each of the 21 samples gave averages of 99.66% SiO_2, 0.05% Al_2O_3, 0.01% Fe_2O_3 and 0.17% TiO_2, indicating very high quality silica sand (Table 42). Analysis of four unprocessed raw samples of white, fine-grained silica sand (GSWA 164540–43), collected by the author from the area explored by Sons of Gwalia Ltd, indicated comparable assays, averaging 99.38% SiO_2, 0.01% Al_2O_3, 0.01% Fe_2O_3, and 0.29% TiO_2 (Table 32). Sample GSWA164540, a composite of fine-grained, rounded, white sand at a depth of 1–2 m, is from the northern wall of an operating sandpit at Lake Kokokup. The thickness of the sand layer at the northern end of the pit is about 3 m (Fig. 48). Sample GSWA164541 is from the southern end of the

Table 32. Chemical analyses of silica sand from the Albany region

GSWA no.	*164549*	*164550*	*164551*	*164552*	*164553*	*164554*	*164555*	*164556*	*164557*	*164558*	*164540*	*164541*	*164542*	*164543*
							Percentage							
SiO_2	99.30	99.40	99.60	99.40	98.80	98.70	99.20	98.40	99.30	99.00	99.50	99.40	99.00	99.60
Al_2O_3	<0.01	0.02	0.01	0.03	0.06	0.07	0.02	0.52	0.04	0.36	0.02	<0.01	<0.01	0.01
Fe_2O_3	0.02	0.02	0.04	0.02	0.03	0.04	0.02	0.15	0.01	0.08	<0.01	0.01	0.01	0.02
MgO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CaO	<0.01	<0.01	<0.01	<0.01	0.01	0.01	0.01	0.01	<0.01	<0.01	0.01	<0.01	0.01	<0.01
Na_2O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
K_2O	<0.01	<0.01	0.01	0.02	0.01	0.02	<0.01	0.15	0.02	0.01	0.01	0.01	<0.01	<0.01
TiO_2	0.53	0.21	0.20	0.36	0.38	0.40	0.43	0.25	0.19	0.20	0.20	0.23	0.45	0.26
MnO	0.01	0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01
P_2O5	0.006	0.006	0.008	0.001	0.011	0.013	0.02	0.01	0.012	0.004	0.003	0.011	0.009	0.009
BaO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
SO_3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	0.08	0.16	0.12	0.17	0.42	0.52	0.14	0.37	0.27	0.44	0.13	0.15	0.30	0.11
Total	**99.95**	**99.83**	**100.00**	**100.01**	**99.72**	**99.77**	**99.84**	**99.89**	**99.84**	**100.10**	**99.87**	**99.81**	**99.78**	**100.01**
H_2O	3.60	3.83	2.98	3.18	8.45	14.22	3.45	4.12	1.87	2.47	10.93	3.48	2.71	3.49

NOTE: 164549: Bon Accord
164550: Marbellup
164551: Kronkup
164552–53: Redmond West Road
164554: Narrikup
164555: Crystal Brook
164556–57: Manypeaks
164558: Wellstead
164540–43: Lake Don

Table 33. Size analyses (µm) of silica sand from the Albany region

GSWA no.	*164549*	*164550*	*164551*	*164552*	*164553*	*164554*	*164555*	*164556*	*164557*	*164558*	*164540*	*164541*	*164542*	*164543*
							Percentage							
>850	1.08	0.33	0.23	0.91	0.31	1.08	4.31	0.64	1.33	0.12	5.38	3.83	3.95	1.46
600–850	4.30	1.57	1.34	4.64	1.76	1.82	5.99	3.64	7.36	0.49	10.07	9.32	10.01	3.91
500–600	2.42	1.14	1.56	2.03	0.71	1.06	2.06	2.38	4.26	0.32	3.17	3.95	3.90	1.94
425–500	3.59	3.26	4.45	3.27	0.90	1.77	3.51	3.29	5.18	0.81	4.86	5.50	5.46	2.76
300–425	8.89	18.25	26.13	11.13	1.59	5.35	9.73	5.22	8.12	6.18	13.87	14.70	12.05	7.66
212–300	7.35	26.64	43.92	18.57	2.28	8.99	11.95	7.18	10.65	22.36	16.71	17.44	10.26	9.58
150–212	7.77	18.95	17.35	21.26	8.86	11.16	17.39	12.44	18.36	28.24	16.85	17.73	10.35	14.12
106–150	16.13	14.98	2.63	13.94	34.30	30.88	25.93	27.56	22.26	22.14	12.56	11.64	16.10	34.51
75–106	27.15	9.03	1.04	12.49	36.51	29.90	14.08	28.41	17.35	17.43	9.55	9.91	20.41	18.63
<75	21.33	5.85	1.35	11.75	12.78	7.99	5.05	9.23	5.14	1.92	6.97	5.98	7.51	5.44

NOTE: 164549: Bon Accord
164550: Marbellup
164551: Kronkup
164552–53: Redmond West Road
164554: Narrikup
164555: Crystal Brook
164556–57: Manypeaks
164558: Wellstead
164540–43: Lake Don


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Figure 46. Silica sand deposit at Bon Accord Road

Table 34. Partial chemical analyses of silica sand from the Bon Accord Road deposit

	Range (%)	*Average (%) (10 samples)*
SiO_2	98.8–99.2	99.02
Fe_2O_3	0.01–0.09	0.04
Al_2O_3	0.03–0.08	0.05
TiO_2	0.28–0.61	0.48
Slime	1.5–3.1	1.89[(a)]
Heavy minerals	0.21–0.69	0.45

NOTE: (a) Average of 9 samples

SOURCE: after Hochwimmer (1982)

Table 35. Particle-size analysis of a bulk silica sand sample from the Bon Accord Road deposit

Grain size (µm)	*Wt%*	*Cumulative wt%*
>850	1.0	1.0
600–850	2.6	3.6
500–600	3.5	7.1
425–500	4.1	11.2
355–425	4.1	15.2
300–355	4.5	19.8
250–300	4.7	24.5
212–250	3.2	27.7
180–212	4.1	31.8
150–180	5.9	37.7
125–150	6.7	44.4
106–125	11.6	56.0
75–106	26.5	82.5
<75	17.5	100.0

SOURCE: after Hochwimmer (1982)

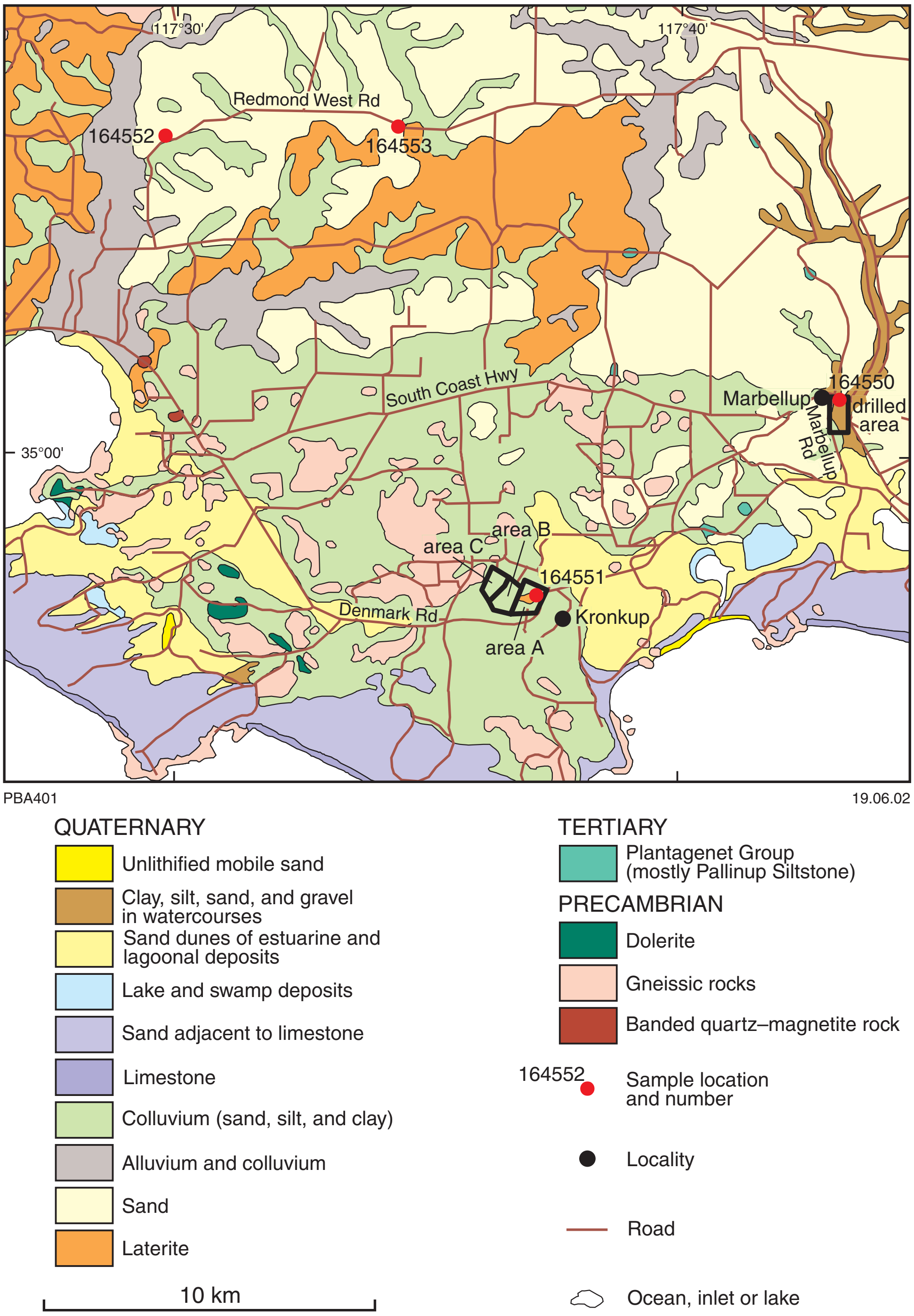

Figure 47. Geology around Kronkup, Marbellup, and Redmond West Road (after Muhling et al., 1984)

Table 36. Partial chemical analyses of silica sand from Areas A and B in the Kronkup deposit

	Range (%)	*Average (%) (9 samples)*
SiO_2	98.9–99.3	99.12
Fe_2O_3	0.04–0.13	0.08
Al_2O_3	0.04–0.15	0.06
TiO_2	0.21–0.49	0.33
Slime	0.75–1.40	1.06
Heavy minerals	0.28–0.63	0.43

SOURCE: after Hochwimmer (1982)

Table 38 Partial chemical analyses of silica sand from the Marbellup deposit

	Range (%)	*Average (%) (5 samples)*
SiO_2	99.1–99.2	99.20
Fe_2O_3	0.03–0.07	0.05
Al_2O_3	0.03–0.04	0.04
TiO_2	0.28–0.40	0.33
Slime	0.75–1.40	1.06
Heavy minerals	0.23–0.48	0.34

SOURCE: after Hochwimmer (1982)

same pit, and is a composite of fine-grained, rounded, white sand from a depth of 1.5–2.5 m. The southern wall of the pit has a 1–2 m thick overburden consisting of dark grey to black organic-rich soil. The watertable lies some 5 m beneath the surface (Fig. 49). Sample GSWA164542 is a one-metre composite of sand from the surface, exposed at the west side of Lake Don, by the side of a track near a paddock. This sand is fine grained, white, rounded, and thicker than 1 m. Sample GSWA164543 is fine-grained, rounded, white sand found in a trench some 3 m deep and 5 m wide, extending to about 75 m in a north–south direction, near Red Hill Road, and west of the railway line.

The size fractions of the 21 samples tested by Sons of Gwalia Ltd averaged 5.09% coarser than 850 µm and 81.65% less than 425 µm, of which 80.76% was within the range 75–425 µm (Table 43). The four samples (GSWA164540–43) collected by the author had very similar results, with 5.38% coarser than 850 µm and 80.13% less than 425 µm, with 73.66% being within the range 75–425 µm (Table 33). These samples show higher proportions of fine-grained material compared with any of the sand from operating silica sand mines in the State (Fig. 50).

Sons of Gwalia Ltd carried out further chemical analyses of different size fractions of one sample (NKU31) (Table 44). The results indicated that there was a distinct increase in titania in the lower size range (<75 µm), but relatively uniform titania in the remaining fractions. Although screening would help to cut down titania levels, the company considered that they would still be too high for glass-grade applications (Monks, 1993).

A total resource of 4 Mt (likely to be in the inferred category) was estimated at the eastern and western zones of the area investigated. At the western zone, the resource was estimated at 3.2 Mt, and that at the eastern zone, which is open ended to the north, was estimated at 0.8 Mt. The silica sand contains up to 1% heavy minerals (Monks, 1993).

Narrikup

Sand is exposed at the western side of Narrikup Road, near Spencer Road intersection, and at the western outskirts of Narrikup township (Fig. 45). The sand appears to continue farther west, but is covered with thick vegetation. The sand

Table 37. Particle-size analysis of bulk silica sand samples from Areas A and B in the Kronkup deposit

	Area A		*Area B*	
Grain size (µm)	*wt%*	*Cumulative wt%*	*wt%*	*Cumulative wt%*
>850	0.5	0.5	0.8	0.8
600–850	1.4	1.9	1.9	2.7
500–600	2.6	4.5	3.3	6.0
425–500	6.7	11.2	7.2	13.2
355–425	8.4	19.6	9.5	22.7
300–355	15.6	35.2	14.4	51.5
250–300	21.1	56.3	19.3	36.4
212–250	15.3	71.6	14.0	70.4
180–212	13.3	84.9	12.7	83.1
150–180	7.7	92.6	8.2	91.3
125–150	2.7	95.3	3.1	94.4
106–125	1.6	96.9	1.7	96.1
75–106	1.9	98.8	2.2	98.3
<75	1.2	100.0	1.7	100.0

SOURCE: after Hochwimmer (1982)

Table 39. Size analysis of a bulk silica sand sample from the Marbellup deposit

Grain size (µm)	*Wt%*	*Cumulative wt%*
>850	0.4	0.4
600–850	1.0	1.4
500–600	1.7	3.1
425–500	3.1	6.2
355–425	4.2	10.4
300–355	6.3	16.7
250–300	10.2	26.9
212–250	8.2	35.1
180–212	11.1	46.2
150–180	14.4	60.6
125–150	13.3	73.9
106–125	10.3	84.2
75–106	12.1	96.3
<75	3.7	100.0

SOURCE: after Hochwimmer (1982)

Table 40. Summary of auger holes at Lake Don

Hole	*From (m)*	*To (m)*	*Thickness (m)*	*Lithology*
NKU 1	0.0	2.1	2.1	Fine-grained, white sand
	2.1	2.4	0.3	Sandy clay with trace of rutile
NKU 2	0	1.3	1.3	Off white, fine-grained silica sand. Sorting moderate
	1.3	1.7	0.4	Off white, coarse-grained silica sand. Sorting moderate. Watertable at 1.5 m. Trace of rutile
	1.7	1.9	0.2	White, fine to very fine silica sand
NKU 3	0.0	3.75	3.75	Off white to white, fine-grained, moderate to well-sorted silica sand. Trace of rutile. Watertable at 3.15 m
NKU 4	0	0.3	0.3	Light brown, iron-stained sand over brown clay
NKU 5	0.0	5.2	5.2	White, fine-grained, well-sorted silica sand
	5.2	5.3	0.1	Brown fine-grained sand and clay
NKU 6	0.0	0.6	0.6	White, fine-grained sand. Moderate to well sorted
	0.6	0.7	0.1	Brown sand due to organic material
NKU 7	0.0	0.2	0.2	Hard grey clay with fine-grained sand
NKU 8	0.0	1.1	1.1	Yellow, fine- to medium-grained, moderately sorted silica sand. Minor clay. Minor rutile
	1.1	1.2	0.1	Laterite
NKU 9	0	1.25	1.25	White, fine-grained, well-sorted silica sand. Trace of rutile
	1.25	1.85	0.6	White to off white, fine- to coarse-grained , poorly sorted silica sand. Watertable at 1.75 m.
	1.85	1.90	0.05	Dark brown clay and medium- to fine-grained sand
NKU 10	0.0	0.2	0.2	Grey clay
NKU 11	0.0	4.6	4.6	White, medium- to fine-grained, moderately sorted, silica sand
	4.6	4.7	0.1	Lateritic clay
NKU 12	0.0	2.55	2.55	White, fine-grained, well-sorted silica sand. Watertable at 1.75 m
NKU 13	0.0	1.40	1.40	White, fine-grained, well sorted silica sand. Trace of rutile. Watertable at 0.75 m
NKU 14	0.0	1.0	1.0	Fine-grained, well-sorted silica sand. Lateritic gravel at bottom
NKU 15	0.0	1.1	1.1	Fine-grained, well-sorted silica sand with trace of rutile. Lateritic gravel at bottom
NKU 16	0.0	2.5	2.5	Fine- to very fine-grained, yellow to white, well-sorted silica sand
	2.5	2.6	0.1	Yellowish clay at top of laterite
NKU 17	0.0	1.2	1.2	Fine- to very fine-grained, yellow, well-sorted silica sand with trace of rutile. Sandy lateritic gravel at bottom
NKU 18	0.0	0.6	0.6	Yellow, fine-grained sand with pisolitic laterite
NKU 19	0.0	1.8	1.8	White, fine-grained, well-sorted silica sand with trace of rutile. Pisolitic lateritic gravel at bottom
NKU 20	0.0	1.0	1.0	White, fine-grained, well-sorted silica sand with trace of rutile. Laterite at bottom
NKU 21	0.0	2.8	0.0–2.8	White, fine-grained, well-sorted silica sand with trace of rutile. Watertable at 2 m
	2.8	2.8	–	Lateritic clay
NKU 22	0.0	0.3	0.3	Yellow, fine-grained silica sand with laterite at bottom
NKU 23	0.0	0.2	0.2	Lateritic gravel
NKU 24	0.0	0.2	0.2	Lateritic gravel
NKU 25	0.0	0.3	0.3	White, fine-grained silica sand with lateritic gravel at bottom
NKU 26	0.0	4.3	4.3	White, fine-grained, well-sorted silica sand
	4.3	5.0	0.7	Fine- to coarse-grained, poorly sorted angular silica sand
	5.0	5.9	0.9	Fine- to very fine-grained, white silica sand. Trace of rutile. Watertable at 5.4 m
NKU 27	0.0	2.3	2.3	Fine-grained, white, well-sorted silica sand
	2.3	2.5	0.2	Coarse-grained, white, poorly sorted silica sand. Bottom sand is well cemented and not possible to auger easily
NKU 28	0.0	2.7	2.7	Fine-grained, white, well-sorted silica sand. Trace of rutile
NKU 29	0.0	1.8	1.8	Fine-grained, white, well-sorted silica sand with trace of rutile
	1.8	3.1	1.3	Coarse-grained, white, poorly sorted silica sand with trace of rutlile. Watertable at 2.6 m
NKU 30	0.0	1.1	1.1	Fine-grained, white, well-sorted silica sand
	1.1	1.3	0.2	Laterite
NKU 31	0.0	7.0	7.0	Fine-grained, white, well-sorted silica sand. Trace of rutile
NKU 32	0.0	4.0	4.0	Fine-grained, white, well-sorted silica sand with trace of rutile. Watertable at 3.9 m. Laterite at bottom
NKU 33	0.0	1.6	1.6	Fine-grained, white, well-sorted silica sand with trace of rutile. Lateritic clay at bottom
NKU 34	0.0	2.1	2.1	Fine-grained, white, well-sorted silica sand with trace of rutile. Watertable at 1.7 m
NKU 35	0.0	0.3	0.3	Yellow clay

SOURCE: after Monks (1993)

Table 41. Results of heavy-liquid separation — Lake Don

Hole	*Dry weight of attritioned sample (g)*	*Slime (%)*	*Weight used for heavy liquid (TBE) separation (g)*	*Weight of sink material (g)*	*Weight of float material (g)*	*Weight % of float material*
NKU 1	1265.0	2.7	317.9	2.2	315.7	99.3
NKU 2	1247.9	4.0	311.5	1.1	310.4	99.6
NKU 3	1269.8	2.3	320.6	1.4	319.2	99.6
NKU 5	1277.5	1.7	319.7	1.5	318.2	99.5
NKU 9	1228.7	5.5	288.3	3.1	285.2	98.9
NKU 11	1278.6	1.6	322.2	1.4	320.8	99.6
NKU 12	1278.8	1.6	318.4	1.7	316.7	99.5
NKU 13	1278.7	1.8	322.2	1.4	320.8	99.6
NKU 16	1280.7	1.6	319.7	1.6	318.1	99.5
NKU 19	1280.7	1.5	319.9	1.6	318.3	99.5
NKU 20	1273.3	2.0	323.3	1.7	321.6	99.5
NKU 21	1277.5	1.7	320.0	1.0	319.0	99.7
NKU 26	1260.7	3.0	315.9	2.3	313.6	99.3
NKU 27	1264.3	2.7	317.1	1.4	315.7	99.6
NKU 28	1261.0	3.0	318.7	1.5	317.2	99.5
NKU 29	1259.0	3.2	313.8	1.1	312.7	99.6
NKU 30	1250.9	3.8	321.2	1.3	319.9	99.6
NKU 31	1272.5	2.1	320.0	2.1	317.9	99.3
NKU 32	1268.2	2.4	307.1	1.2	305.9	99.6
NKU 33	1273.2	2.1	323.2	1.4	321.8	99.6
NKU 34	1262.5	2.9	315.9	1.2	314.7	99.6

SOURCE: after Monks (1993)

Table 42. Chemical analyses of float sand from heavy-liquid separation — Lake Don

	NKU 1	*NKU 2*	*NKU 3*	*NKU 5*	*NKU 9*	*NKU 11*	*NKU 12*	*NKU 13*	*NKU 16*	*NKU 19*	*NKU 20*
						Percentage					
SiO_2	99.55	99.71	99.68	99.79	99.07	99.71	99.75	99.74	99.64	99.74	99.75
$A1_2O_3$	0.038	0.035	0.032	0.030	0.373	0.033	0.030	0.034	0.071	0.031	0.041
Fe_2O_3	0.018	0.010	0.012	0.010	0.037	0.011	0.010	0.012	0.013	0.019	0.011
TiO2	0.301	0.150	0.180	0.083	0.191	0.168	0.122	0.123	0.153	0.117	0.109
CaO	0.008	0.006	0.006	0.005	0.007	0.007	0.004	0.004	0.004	0.004	0.004
MgO	0.003	0.003	0.003	0.003	0.003	0.004	0.003	0.003	0.003	0.004	0.003
Na_2O	0.006	0.006	0.007	0.006	0.013	0.006	0.005	0.005	0.006	0.006	0.005
K_2O	0.002	0.002	<0.001	0.002	0.162	0.002	<0.001	0.002	<0.001	0.003	0.007
Cr_2O_3	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
NiO	<1	<1	<1	<1	<1	1	<1	1	<1	<1	<1
LOI	0.07	0.08	0.06	0.07	0.14	0.08	0.07	0.07	0.11	0.08	0.07
Total	**100.00**	**100.00**	**99.98**	**100.00**	**100.00**	**101.02**	**99.99**	**100.99**	**100.00**	**100.00**	**100.00**

	NKU 21	*NKU 26*	*NKU 27*	*NKU 28*	*NKU 29*	*NKU 30*	*NKU 31*	*NKU 32*	*NKU 33*	*NKU 34*
					Percentage					
SiO_2	99.68	99.56	99.56	99.68	99.72	99.6	99.64	99.65	99.8	99.8
$A1_2O$	0.048	0.031	0.028	0.028	0.028	0.031	0.036	0.016	0.011	0.008
Fe_2O_3	0.014	0.012	0.009	0.01	0.012	0.011	0.023	0.016	0.011	0.008
TiO2	0.154	0.300	0.308	0.193	0.168	0.264	0.19	0.213	0.081	0.052
CaO	0.006	0.005	0.003	0.003	0.005	0.004	0.003	0.004	0.004	0.006
MgO	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.003	0.003	0.003
Na_2O	0.006	0.004	0.005	0.005	0.006	0.005	0.005	0.005	0.005	0.005
K_2O	0.007	0.002	0.002	0.002	0.002	<0.001	0.002	0.002	0.005	<0.001
Cr_2O_3	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
NiO	<1	<1	1	1	1	1	<1	<1	<1	<1
LOI	0.08	0.08	0.08	0.07	0.06	0.08	0 09	0.07	0.06	0.10
Total	**100.00**	**100.00**	**101.00**	**100.99**	**101.00**	**101.00**	**99.90**	**99.98**	**99.98**	**99.88**

SOURCE: after Monks (1993)

PBA477

Figure 48. Northern pitwall of silica sand quarry at Lake Kokokup (location of sample GSWA164540)

PBA478

Figure 49. Southern pitwall of silica sand quarry at Lake Kokokup

Table 43. Size analyses (µm) of silica sand from Lake Don

Hole	*NKU 1*	*NKU 2*	*NKU 3*	*NKU 5*	*NKU 9*	*NKU 11*	*NKU 12*	*NKU 13*	*NKU 16*	*NKU 19*	*NKU 20*
						Percentage					
>1180	1.1	7.7	0.6	0.3	4.5	0.6	0.3	0.3	0.2	0.5	0.5
850–1180	3.7	8.3	3.2	1.1	1.7	2.6	2.6	2.0	0.6	2.1	2.8
600–850	7.0	7.9	5.1	3.3	2.7	6.9	8.8	7.5	1.6	5.7	8.0
425–600	9.2	6.0	8.0	6.1	4.5	11.6	11.8	10.7	4.0	10.8	10.8
300–425	13.0	8.2	14.2	11.7	8.9	20.9	17.5	15.1	11.2	17.9	12.6
212–300	9.0	6.2	13.9	11.7	9.8	16.9	14.6	10.6	12.9	13.3	8.6
150–212	10.5	9.1	16.5	16.9	14.5	12.4	13.3	10.1	17.0	12.3	10.6
106–150	14.9	14.4	17.2	32.1	30.3	13.4	17.2	24.8	26.1	20.9	25.4
75–106	22.6	23.6	14.4	13.2	16.6	10.4	9.8	14.3	19.8	11.6	15.4
53–75	8.0	7.2	5.8	3.2	5.5	3.8	3.5	4.0	5.6	4.1	4.5
<53	1.1	1.4	1.1	0.4	1.0	0.5	0.6	0.8	0.9	0.8	0.9
Total	**100.1**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.2**	**99.9**	**99.9**	**100.1**

Hole	*NKU 21*	*NKU 26*	*NKU 27*	*NKU 28*	*NKU 29*	*NKU 30*	*NKU 31*	*NKU 32*	*NKU 33*	*NKU 34*
					Percentage					
>1180	0.4	4.8	1.5	1.0	2.7	7.6	1.1	0.4	0.6	0.1
850–1180	2.0	4.7	7.0	6.4	6.3	8.9	1.2	1.9	0.7	0.2
600–850	5.2	6.1	9.5	9.5	8.6	7.5	2.0	4.0	1.7	0.5
425–600	7.0	7.1	9.5	10.2	10.4	7.0	3.7	6.0	3.6	1.3
300–425	10.2	11.6	13.6	14.2	13.5	10.0	8.6	11.7	10.7	6.0
212–300	9.2	8.7	9.2	9.6	8.6	7.5	8.9	11.1	14.2	11.4
150–212	13.1	10.6	10.5	11.2	8.6	9.4	12.7	12.7	17.7	29.7
106–150	31.5	17.2	15.5	15.1	13.0	15.3	33.7	25.3	30.0	34.4
75–106	16.1	22.3	17.4	15.6	20.3	19.2	21.8	19.4	14.9	11.9
53–75	4.4	5.9	5.3	5.9	6.9	6.4	5.5	6.5	5.2	3.9
<53	0.7	1.1	1.0	1.2	1.0	1.1	0.8	1.0	0.6	0.6
Total	**99.8**	**100.1**	**100.0**	**99.9**	**99.9**	**99.9**	**100.0**	**100.0**	**99.9**	**100.0**

SOURCE: after Monks (1993)

Table 44. Chemical analyses of particle-size fractions of sample NKU 31 — Lake Don

Grain size (µm)	*Wt% retained*	*Fe_2O_3*	*TiO_2*	*Al_2O_3*
			Percentage	
>1180	0.0	0.000	0.000	0.000
850–1180	0.0	0.000	0.000	0.000
600–850	4.3	0.020	0.083	0.103
425–600	3.7	0.025	0.094	0.182
300–425	8.6	0.011	0.074	0.038
212–300	8.9	0.013	0.058	0.027
150–212	12.7	0.010	0.044	0.026
106–150	33.7	0.011	0.040	0.027
75–106	21.8	0.031	0.130	0.054
<75	6.3	0.180	0.620	0.138

SOURCE: after Monks (1993)

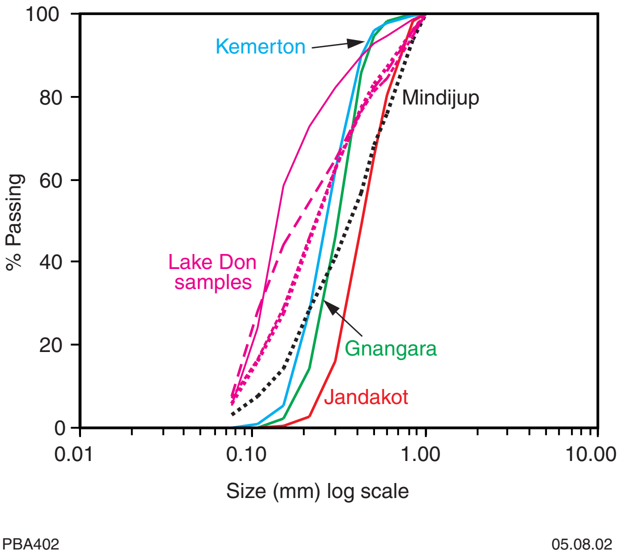

Figure 50. Particle-size distribution of silica sand from Lake Don and operating silica sand mines in Western Australia

is white, fine grained, and about 2 m thick. At a depth of 2 m there is a hard brown layer, similar to the coffee rock found in Bassendean Sand. A sample (GSWA164554) from this location assayed 98.7% SiO_2, 0.07% Al_2O_3, 0.04% Fe_2O_3, and 0.40% TiO_2, indicating silica sand of moderate quality (Table 32). The size analysis of this sample indicates 1.08% coarser than 850 µm, and 94.27% less than 425 µm, of which 86.28% lies within the range 75–425 µm (Table 33).

Occurrences

Redmond West Road

A Tertiary to Quaternary sand unit is widespread around Redmond West Road (Fig. 47), but is generally covered with thick vegetation and often buried under a grey to dark organic-rich sandy layer. However, in places the sand is exposed as white, fine sand on both sides of the road and is often more than one metre deep. Chemical analyses of two raw samples (GSWA164552–53) of white, fine-grained, angular to subrounded silica sand, approximately 7 km apart along Redmond West Road, assayed 99.40–99.80% SiO_2, 0.03–0.06% Al_2O_3, 0.02–0.03% Fe_2O_3 and 0.36–0.38% TiO_2, indicating a moderately high grade sand (Table 32). Size analysis indicates that both samples are generally fine grained, although sample GSWA164552 is coarser, with 59.44% in the <212 µm fraction compared with 92.45% for the other sample. Sample GSWA164552 had 0.91% in the >850 µm fraction and 89.14% in the <425 µm fraction compared with 0.31% and 94.27% respectively for sample GSWA164553 (Table 33). Both chemical and size analyses of the samples suggest that the sand could possibly be upgraded to various high-grade applications such as those in glass manufacture. In the absence of drilling data, it is not possible to comment on the resources available.

Manypeaks

Tertiary to Quaternary sand, similar to that found at the Mindijup mine, is exposed in a number of localities east of Manypeaks (Fig. 41). The sand is exposed on small hillocks, small ridges, and paddocks, on both sides of the highway. The sand in all these localities is probably reworked, being fine-grained and angular to rounded. The colour on the surface is generally white, but at shallow depth in some of these localities may alternate with yellowish-brown sand horizons. For example, sand exposed at the south side of the road on a gentle slope, approximately 1 km east of Manypeaks township, shows alternating yellow-brown and white sand layers of about 0.5 m thickness. Chemical analysis of a composite raw sample (GSWA164556) of this fine, white and yellow-brown sand assayed 98.40% SiO_2, 0.52% Al_2O_3, 0.15% Fe_2O_3, and 0.25% TiO_2 (Table 32). Approximately 0.5 km northeast of the location of sample GSWA164556, on the northern side of the Hassell Highway (Fig. 41), white sand is exposed on a gentle slope near a creek. The sand continues to outcrop on a low hill on the other side of the creek. Chemical analysis of a raw sample (GSWA164557) from this location had 99.30% SiO_2, 0.04% Al_2O_3, 0.01% Fe_2O_3 and 0.19% TiO_2, indicating moderately high quality silica sand (Table 32). Size analyses of the samples indicate that the sand in this area is generally fine grained, but sample GSWA164556 is slightly finer grained than GSWA164557 (Table 33). For example, sample GSWA164556 had 0.64% above 850 µm and 90.04% less than 425 µm, compared with 1.33% and 81.88% in the respective fractions for sample GSWA164557.

Walpole – Lake Muir region

There are a number of Tertiary and Quaternary units in the Walpole – Lake Muir area that are prospective for white quartz or silica sand deposits (Fig. 38).

Tertiary, white colluvial sands are abundant, particularly in the southeastern part of the area (Fig. 38). In this area, these deposits tend to form sinuous ribbons that vary in height and have a hummocky surface. Northwards from Lake Muir, most high-grade Tertiary sands appear as broad tracts of alluvium commonly traversed by dunes and variously reworked by existing drainage channels (Wilde and Walker, 1984b).

Associated with lateritic rocks and Tertiary sedimentary rocks, variously coloured (yellow, white, grey or orange) Tertiary quartz sand units are found in a number of localities in the area (Fig. 38). These sands are generally found overlying laterite, and are related to ancient drainage courses. They have undergone some eolian modification and may grade downslope into colluvial sand or alluvium (Wilde and Walker, 1984b).

Associated with the Tertiary drainage systems there are deposits of Quaternary and Tertiary quartz sand in a number of localities in the area (Fig. 38). The area east of Lake Muir is prominent for such sandy deposits.

Sand has been extracted, probably for local uses, from sandy formations near Walpole, Nornalup, and around Lake Muir (Fig. 38) (Wilde and Walker, 1984b).

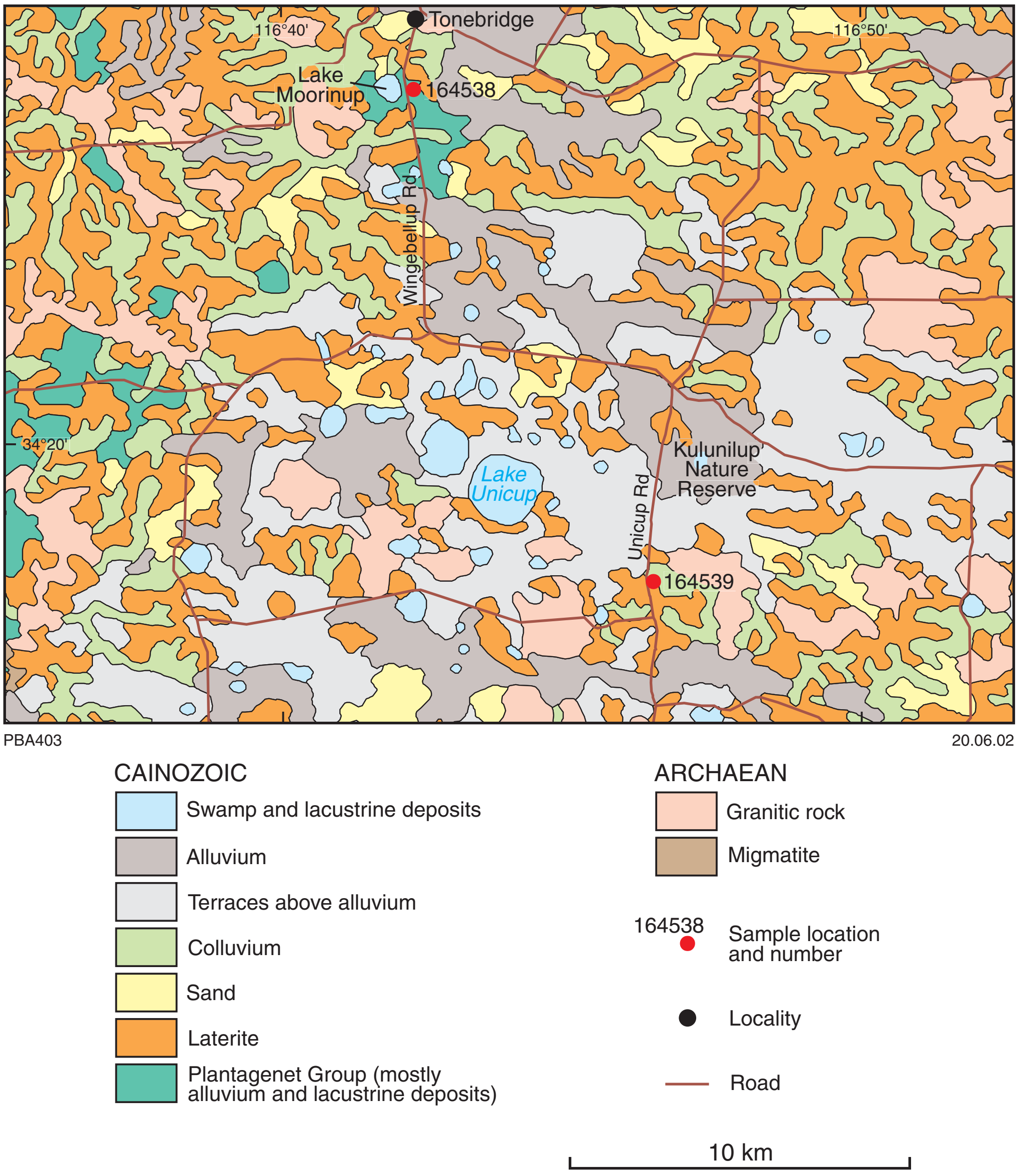

Figure 51. Geology south of Tonebridge and around Unicup Road (after Wilde and Walker, 1984a)

Occurrences

Following are descriptions of samples collected by the author from sand formations exposed at Tonebridge and Unicup Road (Fig. 51).

Tonebridge

White to off-white, medium-grained sand is exposed at the east side of Lake Moorinup, close to the road from Tonebridge to Wingebellup (Fig. 51). The white sand, possibly Tertiary, is found to be about 0.5–1.0 m from the surface and below this the sand is yellow-brown. The surface extent of the sand appears to be significant. A sample (GSWA164538) assayed 98.90% SiO_2, <0.25% Al_2O_3, 0.16% Fe_2O_3 and 0.24% TiO_2, indicating moderately high grade quartz sand (Table 45). Particle-size analysis indicates that about 60% of the sample lies between 106 and 425 µm (Table 46).

Unicup Road

Approximately 2 km south of Kulunilup Nature Reserve, white sand is exposed on both sides of Unicup Road (Fig. 51). This sand is probably Tertiary quartz sand similar to that at Tonebridge. It is white, fine grained, has a vertical thickness of about 2.5 m, and extends to about 100 m along the side of the road. A sample (GSWA164539) assayed 99.30% SiO_2, <0.02% Al_2O_3, 0.08% Fe_2O_3 and 0.31% TiO_2, indicating moderately high grade quartz sand (Table 45). Particle-size analysis shows that more than 75% of the sample lies between 75 and 425 µm (Table 46).

Bremer Bay region

In the Bremer Bay area, a Tertiary to Quaternary sandsheet forms extensive interfluvial plains, which extend inland

Table 45. Chemical analyses of sand from Tonebridge and Unicup Road

GSWA no.	*164538*	*164539*
	Percentage	
SiO_2	98.90	99.30
Al_2O_3	0.25	0.02
Fe_2O_3	0.16	0.08
MgO	<0.01	<0.01
CaO	0.01	<0.01
Na_2O	<0.01	<0.01
K_2O	0.08	0.02
TiO_2	0.24	0.31
MnO	0.01	0.01
P_2O_5	0.014	0.006
BaO	<0.01	<0.01
SO_3	<0.01	<0.01
LOI	0.26	0.12
Total	**99.92**	**99.87**
H_2O	3.18	3.22

more than 50 km from the coast (Thom and Chin, 1984). Sand in these units is yellow to white, commonly clayey, and contains scattered limonite nodules derived from underlying gravel and laterite (Fig. 39). The existing sandplain was probably formed during the late Cainozoic by several eolian reworking and transportation of coastal sands.

There are no known deposits of high-grade silica sand in the area. However, palaeodrainage systems and other ancient valleys or topographic depressions, particularly in the southern belt extending from northeast to southwest in the area, are potential targets for silica sand deposits.

There are vast areas of Tertiary to Quaternary sandplain on each side of the Hassell Highway, but white sands similar to those in the Albany region are rare. In general, the lack of white sand suggests that most of the sandplain consists of material that has not been sufficiently leached or reworked, and the yellowish colour in the sand is likely to be due to iron oxide staining by ferruginous material derived from the underlying laterite.

Occurrence

Wellstead

The only information available on the quality of this sand comes from a sample (GSWA164558) collected by the author approximately 2 km northeast of Wellstead (Fig. 52). The sand on the surface is off-white and fine grained, but within a few centimetres the colour changes to yellow-brown. Chemical analysis of the raw sample indicated 99% SiO_2, 0.36% Al_2O_3, 0.08% Fe_2O_3 and 0.20% TiO_2, indicating moderately high grade sand (Table 32). Size analysis indicates that the sand is very fine, with 90.04% of the sample below 300 µm and only 0.12% above 850 µm (Table 33).

Esperance area

Sand-rich units are distinguished in a number of Quaternary formations in the Esperance area. The more important of these, as sources of quartz, are Pleistocene or younger dune sand (*Qps*) and coastal dune sand (*Qrd*) (Fig. 40).

Dune sand (*Qps*) is white, leached, and fine grained. The unit is extensively exposed in the region north of Condingup forming west-northwesterly trending, rounded dunes. Dune sand (*Qps*), along with sandplain deposits (*Qpp₁*), occupies the central plateau (75–120 m AHD) of the southern half of the area (Fig. 40). Sandplain deposits (*Qpp₁*) consist of grey sand, overlying lateritic pisolites and yellow clay. Agriculturists refer to these deposits as ‘Esperance Sand Plain’ (Morgan and Peers, 1973). The thickness of sand in this unit varies from a few centimetres to a few metres, and the sand has been considerably re-sorted by wind action.

Pleistocene or younger coastal dune sand (*Qrd*) is a relatively narrow unit and consists of white, fine- to medium-grained sand. The dunes on the coastal hills are rounded, whereas those on the coastal plain are elongated. Following are descriptions of samples collected from the above sand units at various locations.

Occurrences

Merivale

There are vast areas of Pleistocene or younger white, rounded, fine-grained coastal dune sand (*Qrd*) exposures in the area south and east of Merivale. The sand forms a series of sand dunes, many of which have approximate east–west to west-northwesterly trends. Road cuttings along Stock Yard Road, Cape Le Grand Road, and Dunn Rock Road display similar vertical sections of the sand dunes (Fig. 53). These vertical sections have alternating white and yellowish sand, of variable thickness, capped by a thin layer (generally not more than a few centimetres) of grey to dark grey organic-rich sandy soil. The thickness of these alternating white and yellow horizons can vary from a few centimetres to a few metres.

Table 46. Size analyses (µm) of sand from Tonebridge and Unicup Road

GSWA no.	*164538*	*164539*
	Percentage	
>850	5.59	2.22
600–850	13.54	6.42
500–600	3.83	3.07
425–500	7.36	4.19
300–425	19.68	12.49
212–300	21.73	16.76
150–212	13.82	19.44
106–150	7.82	21.36
75–106	4.39	11.97
<75	2.23	2.07

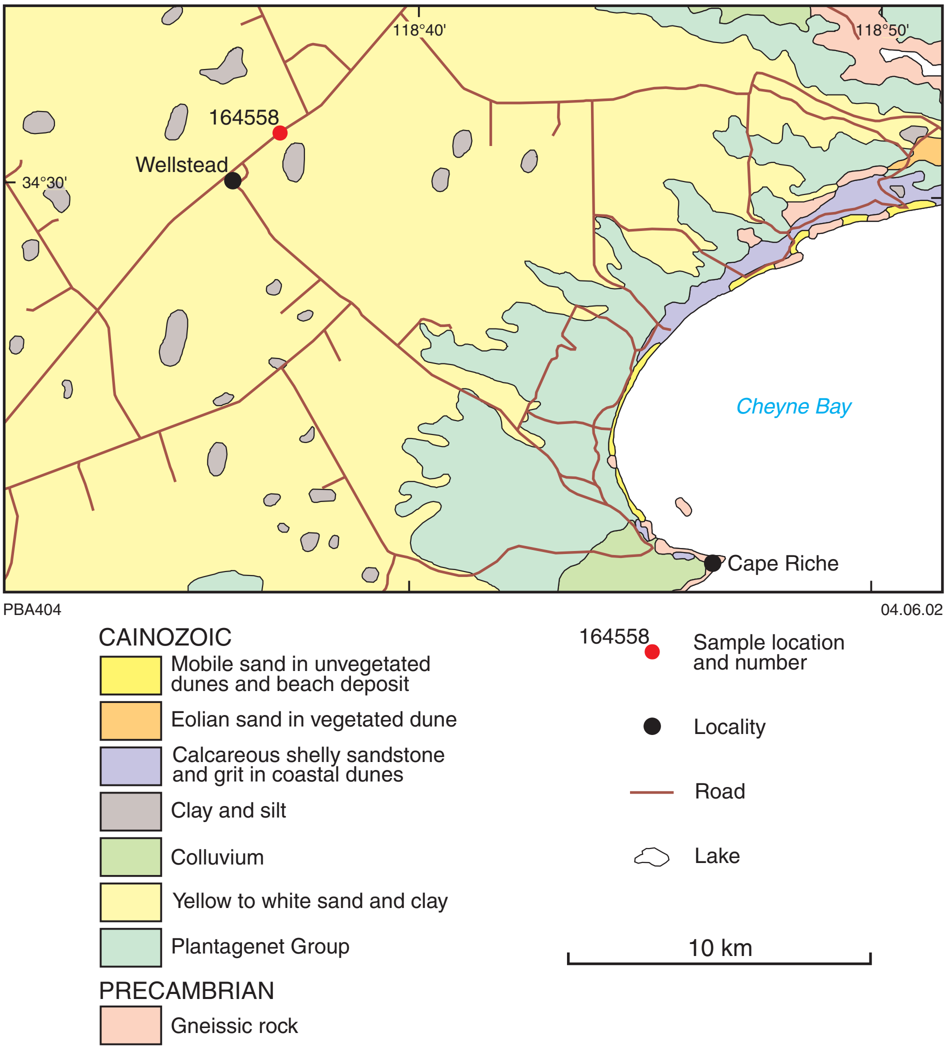

Figure 52. Geology around Wellstead (after Thom and Chin, 1984)

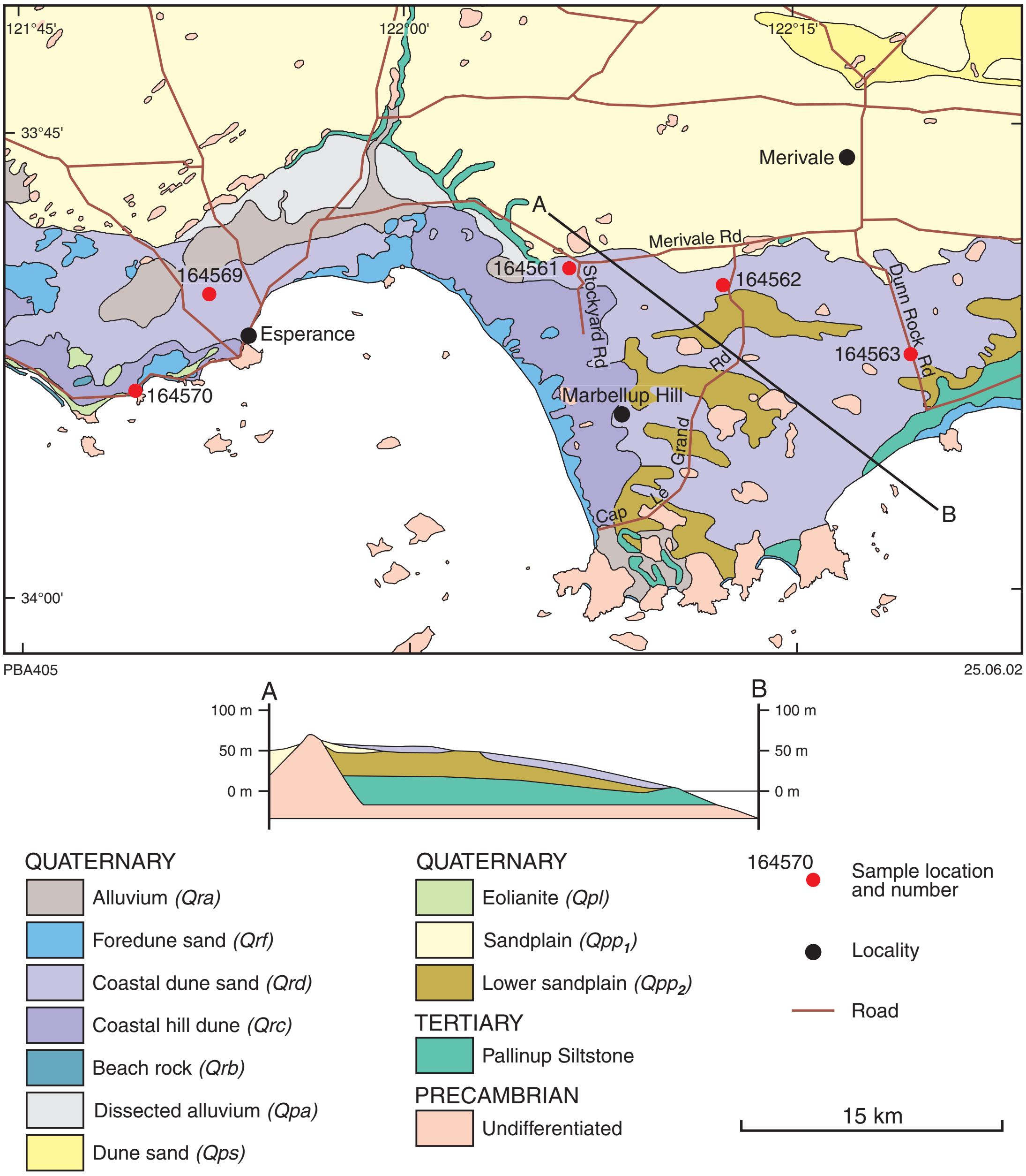

Figure 53. Geology around Esperance and Merivale (after Morgan, 1972)

Table 47. Chemical analyses of silica sand from the Esperance region

GSWA no.	*164559*	*164560*	*164561*	*164562*	*164563*	*164564*	*164565*	*164566*	*164567*	*164568*	*164569*	*164570*
						Percentage						
SiO_2	95.80	99.10	98.90	98.30	98.70	98.30	98.70	98.80	98.80	99.50	64.10	53.10
Al_2O_3	1.62	0.18	0.44	0.71	0.43	0.55	0.47	0.44	0.33	0.14	2.16	1.98
Fe_2O_3	0.43	0.04	0.07	0.08	0.03	0.21	0.09	0.13	0.10	0.04	0.20	0.37
MgO	0.16	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.86	1.59
CaO	0.39	0.01	0.03	0.04	0.04	0.01	0.01	0.02	0.01	0.01	16.90	22.30
Na_2O	0.29	0.01	0.07	0.09	0.07	0.01	0.01	0.03	<0.01	<0.01	0.52	0.53
K_2O	0.44	0.03	0.17	0.20	0.18	0.04	0.04	0.14	0.02	0.02	0.60	0.54
TiO_2	0.18	0.32	0.17	0.11	0.12	0.16	0.16	0.13	0.23	0.19	0.06	0.17
MnO	0.01	0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01
P_2O_5	0.015	0.011	0.009	0.01	0.004	0.01	0.008	0.006	0.011	0.015	0.037	0.052
BaO	0.01	<0.01	0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.02
SO_3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.10	0.18
LOI	0.56	0.23	0.21	0.27	0.27	0.56	0.34	0.16	0.32	0.15	14.30	19.00
Total	**99.91**	**99.94**	**100.08**	**99.83**	**99.85**	**99.85**	**99.83**	**99.86**	**99.83**	**100.08**	**99.86**	**99.83**
H_2O	5.28	14.82	4.22	4.11	13.30	3.89	6.05	3.17	3.98	4.14	3.41	4.69

NOTE: 164559: Stokes Inlet
164560: Dalyup
164561–62: Merivale
164563: Dunn Rock Road
164564: Alexander Bay
164565–68: Condingup
164568–70: Esperance

Dune sand is fairly well exposed along Stock Yard Road for a distance of about 2.5 km. At sample location GSWA164561 (Fig. 53), the vertical profile has about 20 cm of dark grey, organic-rich sandy overburden. This organic-rich layer is underlain by 0.75 m of white, fine-grained sand, which continues at depth as a yellowish sand. Sample GSWA164561, a composite of white and yellowish sand, assayed 98.90% SiO_2, 0.44% Al_2O_3, 0.07% Fe_2O_3 and 0.17% TiO_2 (Table 47), indicating moderately high quality sand. Size analysis indicates that this sand is fine grained, with only 0.7% above 850 µm and 90.39% below 425 µm (Table 48).

At a road cutting near sample location GSWA164562 (Fig. 53) on Cape Le Grand Road, dune sand (*Qrd*) is found on an east-northeasterly elongated dune. The organic-rich overburden at this location is about 10–15 cm thick, and below this is about 1 m of white, fine-grained sand followed by more than 3 m of yellow-brown, fine-grained sand. Sample GSWA164562 is a composite of white and yellow-brown sand and shows a composition similar to that from Stock Yard Road in having 98.30% SiO_2, 0.71% Al_2O_3, 0.08% Fe_2O_3, and 0.11% TiO_2 (Table 47). Sample GSWA164562 is fine, having only 0.04% above 850 µm and 98.41% below 425 µm (Table 47).

The vertical section of another dune sand (*Qrd*) exposure, at Dunn Rock Road near sample GSWA164563 (Fig. 53), has about 20 cm of organic-rich overburden followed by more than 1 m of white, fine-grained sand. The sand is likely to be a continuation of the

Table 48. Size analyses (µm) of silica sand from the Esperance region

GSWA no.	*164559*	*164560*	*164561*	*164562*	*164563*	*164564*	*164565*	*164566*	*164567*	*164568*	*164569*	*164570*
						Percentage						
>850	5.83	0.34	0.70	0.04	1.49	1.27	0.61	0.78	0.09	0.27	0.03	0.02
600–850	2.11	2.91	3.07	0.33	5.10	0.62	2.06	1.16	0.13	0.69	0.28	0.02
500–600	1.63	1.25	2.14	0.35	1.59	0.39	0.60	0.77	0.03	0.36	0.63	0.02
425–500	3.68	0.92	3.70	0.87	3.43	0.88	1.20	0.88	0.08	0.68	1.25	0.08
300–425	21.94	3.91	12.55	7.29	12.91	7.33	8.39	4.75	1.07	3.61	9.32	1.20
212–300	39.20	12.09	21.29	24.94	22.48	28.35	25.79	16.58	8.87	13.47	34.68	12.35
150–212	22.35	31.14	32.53	42.45	32.36	40.61	32.50	30.20	41.09	31.78	45.95	54.98
106–150	2.96	31.94	17.39	21.47	15.56	16.39	18.98	30.27	34.72	30.20	7.66	30.17
75–106	0.18	11.96	3.32	1.62	2.53	2.96	7.89	12.77	12.42	15.02	0.17	1.11
<75	0.13	3.54	3.31	0.64	2.55	1.19	1.99	1.84	1.51	3.91	0.03	0.07

NOTE: 164559: Stokes Inlet
164560: Dalyup
164561–62: Merivale
164563: Dunn Rock Road
164564: Alexander Bay
164565–68: Condingup
164569–70: Esperance

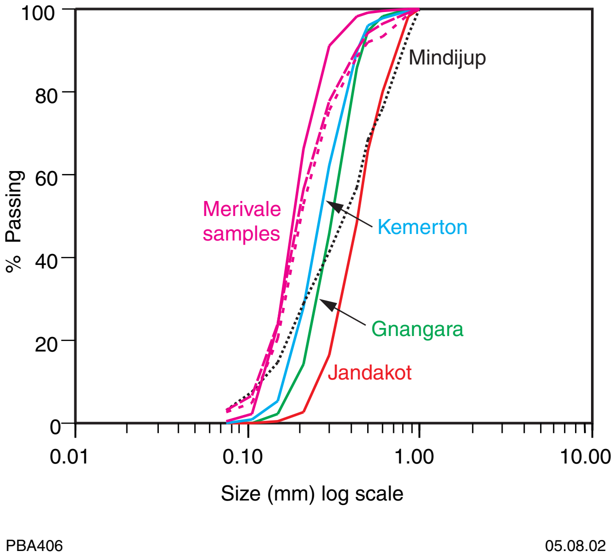

Figure 54. Particle-size distribution of sand from Merivale area and operating silica sand mines in Western Australia

same horizon at Cape Le Grand Road, near sample location GSWA164562. Sample GSWA164563 is a composite of 1 m of only white sand. However, analysis indicates 98.70% SiO_2, 0.43% Al_2O_3, 0.03% Fe_2O_3, and 0.12% TiO_2 (Table 47). Except for a very slightly lower percentage of Fe_2O_3, the other values are comparable with those of previous samples, which are composites of white and yellow or yellow-brown sand. Sample GSWA164562, however, is slightly coarser than the other two and has 1.49% above 850 µm and only 88.39% below 425 µm (Table 48), suggesting that brown sand horizons in the dune sand may be finer than the white horizons. On average, sand sampled from the Merivale area is finer than the sands from operating silica sand mines at Jandakot, Gnangara, Kemerton, and Mindijup (Fig. 54).

Esperance

Analyses of two samples (GSWA164569–70; Fig. 53) from white sand units in the coastal regions west of Esperance indicate that these sands are calcareous with CaO contents of 16.90% and 22.30% respectively (Table 47). Sample GSWA164569 is from a small sandpit (approximately 50 × 25 × 3 m) on the north side of the South Coast Highway and consists of white and fine-grained coastal dune sand (*Qrd*). The other sample (GSWA16970) is from fine- to medium-grained mobile coastal sand (*Qrf*) at the northern side of Oceanic Drive. Particle-size analysis indicates that sample GSWA16969 has 80.63% of sand within the 150–300 µm fraction compared with 67.33% for GSWA164570 (Table 48).

Marbellup Hill

During 1991–92, an area near Marbellup Hill, south of Merivale and about 23 km east of Esperance, was investigated by Kriston Pty Ltd for possible economic sources of glass-grade silica sand (Fig. 53). In this locality, silica sands form part of the dunes deposited on coastal hills (*Qrc*) and coastal dune sand (*Qrd*). The area was investigated by hand augering (depths ≤6 m), but details of the holes were not given. Chemical analyses of four samples from auger holes (sample locations not given) indicated 97.90–99.20% SiO_2, 0.400–1.150% Al_2O_3, 0.028–0.109% Fe_2O_3, 0.047–0.090% TiO_2, 0.030–0.115% CaO, and 0.123–0.400% K_2O. Some sand horizons in the deposit were considered to be of high quality (Menzel, 1993). However, the information available is insufficient to draw any positive conclusions on the quality and quantity of sand available.

Alexander Bay

A sand horizon consisting of alternating layers of white and yellow-brown fine sand is exposed along Alexander Road, close to Ocean View Farm Road, north of Alexander Bay (Fig. 40). The sand in this area has been mapped as a portion of the sandplain deposits (Qpp_1), which generally has a higher proportion of ferruginous and clayey material. A vertical profile at this location indicates at least 3 m of fine-grained sand, of which some 1.5 m is white, fine-grained sand from the surface, followed by about 1 m of yellow-brown, fine-grained sand. Yellow-brown sand then grades downwards to white, fine-grained sand, which continues to an undetermined depth. The chemical analysis of a raw sample (GSWA164564) of white, fine-grained sand assayed 98.30% SiO_2, 0.55% Al_2O_3, 0.21% Fe_2O_3 and 0.16% TiO_2, indicating slightly higher contents of Fe_2O_3 and TiO_2 than in samples from the coastal dune sand (*Qrd*) south of Merivale (Table 47). These higher values are likely to be due to contamination from ferruginous pisolitic material known to exist in the sandplain unit (Qpp_1). Size analysis indicates that the sand is fine grained and has 1.27% above 850 µm and 96.83% below 425 µm (Table 48), and is thus comparable with the sand in the coastal dune sand unit (*Qrd*).

Condingup

Eolian dune sand (*Qps*) is widely distributed in localities north and northwest of Condingup. The sand is found in an approximately 40 km long and 2–10 km wide belt (Fig. 55). The area has a very gentle undulating topography with west-northwesterly trending sand dunes, mostly seen as small ridges and hillocks. From examination of the road cuttings and other vertical profiles in the area, the thickness of the sand unit in the area appears to range from about one metre to more than 3 m. The sand layer is commonly covered with a thin (~10–15 cm) overburden of organic-rich grey sandy material. The sand is generally white, fine grained, and rounded. However, alternating thin layers (≤1 m) of yellowish-brown sand are not uncommon. The resource available is potentially large.

Chemical analyses of four raw samples (GSWA 164565–68) from dune sand (*Qps*), collected approximately 18 km apart, averaged 98.95% SiO_2, 0.35% Al_2O_3, 0.09% Fe_2O_3, and 0.18% TiO_2 (Table 47), comparable with those of samples from the coastal dune sand (*Qrd*) unit. Size analysis of the sample also has results comparable

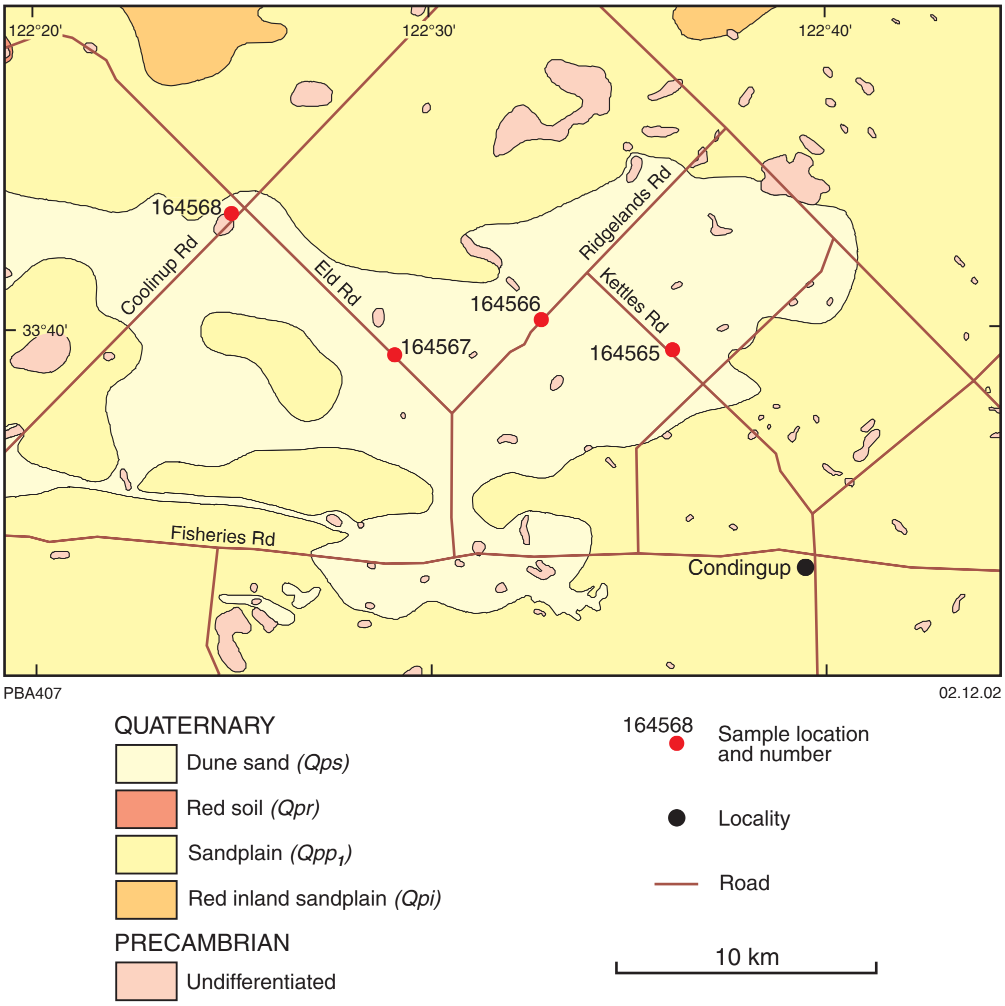

Figure 55. Geology around Condingup (after Morgan, 1972)

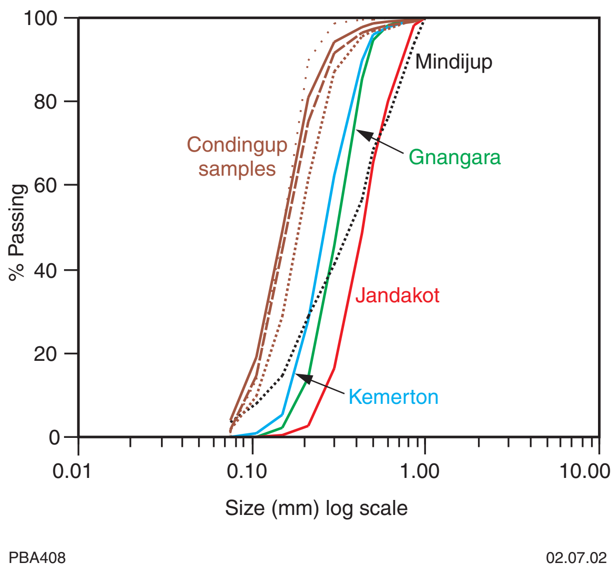

Figure 56. Particle-size distribution of sand from the Condingup area and operating silica sand mines in Western Australia

with coastal dune sand, averaging 0.44% above 850 µm and 97.41% below 425 µm (Table 48). The average size of sand from Condingup region is much finer than any of those from the operating silica sand mines of Western Australia (Fig. 56).

Sample GSWA164565 is a one-metre composite of white, to creamy yellowish fine-grained sand exposed at a low hill, close to a paddock, on the north side of Kettles Road (Fig. 55). The surface exposure of white sand extends for a distance of approximately 600 m along the fence line in a northwesterly direction. The sand bed is more than one metre thick and, at the paddock area, is covered with a thin (approximately 20 cm), light grey organic-rich overburden.

Sample GSWA164566 is a composite of one metre of thick white and slightly yellowish, fine-grained sand at a road cutting near Ridgelands Road (Fig. 55). Sand is exposed as a small ridge with alternating layers of white and slightly yellowish, fine-grained, rounded sand. The sand ridge, probably a relic sand dune, is about 75 m wide and is elongated in a west-northwesterly direction. The vertical thickness of the profile exceeds 3 m, with the top 10–15 cm consisting of plant material, below which is about one metre of fine-grained white sand followed by a layer of more than 2.5 m of white to yellowish sand.

Sample GSWA164567 is white to yellow-brown, fine-grained sand from a sand ridge at a road cutting on the north side of Eld Road. The sand profile is more than 3 m thick and comprises a top layer of about 1.5 m of white, fine sand, followed by about a metre of fine, yellowish-brown sand overlying a layer of more than half a metre of fine, white sand at the base.

Sample GSWA164568 is fine-grained, white sand from a horizon at the western side of the intersection of Coolinup and Eld Roads. The surface layer (10–15 cm) contains dark to grey organic-rich material followed by a layer (approximately 0.5 m) of fine, white sand. Below this is a thin layer (approximately 25 cm) of yellowish-brown sand followed by white sand of uncertain depth.

Dalyup

White, fine-grained sand is exposed approximately 9 km west of Dalyup, on the northern side of the South Coast Highway (Fig. 57). As seen from a farm dam, the sand horizon has a thickness of about 2.5 m. The surface extent of the sand horizon is not clear owing to the thick grass cover. A sample (GSWA164560) collected from the sand formation assayed 99.10% SiO_2, 0.18% Al_2O_3, 0.04% Fe_2O_3 and 0.32% TiO_2, indicating moderately high grade silica sand. Particle-size analysis of the sample shows that the sand is fine grained, with more than 90% below 300 µm (Tables 47 and 48).

Stokes Inlet

At Stokes Inlet, greyish white, fine-grained sand is found mixed with pockets of heavy minerals, particularly ilmenite. The sand is generally widespread near the coast of the inlet. Chemical analysis of a sample (GSWA164559) from the coast of the inlet (Fig. 57) confirms that the sand is not high grade, and has 95.80% SiO_2, 1.62% Al_2O_3, 0.43% Fe_2O_3, and 0.18% TiO_2 (Table 47). Particle-size analysis demonstrates that more than 83% of sand lies within the size fraction 150–425 µm (Table 48).

Yilgarn Craton

On the Yilgarn Craton, sandplains are widespread on the granite and gneissic rocks. These sandy horizons are relatively small, discontinuous, and contain sand of inferior quality compared with sand from the Phanerozoic sedimentary basins (e.g. Perth Basin). The sandplains on the Yilgarn Craton are closely associated with deeply weathered laterite profiles, and are generally underlain by laterite and ferruginous nodules. Sand is also found as colluvial reworked deposits associated with local drainages and also in palaeochannels as fluvial deposits.

Silica sand deposits, either currently or previously exploited, and other occurrences relatively close to potential domestic markets are located on the South West Terrane and Eastern Goldfields Granite–Greenstone Terrane.

South West Terrane

The South West Terrane is bounded by the Albany–Fraser Orogen to the south, the Southern Cross Granite–Greenstone Terrane to the east, the Murchison Granite–Greenstone Terrane to the north, and the Perth Basin to the west (Fig. 58).

The main geological units within the South West Terrane are granite and the Jimperding and Balingup Gneiss Complexes. Granite is the most widespread rock type and intrudes the Jimperding and Balingup Gneiss Complexes. The granitic rocks are partly recrystallized in the 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 metasedimentary rocks are mainly fuchsite-bearing quartzite, quartz–feldspar–biotite–garnet gneiss, andalusite and sillimanite schist, banded iron-formation (BIF), and minor calc-silicate rocks.

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

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

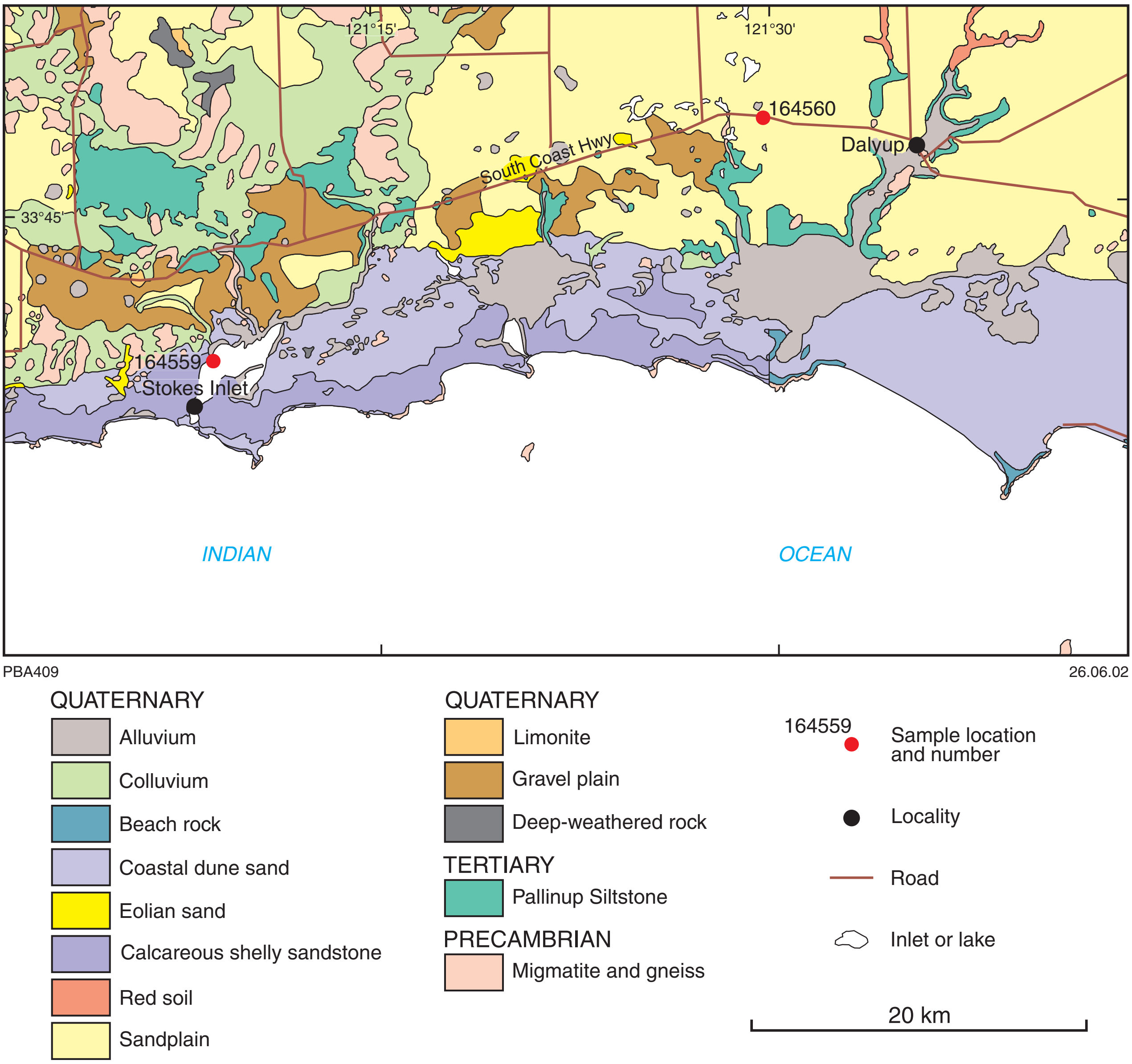

Figure 57. Geology around Stokes Inlet and Dalyup (after Morgan 1972; Thom and Lipple, 1974)

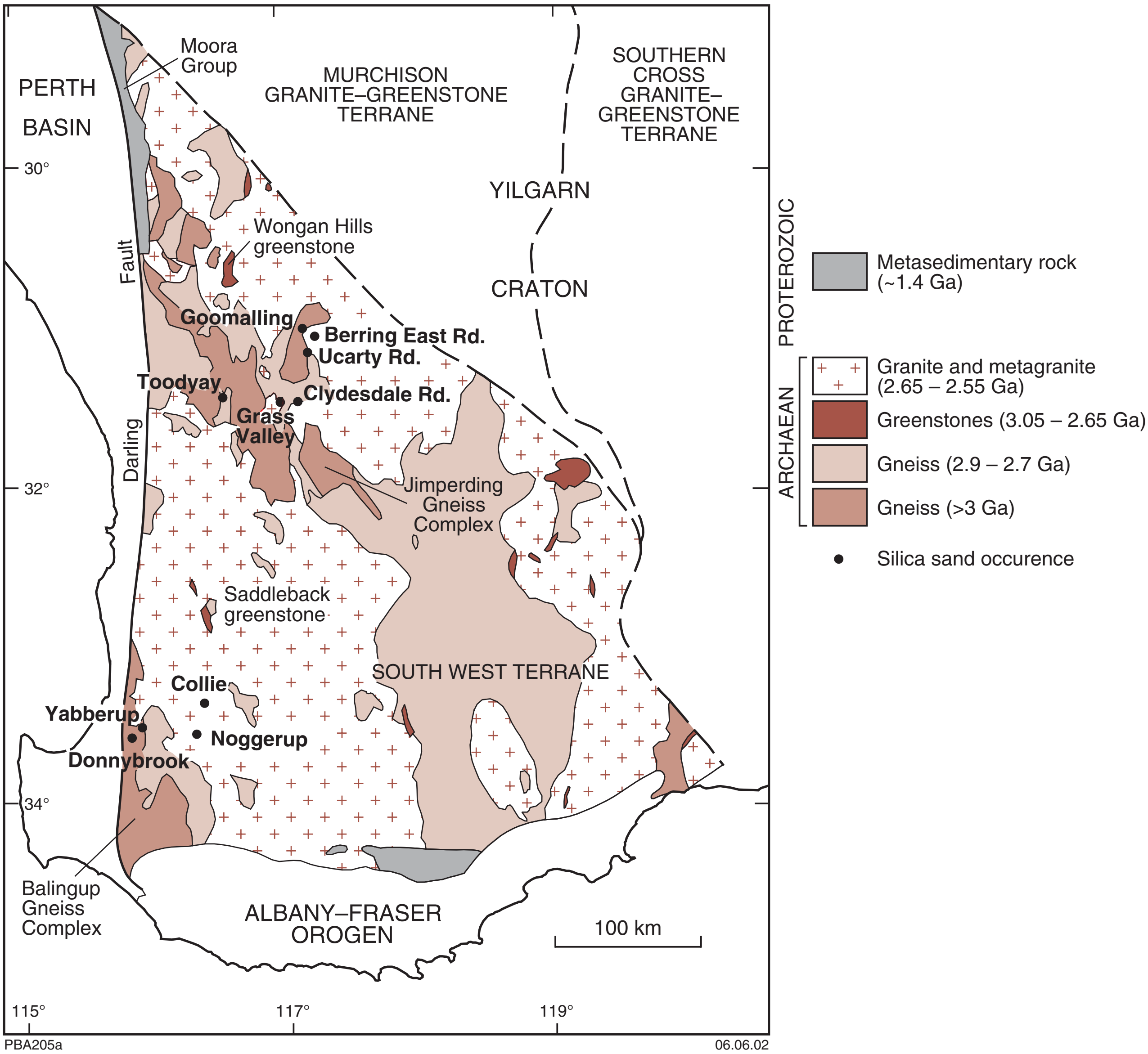

Figure 58. Regional geology of the South West Terrane, Yilgarn Craton (after Abeysinghe and Fetherston, 1999)

Sand formations in numerous localities on the South West Terrane indicate white to yellowish to grey eluvial sand overlying lateritic formations. Sand is also found as colluvial reworked deposits associated with local drainages and as fluvial deposits. Following are descriptions of sand occurrences in the South West Terrane.

Occurrences

Toodyay (Sandplain Road)

Approximately 6 km southwest of Toodyay, on the western side of Sandplain Road (Fig. 59), medium-grained, white sand has been mined, presumably for construction applications. The abandoned pit is about 100 m long, 75 m wide, and more than 1 m deep. The sand horizon appears to be fairly extensive, but the pit is filled with water and therefore the thickness of the profile cannot be ascertained. Chemical analysis of a raw sample (GSWA164580) indicates moderately high grade silica sand with 99.10% SiO_2, 0.22% Al_2O_3, 0.03% Fe_2O_3, and 0.22% TiO_2 (Table 49). More than 85% of the raw sand in sample GSWA164580 lies within the size range 150–850 µm (Table 50) and could be beneficiated for use in high-grade applications such as in the glass and foundry industries.

Grass Valley (Clydesdale Road)

Approximately 6 km east of Grass Valley (110 km east-northeast of Perth), on the south side of Clydesdale Road and a few tens of metres east of the turnoff to Moore Road (Fig. 60), brown to yellowish, medium-grained sand has been extracted, presumably for construction applications. The abandoned pit is approximately 100 m long, 75 m wide, and more than 2 m deep. The sand formation is fairly extensive and spreads outside the pit area. The chemical analysis of a raw sample (GSWA164582) indicates 98.10% SiO_2, 0.95% Al_2O_3, 0.19% Fe_2O_3 and 0.25% TiO_2, suggesting the presence of undesirable quantities of Al_2O_3, TiO_2, and Fe_2O_3 inimical to high-grade applications such as in the glass industry (Table 49). More than 85% of the raw sand (sample GSWA164582) is within the size range 150–850 µm (Table 50).

Goomalling (Ucarty Road)

Approximately 12 km southeast of Goomalling (130 km northeast of Perth), on the south side of Ucarty Road (Fig. 61), brownish to white medium-grained sand is found in a pit some 100 m long, 40 m wide, and over 3 m deep. The sand from the pit appears to be used locally, presumably for construction applications. The sand in the west side of the pit is whiter than that on the east side. The eastern pitwall indicates that the thickness of the sand bed extends at least 3 m from the surface to the watertable. Chemical analysis of a raw sample (GSWA164583) indicates 97.20% SiO_2, 1.34% Al_2O_3, 0.34% Fe_2O_3 and 0.23% TiO_2, suggesting the presence of undesirable quantities of Al_2O_3, TiO_2 and Fe_2O_3, which would preclude high-grade applications (Table 49). Sample GSWA164583 shows that more than 80% of raw sand is within the size range 150–850 µm (Table 50).

Goomalling (Berring East Road)

Approximately 8 km northeast of Goomalling, both sand and gravel are extracted from a small pit on the south side of Berring East Road (Fig. 61). The sand bed, which extends at least 3 m from the surface, overlies the gravel bed (>2 m thick). The sand is yellowish brown and medium grained and appears to be suitable for construction applications such as filling or concrete sand. Chemical analysis of a raw sample (GSWA164584) gives low SiO_2 (88.20%), high Al_2O_3 (6.92%), and high Fe_2O_3 (1.41%), which is unsuitable for high-grade applications such as those in the glass industry (Table 49). Sample (GSWA164584) has 12.89% exceeding 850 µm and 65.08% within the size range 150–850 µm (Table 50).

Collie area

In the Collie area, east of the Darling Fault, sand is found in Quaternary and Tertiary sediments. Three types of deposit are found in the region: sand deposits associated with older stream channels found as reworked material, sand overlying laterite, and locally lateritized sandy alluvium forming terraces near the Tertiary Nakina Formation. Ribbons of reworked sand associated with Tertiary drainage systems generally have a hummocky surface with considerable variation in sand thickness and commonly link-up separate areas of alluvium (Wilde and Walker, 1982).

The Quaternary and Tertiary sands in the areas east of Collie have been extracted for local uses (Fig. 62). These sands have higher proportions of coarse-grained material compared with those of Bassendean Sand in the Perth and Kemerton regions and also those in the Mindijup area. However, some samples (GSWA164519 and 164521–2, Fig. 63) have size ranges comparable with those of sands in the operating silica sand mines at Perth, Kemerton, and Mindijup. The chemical composition of the sand from some of these deposits around Collie indicates high silica percentages (>99%). As this sand has enhanced commercial potential, the following notes provide more detail on samples collected by the author in the Collie region.

Collie (Williams Road)

White, coarse-grained sand is found towards the end of Williams Road, a few kilometres northeast of Collie (Fig. 62). The sand is generally covered with a thin, dark, clayey sand layer (15–30 cm) containing organic material. Within about a metre from the top of the coarse sand, there is a relatively hard coffee-brown layer somewhat similar to the coffee rock seen in Bassendean Sand in the Perth Basin. Although, in the past, there has been extraction of sand from the locality, the area appears to now be rehabilitated and covered with thick vegetation. A raw sample (GSWA164516) from this locality indicates 99.00% SiO_2, 0.25% Al_2O_3, 0.09% Fe_2O_3, and 0.32% TiO_2 (Table 51). Size analysis of the raw sample (GSWA164516) demonstrates that the sand is coarse grained, with 34.33% exceeding 850 µm (Table 52). Both analyses indicate that the sand is unsuitable for high-grade applications such as in the glass industry, and the sand was probably mined for local construction.

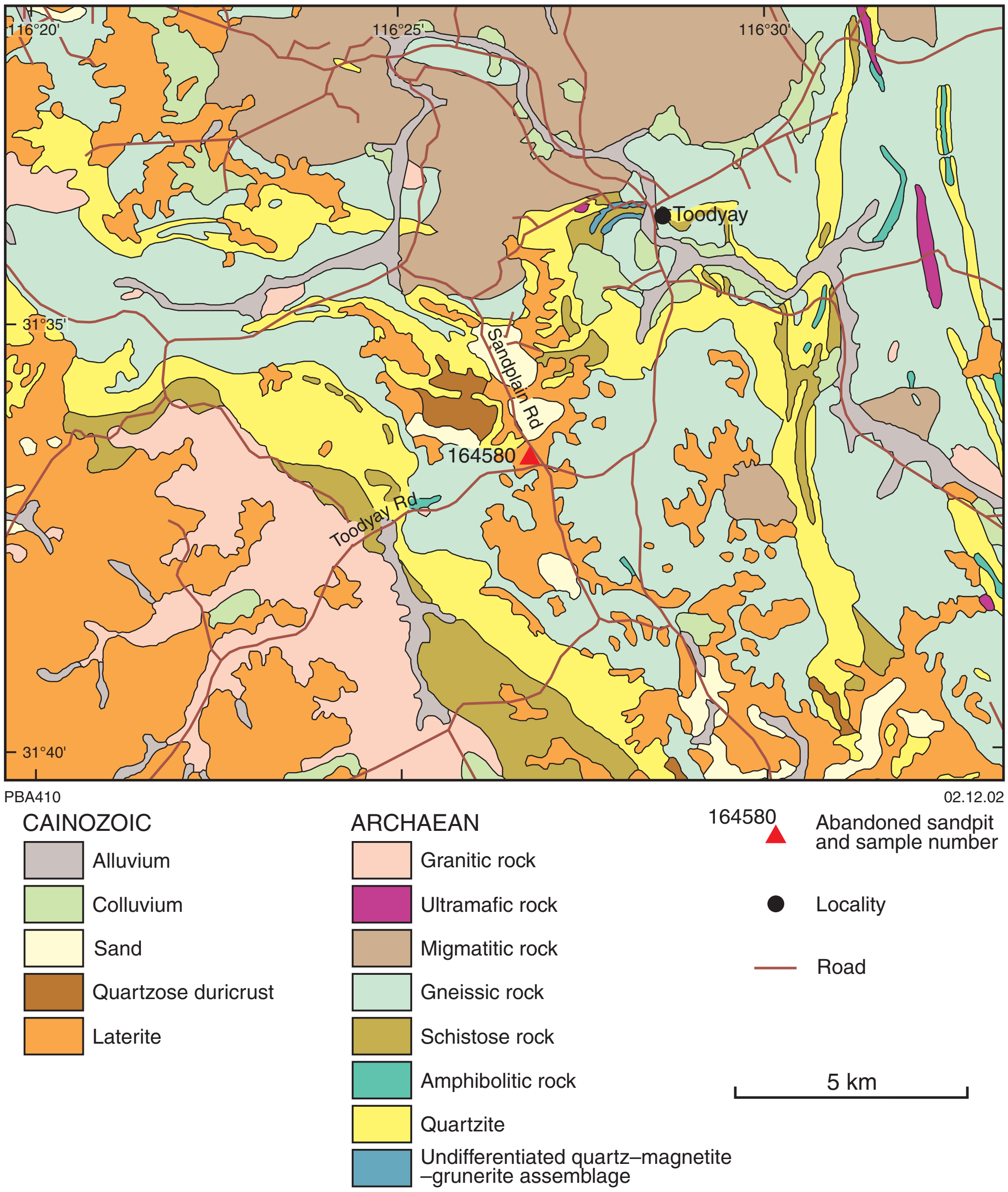

Figure 59. Geology around Toodyay (after Low et al., 1978)

Table 49. Chemical analyses of silica sand from the Toodyay, Grass Valley, and Goomalling regions

GSWA no.	*164580*	*164582*	*164583*	*164584*
		Percentage		
SiO_2	99.10	98.10	97.20	88.40
Al_2O_3	0.22	0.95	1.34	6.92
Fe_2O_3	0.03	0.19	0.34	1.41
MgO	<0.01	<0.01	0.01	0.04
CaO	0.01	0.01	0.01	0.02
Na_2O	0.02	0.02	0.03	0.01
K_2O	0.06	0.12	0.12	0.06
TiO_2	0.27	0.25	0.23	0.39
MnO	0.01	<0.01	<0.01	0.01
P_2O_5	0.009	0.015	0.012	0.02
BaO	<0.01	<0.01	<0.01	<0.01
SO_3	<0.01	<0.01	<0.01	<0.01
LOI	0.10	0.35	0.56	2.71
Total	**99.83**	**100.01**	**99.85**	**99.99**
H_2O	11.15	2.33	10.92	4.63

NOTE: 164580: Sandplain Road, Toodyay
164582: Clydesdale Road, Grass Valley
164583: Ucarty Road, Goomalling
164584: Berring East Road, Goomalling

Table 50. Size analyses (µm) of silica sand samples from the Toodyay, Grass Valley, and Goomalling regions

GSWA no.	*164580*	*164582*	*164583*	*164584*
		Percentage		
>850	7.19	4.59	9.85	12.89
600–850	17.84	13.71	12.27	8. 43
500–600	14.28	11.73	7.03	4.37
425–500	13.02	11.13	6.70	4.02
300–425	22.49	24.32	16.52	11.85
212–300	11.42	15.56	16.24	17.37
150–212	5.77	8.22	12.65	19.04
106–150	2.89	4.16	6.88	9.96
75–106	1.81	2.87	4.95	6.10
<75	3.29	3.70	6.91	5.97

NOTE: 164580: Sandplain Road, Toodyay
164582: Clydesdale Road, Grass Valley
164583: Ucarty Road, Goomalling
164584: Berring East Road, Goomalling

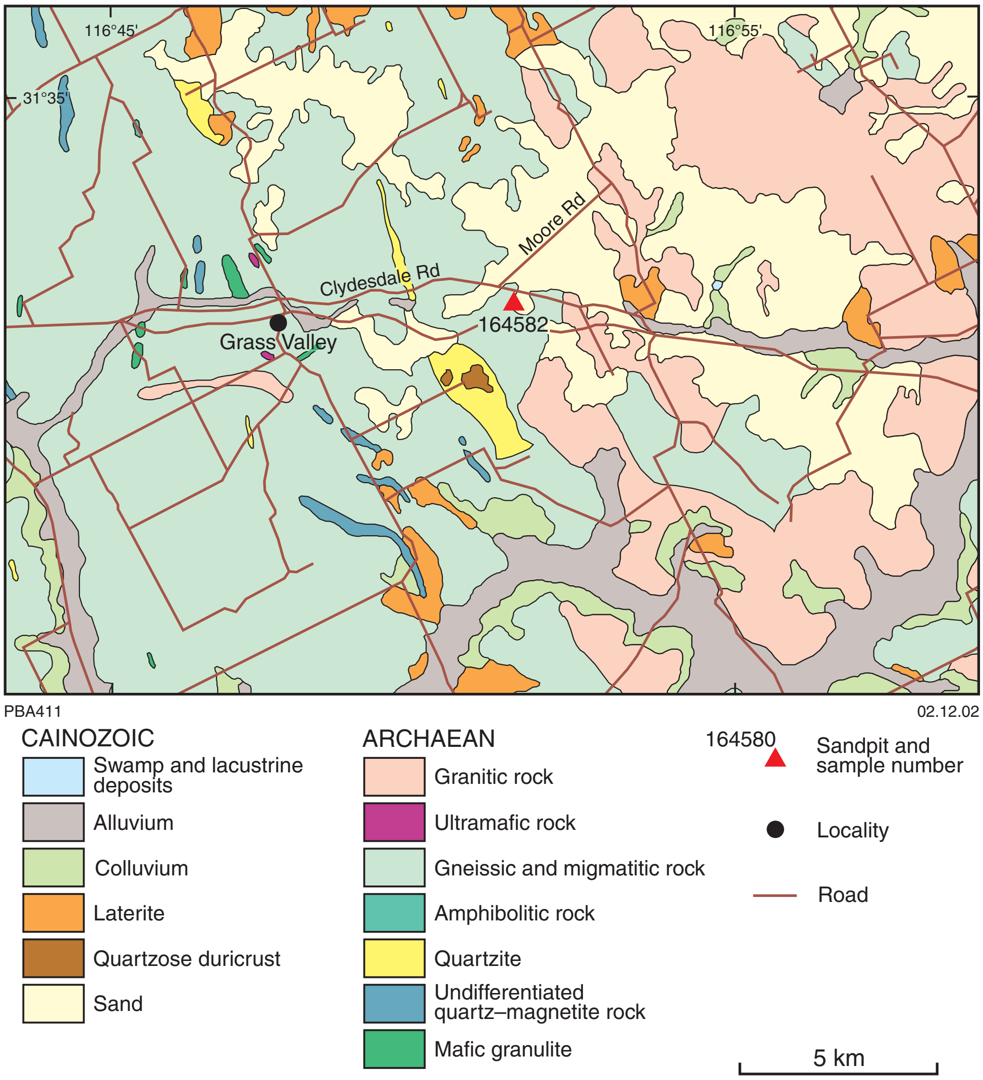

Figure 60. Geology around Grass Valley (after Low et al., 1978)

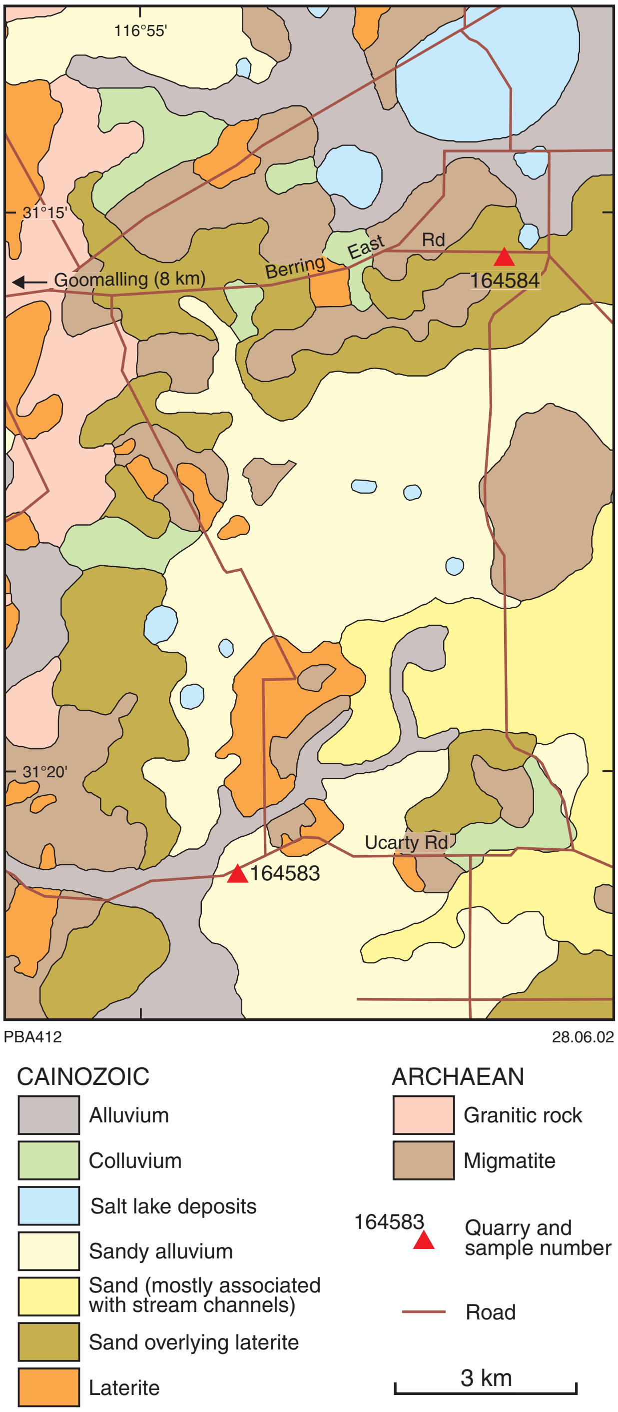

Figure 61. Geology around Ucarty and Berring East Roads (after Low et al., 1978)

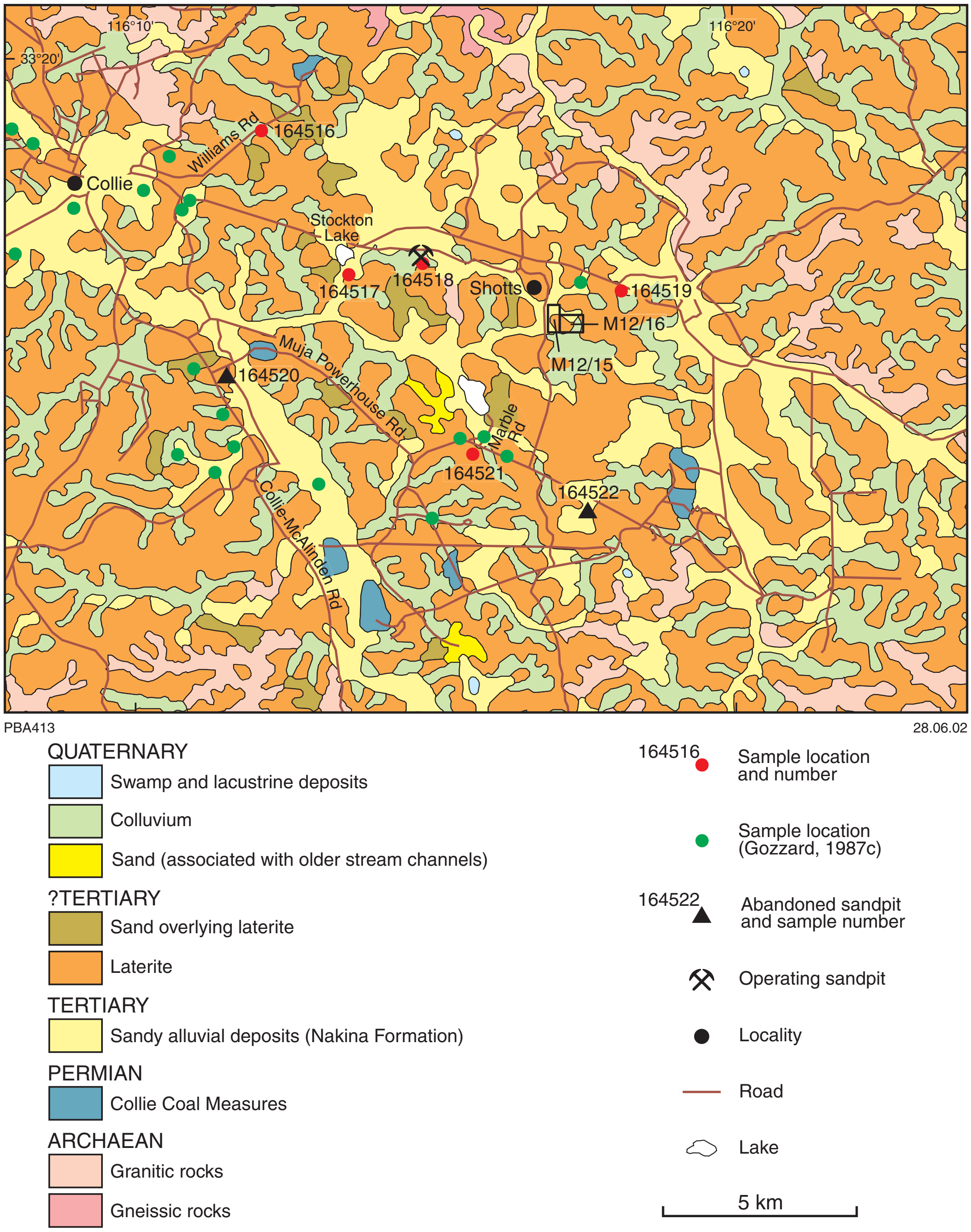

Figure 62. Geology of the area east of Collie (after Lowry et al., 1983)

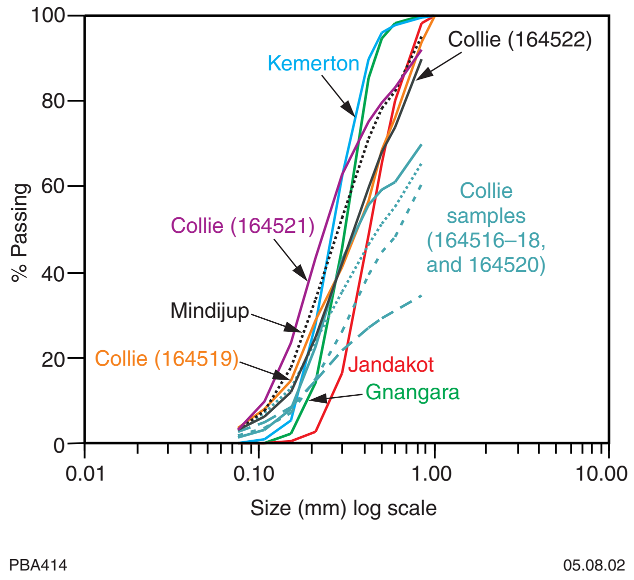

Figure 63. Particle-size distribution of sand from Collie area and operating silica sand mines of Western Australia

Shotts area

There is a significant deposit of sand approximately 3.5 km west-northwest of Shotts area. The sand is white, coarse grained, angular and has an approximately 1 m-thick overburden rich in organic material. The thickness of the sand bed appears to exceed 5 m in places (Fig. 64). A raw sample (GSWA164518) from this locality assayed 98.20% SiO_2, <0.01% Al_2O_3, 0.43% Fe_2O_3 and 1.20% TiO_2, indicating that this sand has marginally high Fe_2O_3 and TiO_2 possibly due to the presence of heavy minerals such as ilmenite (Table 51). Particle-size analysis of the raw sample (GSWA164518) shows the sand to be coarse grained, with 30.04% exceeding 850 µm (Table 52). The sand has been quarried for local consumption.

Approximately 2 km east of Shotts, white, coarse- to medium-grained sand is found in a relatively low lying area (Fig. 62). The thickness of the sand unit is more than 1 m, and is overlain by a thin (approximately 15 cm) layer rich in organic material. A raw sample (GSWA164519) from this locality yields 99.10% SiO_2, 0.15% Al_2O_3, 0.04% Fe_2O_3 and 0.42% TiO_2, reflecting moderately high grade silica sand (Table 51). Size analysis of the raw sample (GSWA164519) indicated that the sand is finer grained than that from the location west of Shotts, and has only 4.86% in the >850 µm fraction with a cumulative 92.30% in the >106 µm fraction (Table 52). These size fractions are comparable with those of the sands from operating silica sand mines at Kemerton and Gnangara (Fig. 63). On the basis of these results, the sand can be considered acceptably high grade, but more testing is required.

Approximately 5 km west of Shotts, adjacent to Stockton Lake, which is a rehabilitated coal mine, a sand horizon is developed on the lateritic duricrust (Fig. 62). This sand, which is mixed with ferruginous and clayey material and hardened in places, has a maximum thickness of about 3 m. A raw sample (GSWA164517) from this locality indicated 92.30% SiO_2, 2.44% Al_2O_3, 3.01% Fe_2O_3 and 0.56% TiO_2, reflecting the presence of abundant ferruginous and clay impurities (Table 51). Size analysis of the raw sample (GSWA164517) indicated that the sand is coarse grained, with 39.26% exceeding 850 µm (Table 52). These results indicate that the sand is unsuitable for high-grade applications.

Table 51. Chemical analyses of sand from the Collie region

GSWA no.	*164516*	*164517*	*164518*	*164519*	*164520*	*164521*	*164522*
				Percentage			
SiO_2	99.00	92.30	98.20	99.10	99.40	93.70	98.80
Al_2O_3	0.25	2.44	<0.01	0.15	<0.01	2.73	<0.01
Fe_2O_3	0.09	3.01	0.43	0.04	0.05	0.62	0.04
MgO	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01
CaO	0.02	0.02	0.01	0.01	0.01	0.01	<0.01
Na_2O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
K_2O	0.01	0.03	0.01	0.02	0.01	0.03	<0.01
TiO_2	0.32	0.56	1.20	0.42	0.46	1.02	0.60
MnO	0.01	<0.01	0.03	0.01	0.01	0.01	<0.01
P_2O_5	0.013	0.018	0.008	0.015	0.008	0.011	0.009
BaO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
SO_3	0.01	0.06	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	0.25	1.41	0.13	0.25	0.05	1.59	0.41
Total	**99.97**	**99.85**	**100.02**	**100.02**	**100.00**	**99.74**	**99.86**
H_2O	3.74	2.80	2.55	3.23	2.59	2.86	4.09

NOTE: 164516: Williams Road, Collie
164517: Stockton Lake
164518–19: Shotts
164519–22: Muja Powerhouse Road

Table 52. Size analyses (µm) of sand from the Collie region

GSWA no.	164516	164517	164518	164519	164520	164521	164522
				Percentage			
>850	34.33	39.26	30.04	4.86	65.67	7.86	10.34
600–850	10.34	12.32	8.76	12.88	3.51	8.92	15.59
500–600	4.00	3.59	2.04	3.92	1.64	3.46	5.91
425–500	4.75	5.64	3.51	7.04	2.03	4.50	8.46
300–425	10.98	12.92	12.53	18.50	5.52	12.47	17.79
212–300	11.52	11.32	20.43	19.34	7.18	19.30	17.27
150–212	11.06	8.08	14.68	15.73	6.22	19.88	12.67
106–150	5.87	3.37	4.79	10.03	3.32	13.72	5.69
75–106	4.06	1.96	1.88	4.81	2.07	6.66	2.98
<75	3.09	1.56	1.34	2.89	2.83	3.24	3.29

NOTE: 164516: Williams Road, Collie
164517: Stockton Lake
164518–19: Shotts
164519–22: Muja Powerhouse Road

Muja Powerhouse Road

Silica sand horizons are exposed in a number of localities around the Muja Powerhouse Road. Some of these sand units have been quarried in the past, presumably for local uses (Fig. 62). A small abandoned pit just south of the Collie–McAlinden Road, near the turnoff to the Muja Powerhouse Road, exposes a bed of uncertain thickness (>1 m) of coarse-grained, subrounded quartz sand mixed with some pebbly quartz below a surface layer (approximately 15 cm) consisting of pebbly quartz (3–10 cm across). Below the white, coarse-grained sand layer is a relatively hard coffee-brown sandy layer. Chemical analysis of a raw sample (GSWA164520) from this pit indicates moderately high grade quartz sand having 99.40% SiO_2, <0.01% Al_2O_3, 0.05% Fe_2O_3 and 0.46% TiO_2 (Table 51). However, size analysis of the raw sample (GSWA164520) indicates that the sand is very coarse grained, having 65.67% in the >850 µm fraction (Table 52).

Yellowish-brown, fine-grained sand is exposed on the south side of the Muja Powerhouse Road, close to the

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Figure 64. Northern pitwall of a sand quarry 3 km west-northwest of Shotts (location of sample GSWA164518)

turnoff to Marble Road (Fig. 62). The sand unit is more than 1.5 m thick and has a thin (10 cm) surface layer rich in organic material. Chemical analysis of a raw sand sample (GSWA164521) indicated relatively low SiO_2 (93.70%), high Al_2O_3 (2.73%), appreciable Fe_2O_3 (0.62%), and high TiO_2 (1.02%), suggesting its unsuitability for high-grade applications such as in the glass industry (Table 51). Size analysis of the sample (GSWA164521) showed 7.86% to exceed 850 µm and 65.37% to be within the 106–425 µm fraction (Table 52).

A creamy, fine- to medium-grained sand unit is found some 3.5 km southeast of the previous location (Fig. 62). This unit appears to be about 2 m thick and spreads over a significant surface area, but the available resource may not be extensive. The sand from this location appears to have been extracted in the past for local uses. A raw sample (GSWA164522) from this locality indicated 98.80% SiO_2, <0.01% Al_2O_3, 0.04% Fe_2O_3 and 0.60% TiO_2, suggesting that the sand is of moderately high quality (Table 51). Size analysis of the sample (GSWA164522) yielded 10.34% greater than 850 µm and 83.38% within the 106–850 µm fraction (Table 52).

Other

Gozzard (1987c) gave sieving results of 27 sand samples collected from different localities in the Collie area (Fig. 62). Two mining leases (M12/15–16, Fig. 62) close to Shotts are held for their silica sand potential by private operators.

Noggerup

Sand has been extracted in the past from a quarry approximately 6 km north of Noggerup (25 km south of Collie) along Rosewood Road. Although white, medium-grained sand associated with drainage courses is exposed in the area, an attempt to locate the abandoned quarry was not successful due to rehabilitation and thick vegetation in the area. The sand is only about a metre thick, and below this is a relatively hard coffee-brown clayey sand unit. A raw sample (GSWA164523; Fig. 65) from this locality indicates 98.70% SiO_2, <0.01% Al_2O_3, 0.10% Fe_2O_3 and 0.83% TiO_2, suggesting the sand is of moderately high quality (Table 53). Size analysis of the sample (GSWA164523) indicates 18.87% exceeding 850 µm and 69.37% lying within the range 106–850 µm (Table 54).

Yabberup

In the past, sand has been quarried from a pit located on the west side of Lowden–Grimwade Road, 2.5 km west of Yabberup (Fig. 66). The pit is approximately 40 m long, 15 m wide and 3 m deep. The sand is white to brownish, very coarse grained, and has a thickness of more than 3 m, which increases towards a hilly area to the west. The tonnage available could be significant. At the pit floor, the rock is hard and coffee brown in colour. A raw sand sample (GSWA164524) from the pit assayed 99.50% SiO_2, <0.01% Al_2O_3, 0.01% Fe_2O_3 and 0.31% TiO_2, indicating that the sand is of high-quality (Table 53). Size analysis of the sample (GSWA164524) confirms the sand is very coarse with 61.17% exceeding 850 µm and 27.63% within the fraction 600–850 µm (Table 54).

Donnybrook

Sand has been quarried in the past, presumably for local consumption, from a few localities east of Donnybrook, along Sandhills Road, off Donnybrook–Boyup Brook Road (Fig. 67). Sand horizons in this area form gentle hills extending in a northerly direction from Sandhills Road, and appear to contain a significant sand resource. Sand samples (GSWA164525–26) were collected from two abandoned quarries some 1.7 km apart close to, and on the north side of, Sandhills Road (Fig. 67). Sample GSWA164525 is white to creamy coarse-grained sand from a small abandoned pit. The northern pitwall reveals a 2 m-thick sand profile with thickness increasing farther to the north. The sand horizon has pockets of small ferruginous gritty material. Chemical analysis of the sample (GSWA164525) indicates quite high quality silica with 99.10% SiO_2, <0.01% Al_2O_3, 0.06% Fe_2O_3 and 0.68% TiO_2, but the sand is very coarse, with 63.89% in the >850 µm fraction and 28.81% in the 150–850 µm range (Tables 53 and 54). Sample GSWA164526 (Fig. 67) is from a larger abandoned pit containing coarse- to medium-grained white sand. The sand from the location of GSWA164526 is of better quality than that from the location of GSWA164525, does not appear to contain ferruginous grit, and is of smaller grain size. Chemical analysis of sample GSWA164526 also indicates moderately high quality silica with 99.30% SiO_2, <0.01% Al_2O_3, 0.04% Fe_2O_3, and 0.57% TiO_2 (Table 53). Size analysis places 16.10% in the >850 µm fraction and 68.37% in the 150–850 µm fraction, which shows that sand in this pit is finer than that from the other pit (Table 54). Although sample GSWA164526, from the larger pit, has a higher percentage of coarse-grained sand (Fig. 68), grain-size distribution is comparable with that from the operating mines in the Jandakot, Gnangara, Kemerton, and Mindijup regions. Sample GSWA164525, from the smaller pit, is much coarser than any sand from the above mines. Chemically, the sand from these two Donnybrook localities has a higher percentage of TiO_2 than that from operating mines in the Jandakot, Gnangara, Kemerton, and Mindijup regions (which generally have TiO_2 values <0.1%).

Eastern Goldfields Granite–Greenstone Terrane

The Archaean Eastern Goldfields Granite–Greenstone Terrane occupies the eastern part of the Yilgarn Craton. The terrane consists of large areas of granitic rocks and linear to arcuate belts of greenstone, mainly with a north-northwesterly trend (Fig. 69). The greenstones exhibit various degrees of deformation, and have mainly undergone greenschist-facies metamorphism (Griffin, 1990). The Eastern Goldfields Granite–Greenstone Terrane is unconformably overlain by sedimentary rocks of the Earaheedy and Yerrida Basins to the north and northeast respectively, and by sedimentary rocks of the

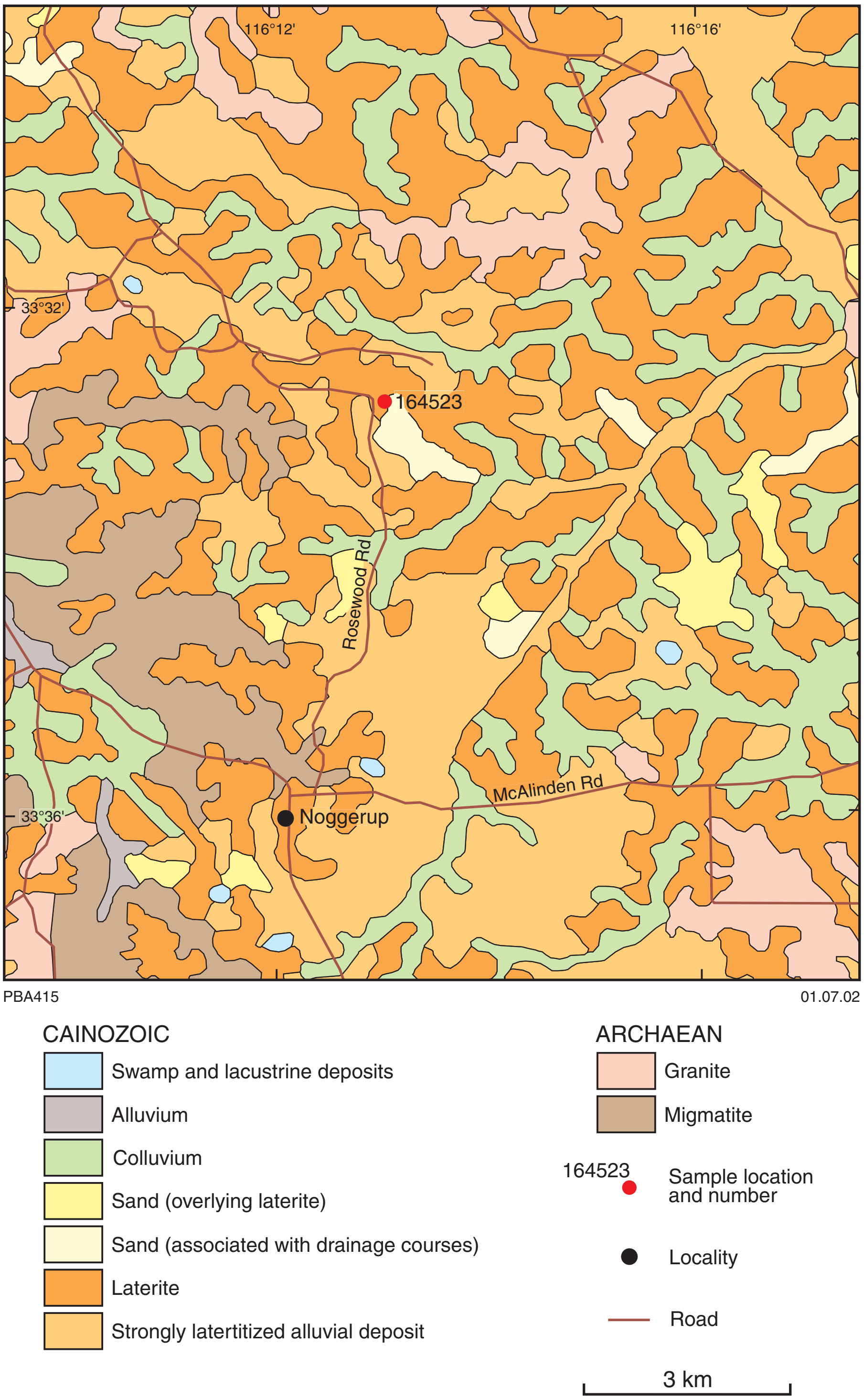


Figure 65. Geology around Noggerup (after Lowry et al., 1983)

Table 53. Chemical analyses of sand from the Noggerup, Yabberup, and Donnybrook regions

GSWA no.	*164523*	*164524*	*164525*	*164526*
		Percentage		
SiO_2	98.70	99.50	99.10	99.30
Al_2O_3	<0.01	<0.01	<0.01	<0.01
Fe_2O_3	0.10	0.01	0.06	0.04
MgO	<0.01	<0.01	<0.01	<0.01
CaO	0.01	<0.01	0.01	<0.01
Na_2O	<0.01	<0.01	<0.01	<0.01
K_2O	<0.01	<0.01	0.01	<0.01
TiO_2	0.83	0.31	0.68	0.57
MnO	0.01	<0.01	0.01	<0.01
P_2O_5	0.006	0.008	0.014	0.007
BaO	<0.01	<0.01	<0.01	<0.01
SO_3	<0.01	<0.01	<0.01	<0.01
LOI	0.15	0.05	0.08	0.06
Total	**99.81**	**99.88**	**99.96**	**99.98**
H_2O	0.77	2.69	1.26	3.36

NOTE: 164523: Rosewood Road, 7 km northeast of Noggerup
164524: Lowden–Grimwade Road, 1 km west of Yabberup
164525–26: Sandhills Road, Donnybrook

Table 54. Size analyses (µm) of sand from the Noggerup, Yabberup, and Donnybrook regions

GSWA no.	*164523*	*164524*	*164525*	*164526*
		Percentage		
>850	18.87	61.17	63.89	16.10
600–850	13.08	27.63	3.89	13.10
500–600	3.60	3.94	1.54	3.67
425–500	4.82	1.60	2.17	5.45
300–425	11.63	1.47	6.71	14.91
212–300	13.22	1.32	8.28	17.72
150–212	12.56	1.24	6.22	13.52
106–150	10.47	0.73	3.76	7.41
75–106	6.67	0.43	1.94	4.47
<75	5.09	0.45	1.60	3.66

NOTE: 164523: Rosewood Road, 7 km northeast of Noggerup
164524: Lowden–Grimwade Road, 1 km west of Yabberup
164525–26: Sandhills Road, Donnybrook

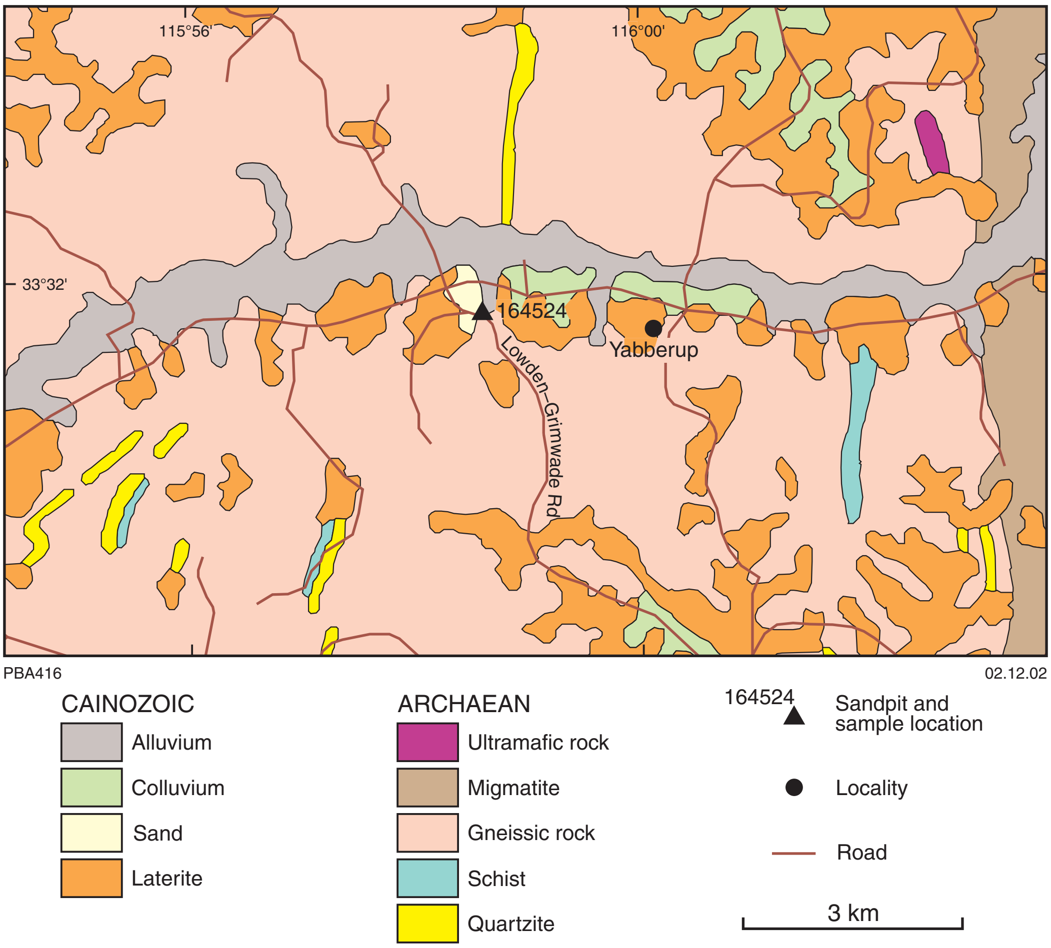


Figure 66. Geology around Yabberup (after Lowry et al., 1983)

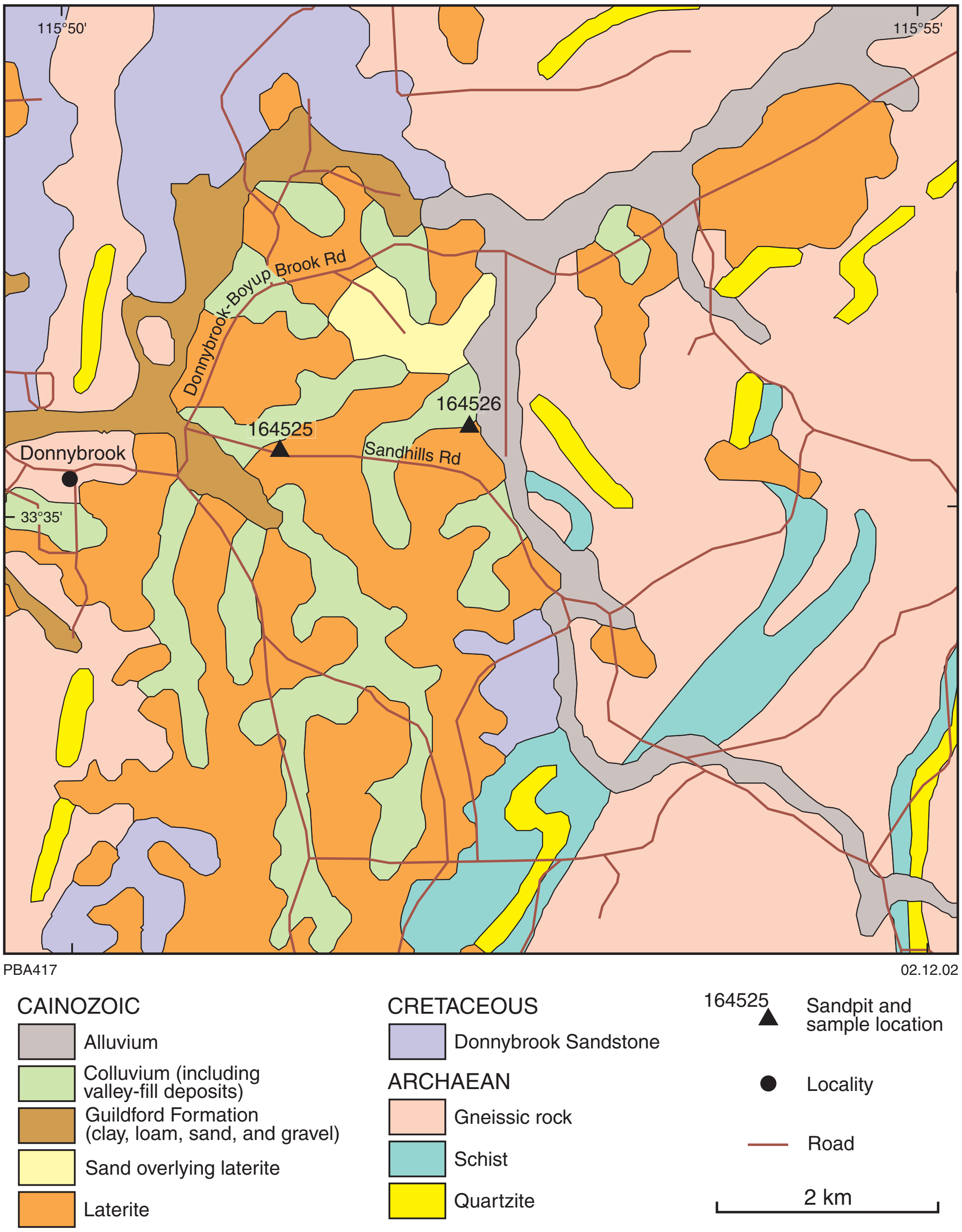


Figure 67. Geology of the area east of Donnybrook (after Lowry et al., 1983)

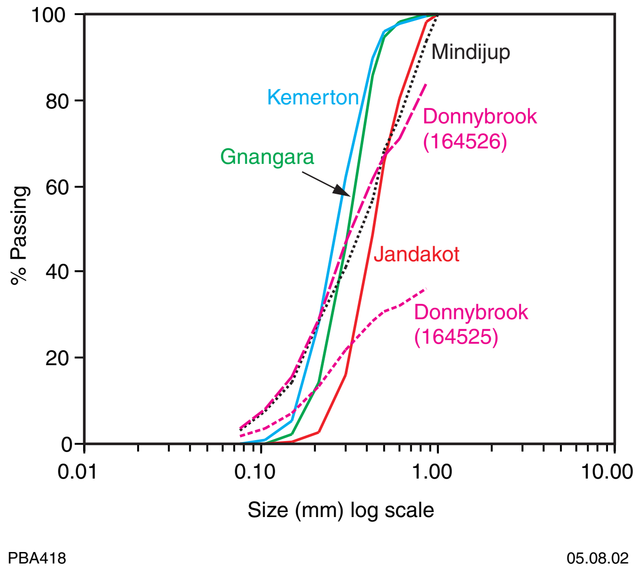


Figure 68. Particle-size distribution of sand from Donnybrook area and operating sand mines in Western Australia

Gunbarrel Basin in the east. In the south, Archaean rocks have been incorporated into the Proterozoic Albany–Fraser Orogen. The main granitoid varieties are granitic gneiss, foliated and unfoliated granites, and small discordant granitoid stocks. In the greenstone belts, the older units are mostly mafic to ultramafic volcanic rocks overlain by felsic volcanic rocks and clastic sedimentary rocks. The age of the granite–greenstone rocks in the region is 2800–2600 Ma (McCulloch et al., 1983). Throughout the region, granitoid rocks are generally more poorly exposed than the greenstone belts. The granitoid areas represent about 70% of the total area and hence are obvious source rocks for quartz to be reworked into younger silica sand deposits.

On the Eastern Goldfields Granite–Greenstone Terrane, sandplains and dunes are extensively developed as sheets of variable thickness on duricrust plateaus overlying granitoid rocks, on laterite, and adjacent to playa lakes. Typically, the sand is medium grained, has undergone little sorting, and has derived from the physical disintegration of the mottled-pallid zone of the laterite (Brewer and Bettenay, 1973). The sand formations show features of colluvial transport over relatively short distances and are of variable size and character and of lesser chemical quality than those found in the Perth Basin and the Albany–Fraser Orogen. Deposits of sand and loam, largely derived from weathered granitoid, are found in low-lying areas. Localized concentrations of sand of variable character are also found associated with drainages and palaeochannels. Quaternary sand overlying Tertiary sediments in palaeochannels in the Kalgoorlie region is very fine, silty, generally poorly sorted, and more angular than those in Tertiary sediments (Commander et al., 1992).

Sand from a deposit near Mount Burges (23 km north-northwest of Coolgardie) is used for nickel smelting at Kalgoorlie. Most of the sand in the Kalgoorlie area is used in local construction (e.g. in concrete and filling).

The Kalgoorlie region has a strongly established mining and service industry with good infrastructure, and it is therefore desirable to establish potential in the area for silica sand deposits. Accordingly, a few samples from various sand formations within about 100 km of Kalgoorlie were collected from reconnaissance traverses for chemical and sieve analyses to obtain an understanding of the quality. Following are descriptions of some localities where samples have been collected or exploration results are available.

The main sand deposits on the Eastern Goldfields Granite–Greenstone Terrane are at Mount Burges and Goongarrie with occurrences known at the Stewart Siding, Smith Dam, Lake Lefroy, Widgiemooltha, and Queen Victoria Park areas.

Mount Burges

Approximately 8 km northwest of Mount Burges, sandplains and dunes are extensively developed as sheets of variable thickness on duricrust plateaus overlying granitoid. A large sand deposit exists on a ridge close to the road from Coolgardie (Fig. 70). The deposit has been mined sporadically from 1985 by Western Mining Corporation Ltd (Mining Lease 15/125) for use as flux in its nickel smelter in Kalgoorlie. The quarry is about 200 m long, 75 m wide, and 5 m deep. As mining proceeds towards the west the quarry walls are progressively rehabilitated. Approximately 150 m length of each of the north and south walls are already rehabilitated.

The sand in this area overlies gravel, which is also mined for use in maintaining the haulage tracks to the sand-mining lease. The thickness of the sand formation on the west side of the road, where the sand is mined, is over 5 m and that on the eastern side of the road exceeds 4 m.

Sand reserves in the deposit are estimated at 4.65 Mt grading 85% SiO_2, 7.5% Al_2O_3, 2.14% Fe_2O_3, and 0.4% CaO. Resources in addition to reserves are 0.83 Mt at a similar grade (Western Mining Corporation, 1997).

Two sand samples (GSWA164596–97) were collected for testing. Sample GSWA164597 is from the sand profile that is being currently mined, and the other sample (GSWA164596) is from the ridge of sand on the eastern side of the road (Fig. 70). The two samples contain 88.50–91.7% SiO_2, 4.45–6.36% Al_2O_3, and 1.64–2.17% Fe_2O_3, indicating that the quality of sand is too low for high-grade applications (Table 55). Size analyses show that the sand is relatively fine grained; sample GSWA14596 contains 10.91% above 425 µm and the other sample contains 21.99% in the same fraction (Table 56).

Goongarrie

Extensive areas of sand sheets lie in the area west of Lake Goongarrie, and these have been mapped by Groenewald et al. (2000; Fig. 71). The sand is reddish brown to yellowish brown, and medium to fine grained.

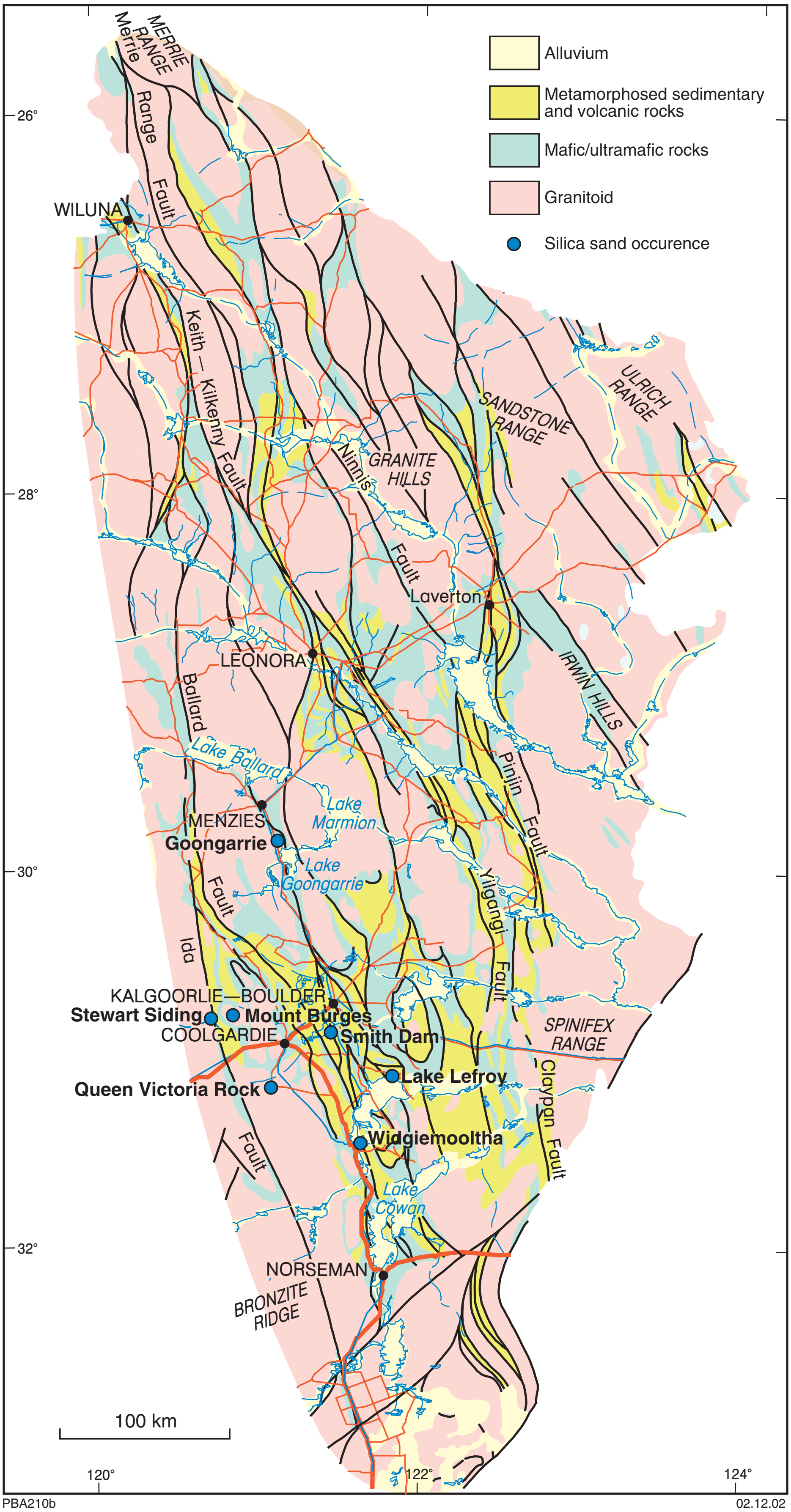


Figure 69. Regional geology of the Eastern Goldfields Granite–Greenstone Terrane, Yilgarn Craton (modified from Griffin, 1990)

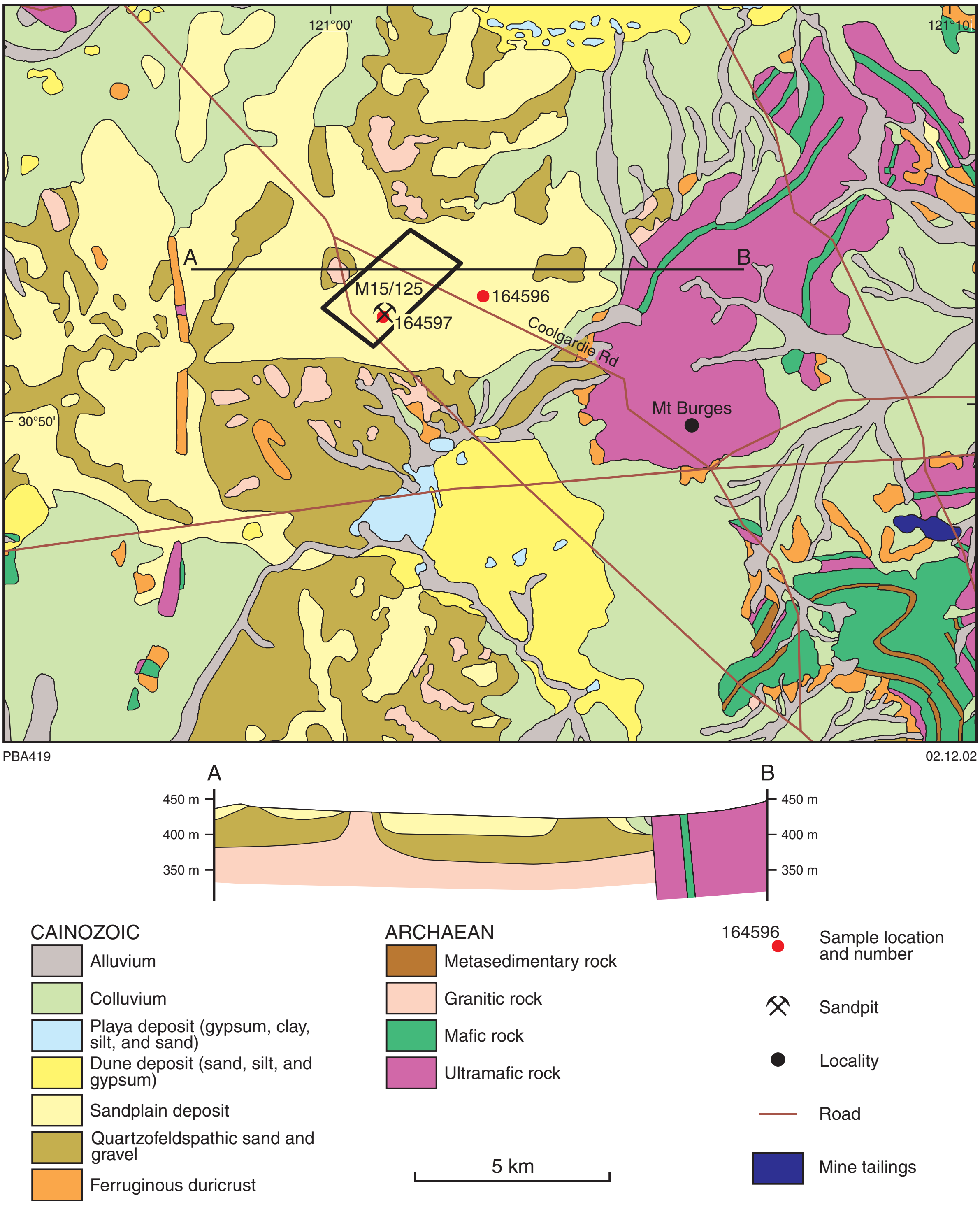


Figure 70. Geology around Mount Burges (after Groenewald et al., 2000)

Table 55. Chemical analyses of sand from Mount Burges, Goongarrie, Coolgardie, Stewart Siding, Lake Lefroy, and Queen Victoria Rock

GSWA no.	*164596*	*164597*	*145205*	*164592*	*164593*	*164594*	*164595*	*145201*	*145202*	*145203*	*145204*	*164598*	*164599*	*164600*
							Percentage							
SiO_2	91.70	88.50	90.80	83.20	90.20	87.30	91.00	68.90	84.80	91.10	95.70	88.00	84.50	93.30
Al_2O_3	4.45	6.36	4.92	9.09	5.02	5.97	4.91	4.60	5.16	2.38	1.29	6.78	8.90	3.67
Fe_2O_3	1.64	2.17	1.80	3.42	1.95	3.85	1.54	22.60	6.55	4.60	1.72	1.76	2.45	0.92
MgO	0.04	0.06	0.03	0.06	0.07	0.05	0.03	0.43	0.49	0.09	0.06	0.05	0.04	0.04
CaO	0.04	0.02	0.01	0.03	0.04	0.02	0.02	0.20	0.20	0.09	0.06	0.07	0.01	0.05
Na_2O	0.03	0.03	<0.01	0.02	0.02	0.01	0.01	0.43	0.29	0.13	0.08	0.02	0.01	0.04
K_2O	0.14	0.14	0.12	0.16	0.18	0.14	0.15	0.41	0.47	0.28	0.12	0.12	0.09	0.17
TiO_2	0.22	0.29	0.20	0.42	0.26	0.29	0.24	0.69	0.33	0.27	0.11	0.30	0.38	0.20
MnO	<0.01	0.01	<0.01	0.01	<0.01	0.01	<0.01	0.07	0.02	0.01	<0.01	<0.01	0.01	<0.01
P_2O_5	0.005	0.009	0.012	0.01	0.011	0.012	0.011	0.039	0.019	0.01	0.012	0.013	0.004	0.018
BaO	<0.01	<0.01	<0.01	0.01	0.01	<0.01	<0.01	0.10	0.02	0.03	0.01	<0.01	<0.01	0.01
SO_3	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.05	<0.01	<0.01	0.01	<0.01	<0.01	<0.01
LOI	1.81	2.42	1.98	3.58	2.05	2.43	2.17	1.35	1.65	0.86	0.63	2.93	3.68	1.67
Total	**100.08**	**100.01**	**99.87**	**100.01**	**99.81**	**100.09**	**100.08**	**99.87**	**100.00**	**99.85**	**99.80**	**100.04**	**100.07**	**100.09**
H_2O	3.34	4.45	2.97	3.39	3.49	8.23	3.44	2.04	3.47	1.51	1.67	2.67	4.25	1.34

NOTE: 164596–97: Mount Burges
145205: Goongarrie
164592: 20 km southwest of Coolgardie
164593–95: Stewart Siding
145201–04: Lake Lefroy shorelines
164598–600: Queen Victoria Rock

Table 56. Size analyses (µm) of sand from Mount Burges, Goongarrie, Coolgardie, Stewart Siding, Lake Lefroy, and Queen Victoria Rock

GSWA no.	*164596*	*164597*	*145205*	*164592*	*164593*	*164594*	*164595*	*145201*	*145202*	*145203*	*145204*	*164598*	*164599*	*164600*
							Percentage							
>850	0.08	0.56	0.20	33.55	2.30	12.80	9.82	3.23	2.23	0.42	1.38	3.57	17.02	1.40
600–850	1.29	4.54	1.77	8.48	8.43	12.27	14.41	9.80	5.27	2.70	5.23	7.95	12.30	2.89
500–600	3.28	8.11	4.05	2.54	8.57	7.42	7.96	8.28	4.77	4.02	6.53	7.03	3.78	4.52
425–500	6.28	8.79	6.35	1.81	8.23	4.70	6.56	7.49	4.74	5.95	8.33	7.74	3.21	7.13
300–425	24.77	22.60	21.04	4.81	21.47	12.17	14.79	17.20	13.45	20.98	25.03	16.02	10.13	25.05
212–300	27.59	22.41	26.55	8.58	19.21	14.11	14.84	17.25	19.28	26.52	25.68	17.67	15.79	24.90
150–212	19.40	16.93	23.03	12.62	14.92	13.79	14.26	17.28	23.84	22.47	16.62	17.88	16.84	17.07
106–150	9.26	8.74	10.54	9.43	8.10	9.23	8.17	10.52	14.22	10.08	6.34	10.72	9.31	8.36
75–106	5.33	4.96	4.58	7.30	5.29	7.03	5.26	5.92	7.99	4.89	3.22	6.97	6.18	5.16
<75	2.72	2.37	1.90	10.88	3.48	6.49	3.94	3.01	4.21	1.98	1.65	4.44	5.43	3.51

NOTE: 164596–97: Mount Burges
145205: Goongarrie
164592: 20 km southwest of Coolgardie
164593–95: Stewart Siding
145201–04: Lake Lefroy shorelines
164598–600: Queen Victoria Rock

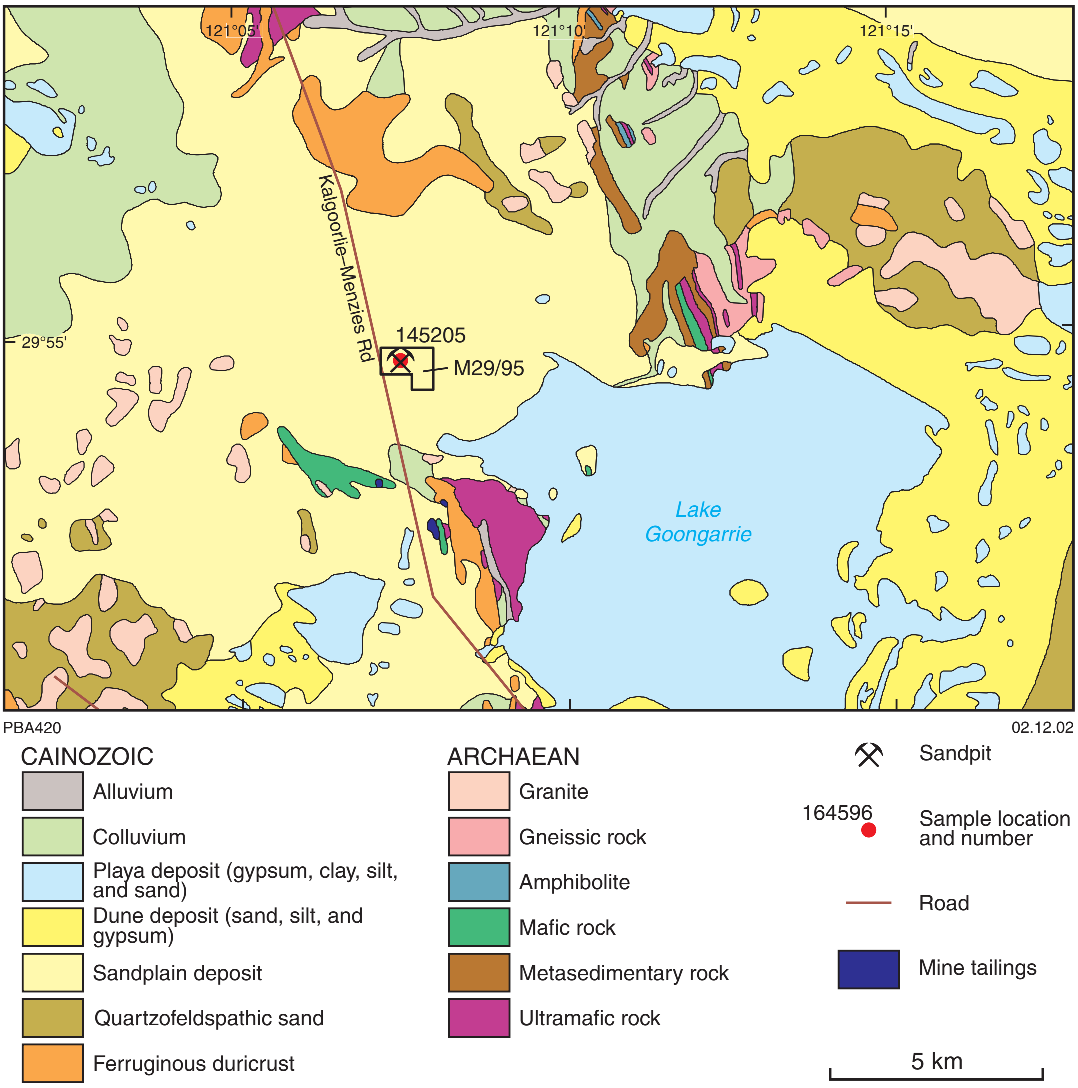


Figure 71. Geology around Lake Goongarrie (after Groenewald et al., 2000)

The available resource appears to be very large, but little information on grade is available. The sand is mined from Mining Lease M29/95 (held by CSR Ltd) on the eastern side of the Kalgoorlie–Menzies Road, presumably for construction applications. The sandpit is about 200 m long, 75 m wide, and the sand horizon is 3–6 m thick. Chemical analysis of a raw sand sample (GSWA145205) from this deposit indicates that the sand is of low quality and unsuitable for high-grade applications. The sample assayed 90.80% SiO_2, 4.92% Al_2O_3, and 1.80% Fe_2O_3 (Table 55). Size analysis of the sample indicates that 12.37% of sand exceeds 425 µm (Table 56).

Occurrences

Stewart Siding – Coolgardie

Extensive areas of medium to fine-grained, reddish-brown clayey sandplains are found in the area immediately west of Stewart Siding (35 km west of Coolgardie) (Fig. 72). The thickness of the sand horizon is uncertain. Assays of three samples (GSWA164593–95) averaged 89.50% SiO_2, 5.30% Al_2O_3 and 2.45% Fe_2O_3 (Table 55), indicating that the sand is chemically unsuitable for high-grade applications. Size analyses show variability, with 2.30–12.80% in the >850 µm fraction and 27.53–38.75% in the >425 µm fraction (Table 56).

Chemical analysis of another sample (GSWA164592) from sand on the south side of the Perth–Kalgoorlie highway and approximately 20 km south-southwest of Coolgardie (Fig. 72) yields 83.20% SiO_2, 9.09% Al_2O_3, and 3.42% Fe_2O_3 (Table 55). The sand from this location appears to have been used locally, probably for construction applications. The sandy layer is gravelly to a depth of around one metre, but cemented beyond. Size analysis of the sample showed 33.55% to exceed 850 µm, reflecting the presence of a high proportion of coarse-grained material (Table 56).

Smith Dam

In 1971, Western Mining Corporation carried out a vacuum drilling program on Mineral Claims MC15/3576 and 15/3790, 5 km west of Smith Dam (some 20 km south of Kalgoorlie). The objective was to assess the quality of sand for use as smelter silica flux. The area investigated is covered with Cainozoic dunes, which are located close to some playa lakes (Fig. 73). Of 40 holes drilled into the sand dunes, 28 had an average of 3 m of silica sand containing 80–90% SiO_2 (Western Mining Corporation, 1973).

Lake Lefroy and Widgiemooltha

Dunes are well developed on the north, east, and southern shorelines of Lake Lefroy (Figs 74 and 75). The dunes along the northern shore contain red-brown, medium-grained sand with a high proportion of dark minerals that appear to be ferromagnesian or iron minerals such as hematite or magnetite. Along the northern and eastern shorelines of the salt lake, the sand dunes extend to about 1.5 km inland and are aligned in various directions with no apparent trend. Sample GSWA145201 is taken from the northern shore (Fig. 74), where the maximum thickness of the sand horizon is at least 3 m. The sand is of too low a quality to be considered for use as a source of high-grade silica sand. The chemical composition of this raw sample (GSWA145201) is 68.90% SiO_2, 4.60% Al_2O_3 and 22.6% Fe_2O_3, confirming a high proportion of iron minerals and therefore low quality as a source of silica sand. Size analysis of the sample indicates that 28.81% of the material exceeds 425 µm. These occurrences are located a few tens of kilometres east of the sealed road from Kalgoorlie to Kambalda and are not easily accessible.

The sand dunes along the southern shorelines of the salt lake extend to about 1.5 km inland and may be as high as 4 m. The sand on the southern shore is red-brown, medium grained, and contains a lower proportion of heavy minerals than that from the northern shore. Chemical quality is too low for high-grade applications. Three raw samples (GSWA145202–04, Fig. 75) from different locations along the southern shoreline assayed 84.80–95.79% SiO_2, 1.29–5.16% Al_2O_3, and 1.72–6.55% Fe_2O_3 (Table 55). Sample GSWA145202 is from a northerly trending sand dune on the eastern shoreline of the southern extension of the lake, 12 km northeast of Widgiemooltha. Samples GSWA145203–04 are from easterly trending dunes, about 10 and 13 km respectively east of Widgiemooltha, along Salt Road (Fig. 75). Size analyses of the samples indicate that sand from the southern shorelines is somewhat finer than that from the northern shoreline. The average percentage of the material of size greater than 425 µm for the three samples (GSWA145202–04) from the southern bank is 19.63% compared with 28.81% of the sample (GSWA145201) from the northern bank (Table 56).

Queen Victoria Rock

Sand deposits developed in the region north and west of Queen Victoria Rock (approximately 45 km southwest of Coolgardie) consist mostly of a sandplain with limonite and pisolite at the base, and smaller areas of quartzo-feldspathic sand over granitoid rock at shallower depth (Fig. 76). The thickness of this sand formation is uncertain, but exceeds 1 m in three locations where samples GSWA164598–600 were collected (Fig. 76).

Sand overlying the lateritic gravel in the area is yellow brown and medium grained. Chemical analyses of the above three raw samples give an average of 88.60% SiO_2, 6.45% Al_2O_3, and 1.71% Fe_2O_3 and is thus of too low a quality for high-grade applications (Table 55). Sand with similar characteristics is mined from a quarry on the west side of Queen Victoria Rock Road, and is probably used for construction in the Kalgoorlie region.

Size analyses indicate that sample GSWA164599 is coarser than the other two, and has 17.02% in the >850 fraction compared with an average of only 2.48% for the other two samples (GSWA164598 and GSWA164600) (Table 56).

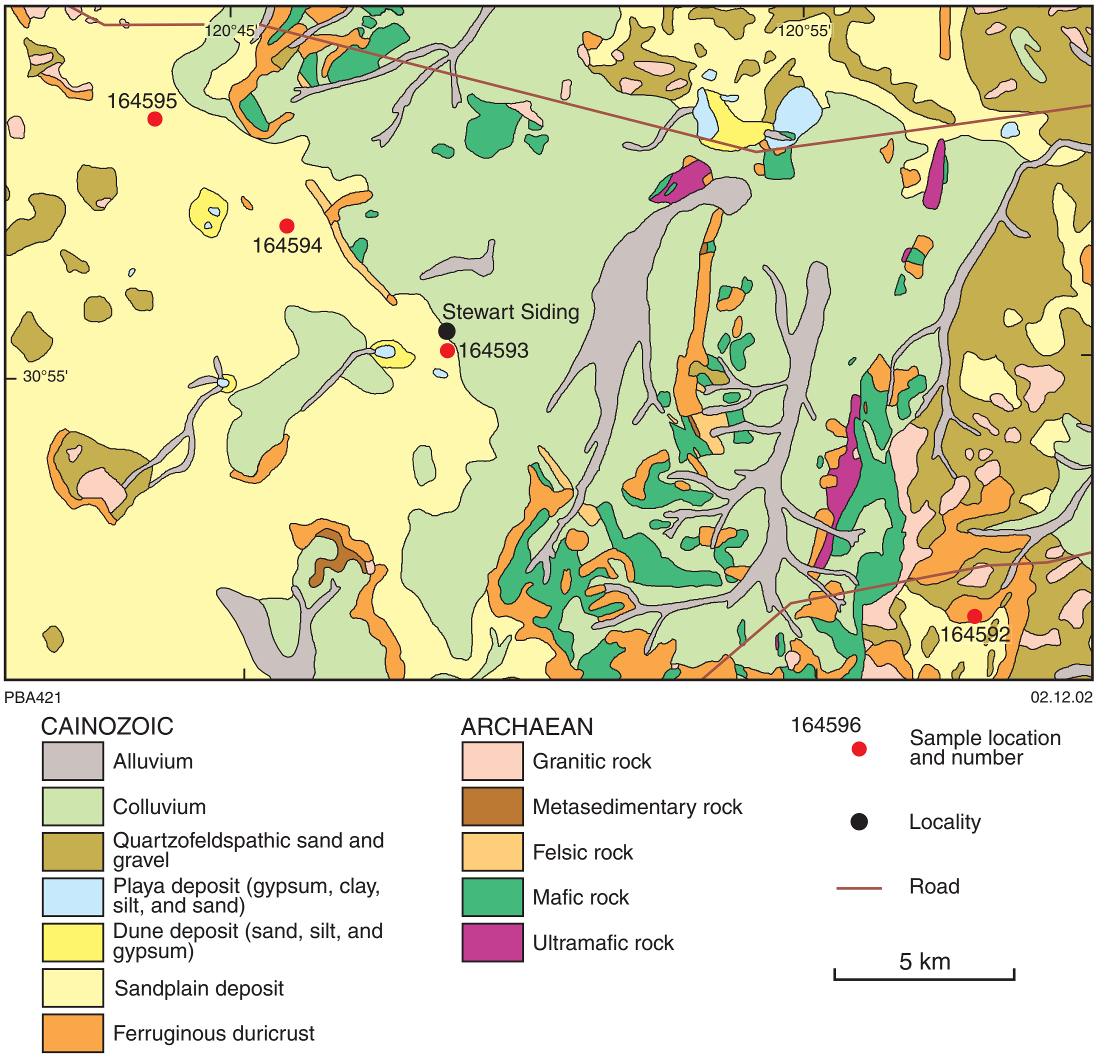


Figure 72. Geology around Stewart Siding (after Groenewald et al., 2000)

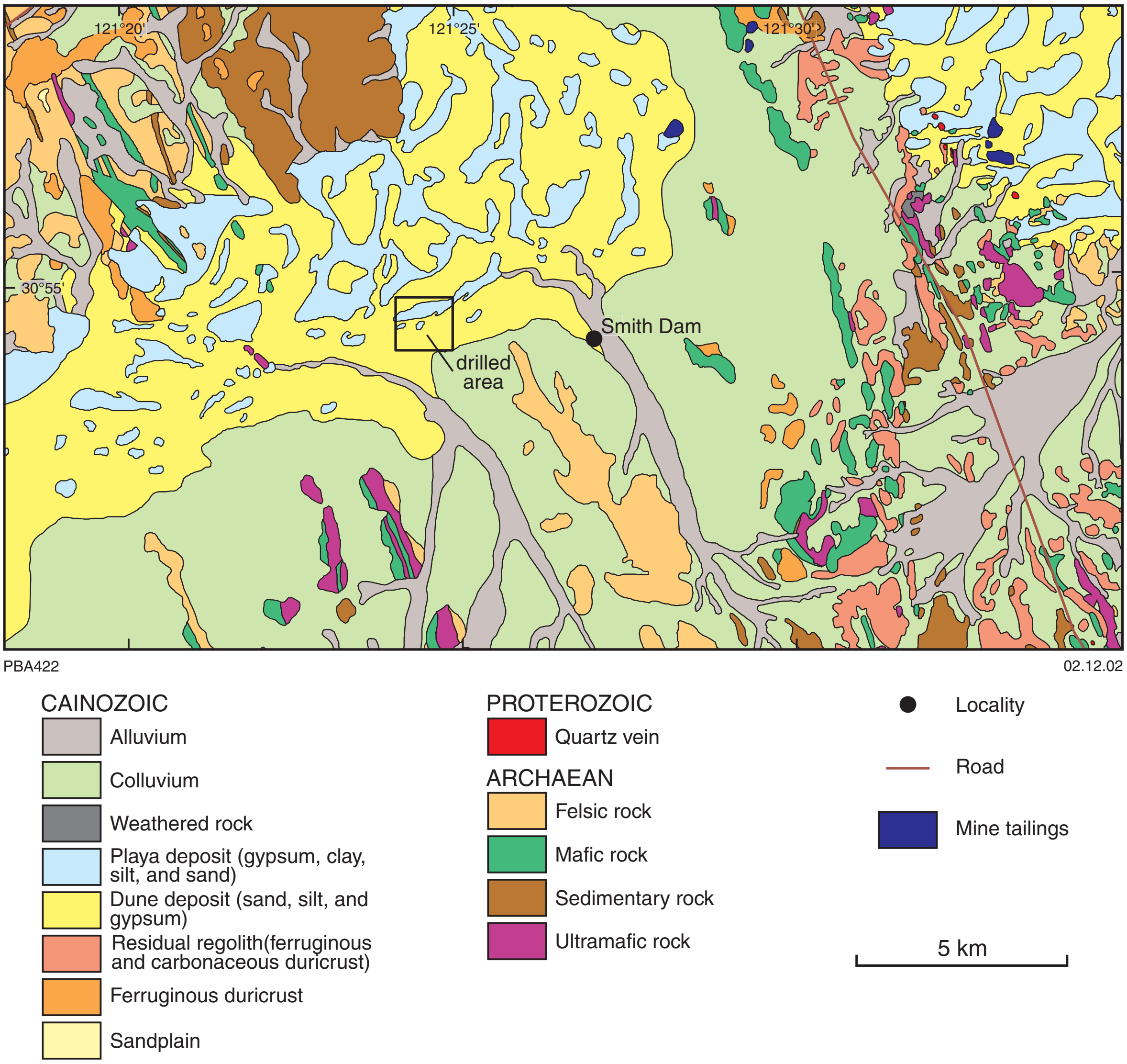


Figure 73. Geology around Smith Dam (after Groenewald et al., 2000)

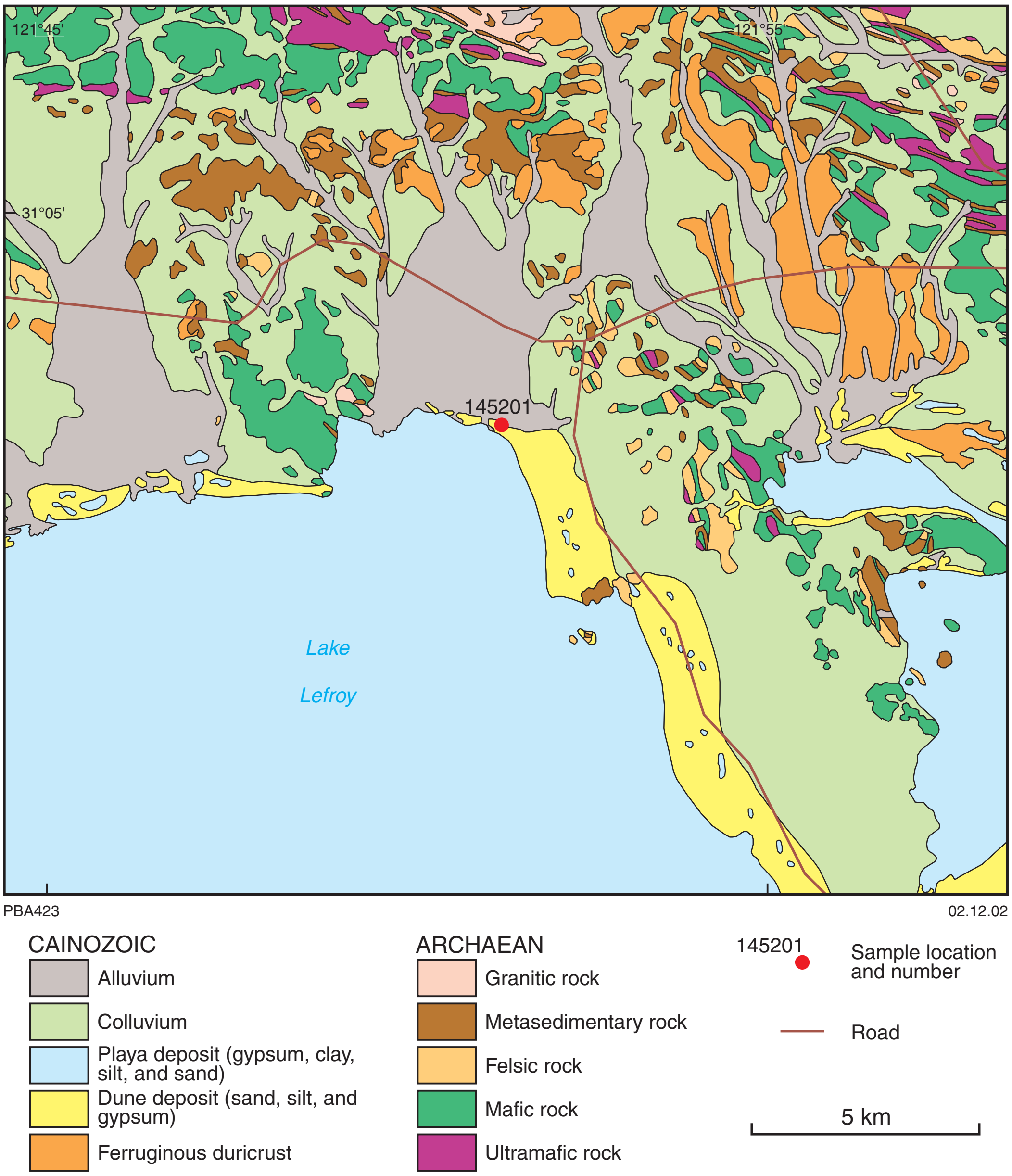


Figure 74. Geology of the area north and east of Lake Lefroy (after Groenewald et al., 2000)

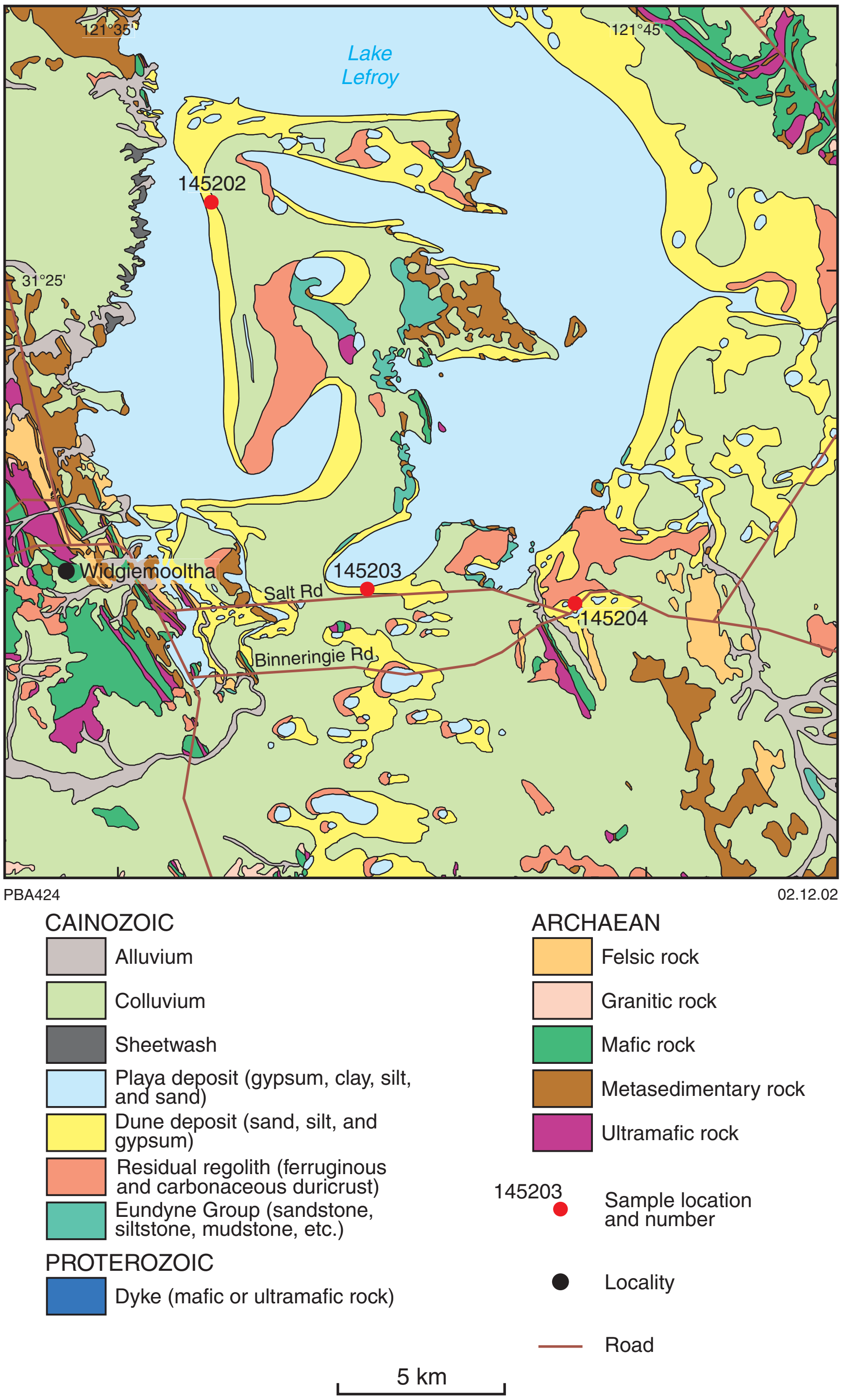


Figure 75. Geology of the area south of Lake Lefroy and east of Widgiemooltha (after Groenewald et al., 2000)

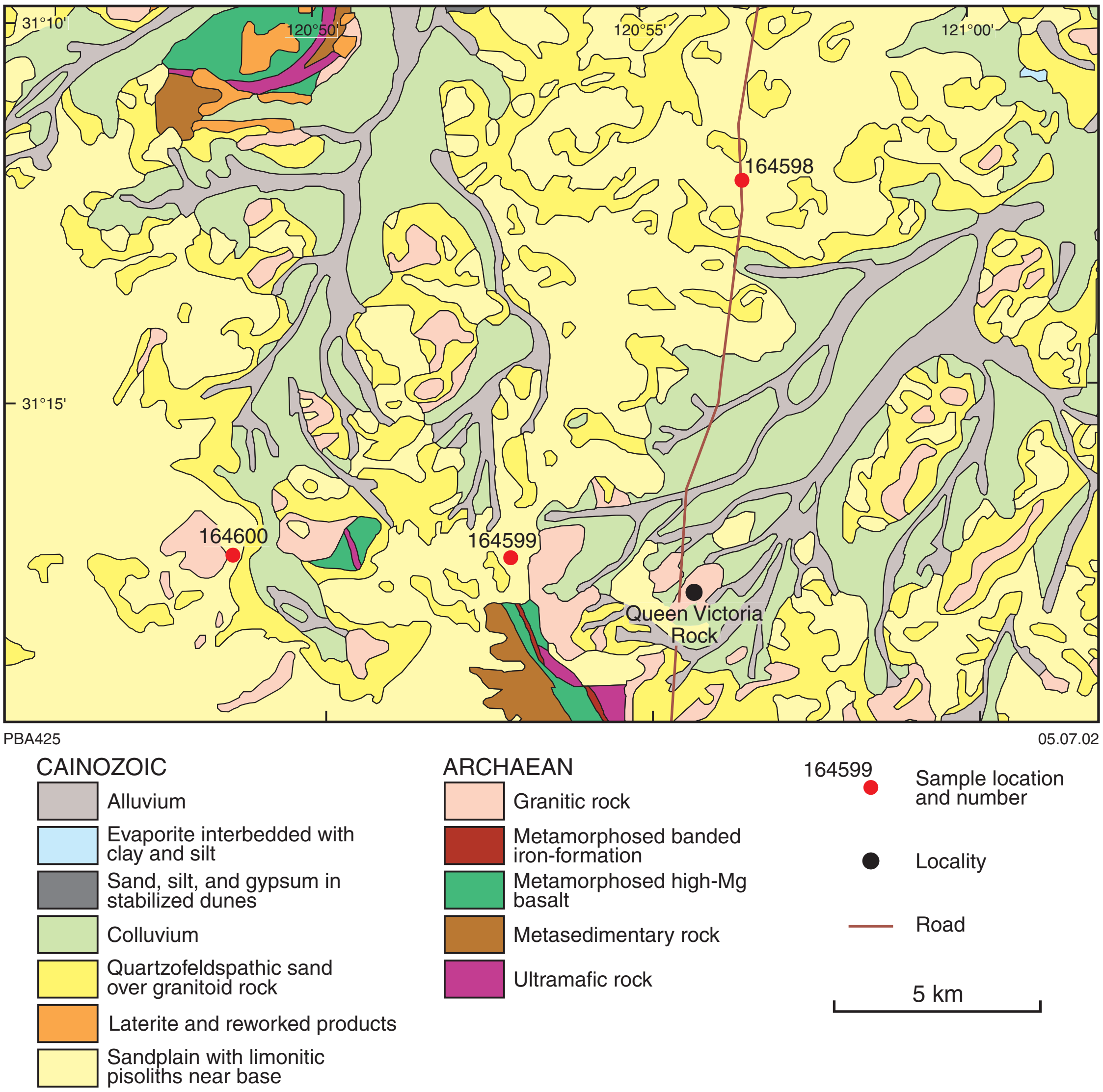


Figure 76. Geology around Queen Victoria Rock (after Hunter, 1988)

Carnarvon Basin

The onshore Carnarvon Basin extends for a distance of about 1000 km from Geraldton to Karratha along the western and northwestern coastline of Western Australia. The width of the basin onshore ranges from about 50 to 300 km. Sedimentary rocks in the Carnarvon Basin range in age from Silurian to Holocene (Fig. 77), and a detailed description of the geology of the basin is given by Hocking et al. (1987) and Hocking (1994).

There are vast eolian sandplains within the areas covered by AJANA*, WINNING POOL – MINILYA, KENNEDY RANGE, YANREY–NINGALOO, QUOBBA, YARINGA, SHARK BAY – EDEL, and WOORAMEL 1:250 000 geological sheets (Fig. 78) (Hocking et al., 1982, 1985a,b; van de Graaff et al., 1980, 1983; Denman et al., 1985).

AJANA and GLENBURGH 1:250 000 geological sheets, the most prospective of the areas within the Carnarvon Basin, are the only sheets in the basin with any information on chemical quality of the sand formations.

Reddish-brown, quartzose eolian sand covers much of the WOORAMEL 1:250 000 geological sheet. The morphology of this sand includes gently undulating sandplain with minor dunefields of hummocky dunes, areas of hummocky and indistinct network dunes, and longitudinal dunes with unconsolidated sandy interdune areas (Denman et al., 1985). There is no information on the quality of the sand.

In the area of the YANREY–NINGALOO, YARINGA, and KENNEDY RANGE 1:250 000 geological sheets, claypans grade laterally into vast areas of sandplain and dune deposits. The sand in these formations is generally reddish-brown to yellowish (van de Graaff et al., 1980, 1983; Hocking et al., 1985a,b). There is no information on the quality of the sand.

Sandplain and dune deposits are also abundant on the WINNING POOL – MINILYA geological sheet. These sands range from orange to deep red-brown and become partly calcareous towards the coast. There is an increase in the density and height of sand dunes close to Permian sandstone ridges, suggesting that at least some of the sand is locally derived and that Permian rocks represent an important source of sand (Hocking et al., 1985a).

During geochemical mapping of the AJANA 1:250 000 sheet, Sanders and McGuinness (2000) reported chemical analyses of 820 samples collected from regolith material. Of these, 142 samples assayed >95% SiO_2. Most of these high-value silica samples were collected from the western half of the sheet, where Cretaceous Winning Group rocks and Tumblagooda Sandstone are distributed (Fig. 79).

On the AJANA sheet, the Winning Group is a siliciclastic sequence consisting of Birdrong Sandstone, Windalia Radiolarite, and Alinga Formation. The Birdrong Sandstone consists of shallow-marine, commonly glauconitic, poorly consolidated sandstone to loose sand.

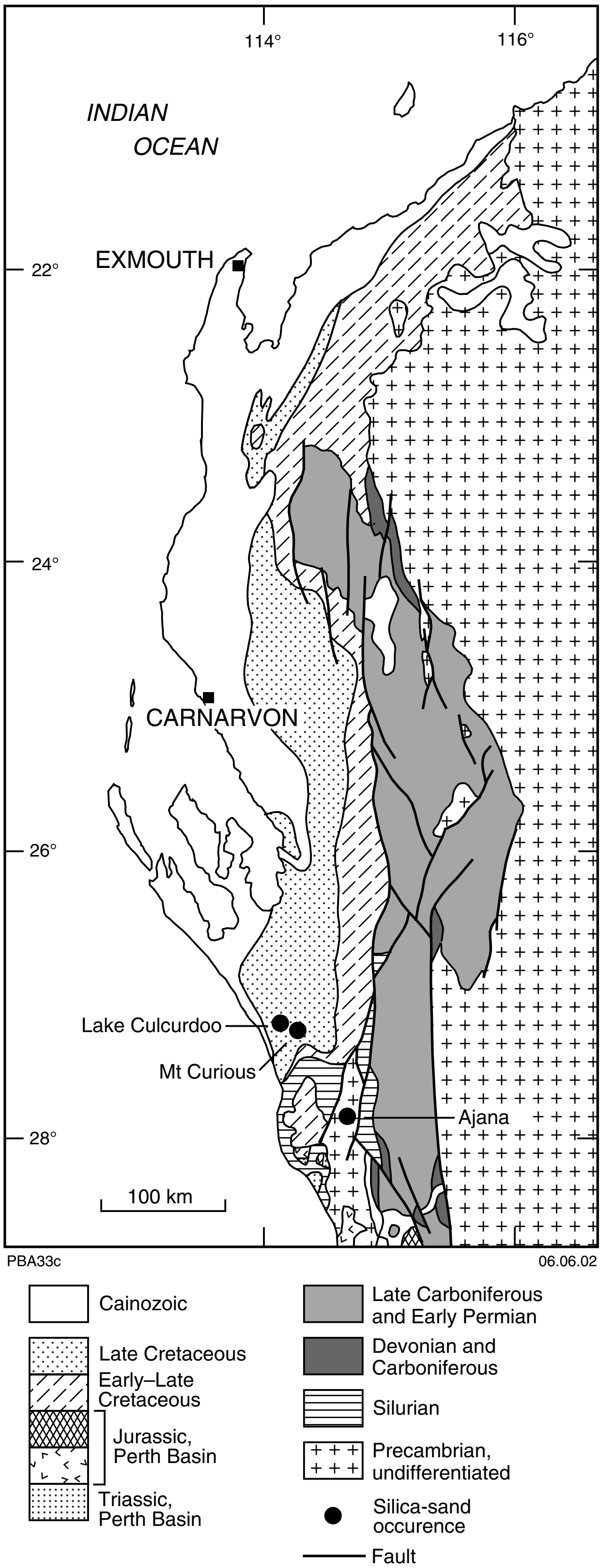


Figure 77. Regional geology of the Carnarvon Basin (after Hocking et al., 1987)

It is overlain by the Windalia Radiolarite, which is a variably porcellanized, radiolarian siltstone to chert, which is in turn overlain by the Alinga Formation. The Alinga

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

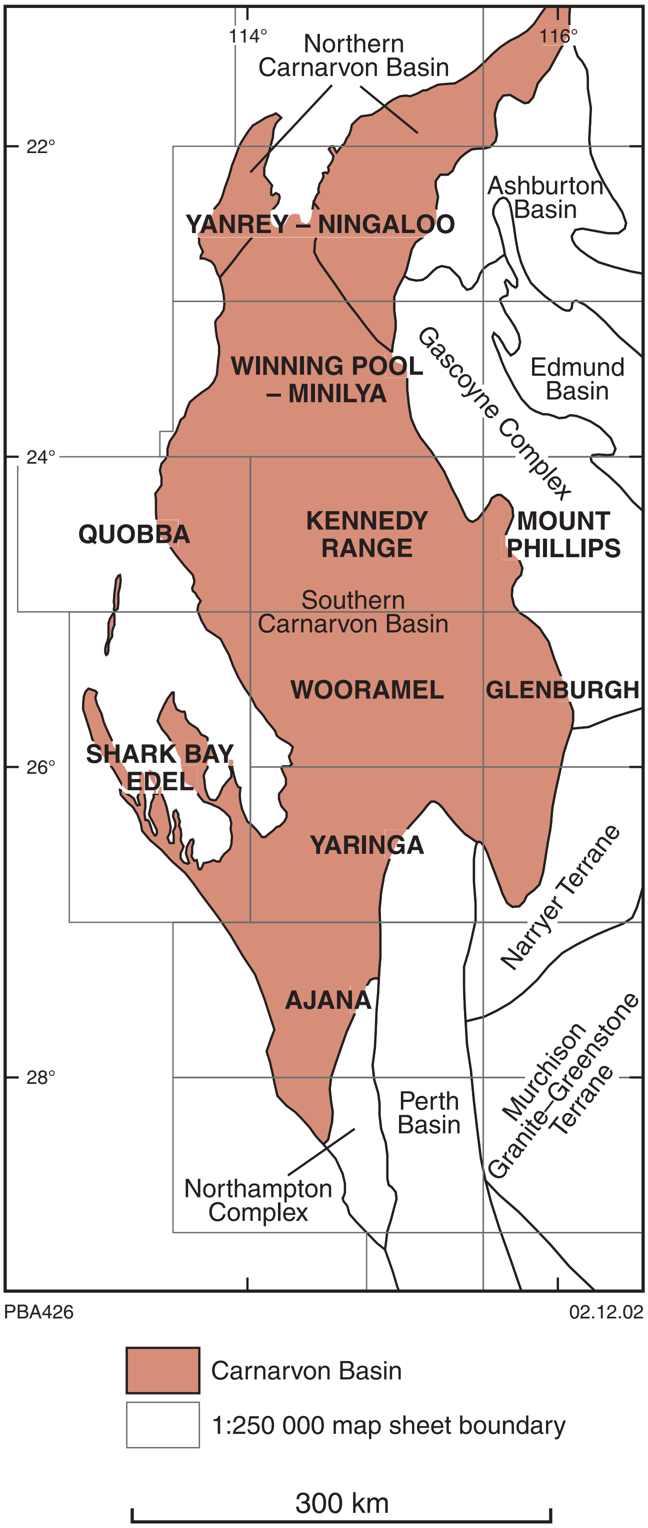


Figure 78. Distribution of 1:250 000 geological sheets in the area covered by the Carnarvon Basin

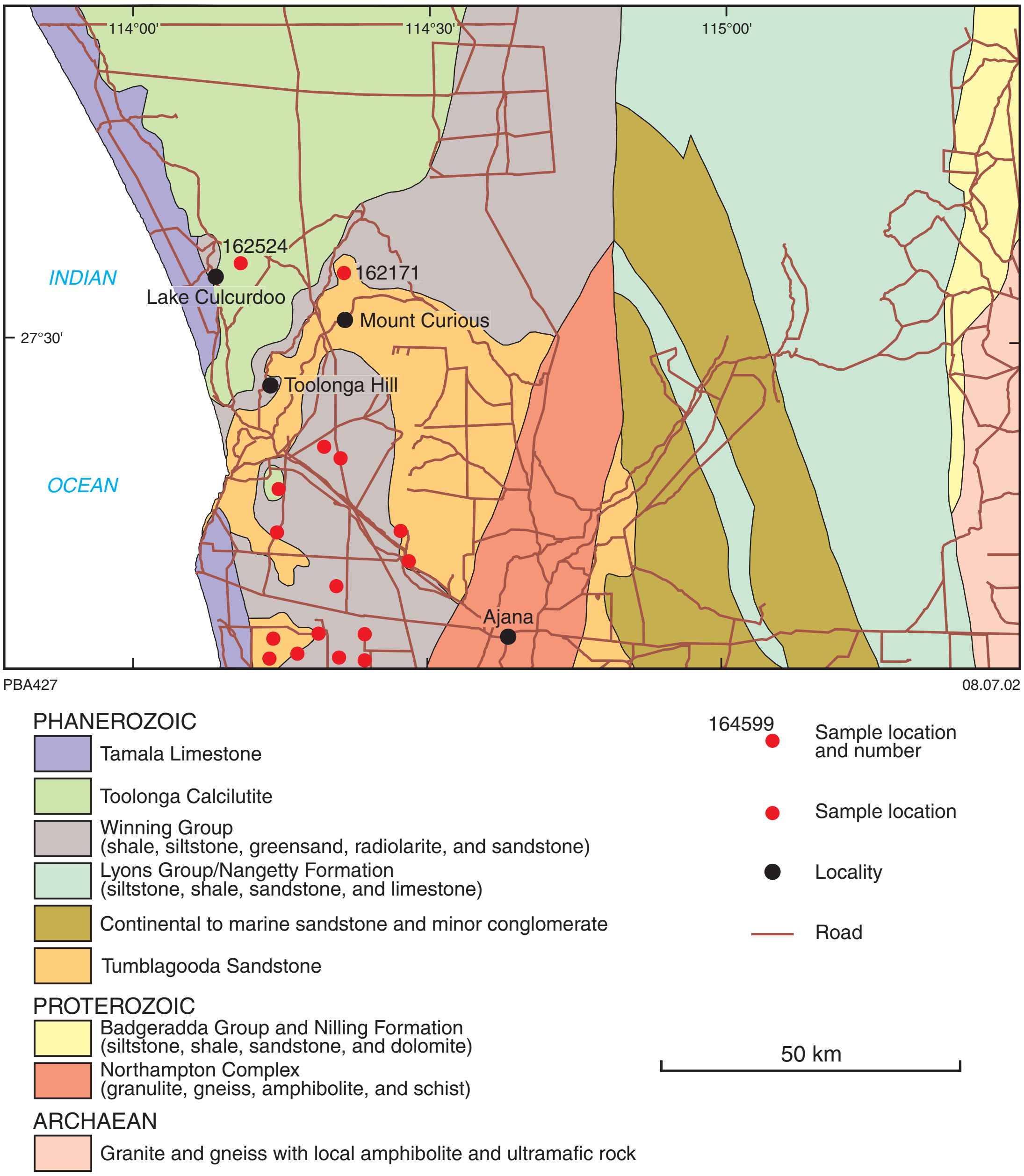


Figure 79. Sample locations with >95% SiO_2 and <0.5% Fe_2O_3 in the AJANA 1:250 000 map sheet (after Sanders and McGuinness, 2000)

Table 57. Chemical analyses of sand samples (>95% SiO_2) from the AJANA map sheet

GSWA no.	*161989*	*161990*	*162171*	*162192*	*162196*	*162197*	*162367*	*162524*	*162964*	*162978*	*162979*	*162980*	*162983*	*162988*	*162990*	*162992*
								Percentage								
SiO_2	97.30	96.80	99.70	95.60	96.90	97.80	97.30	99.30	96.40	98.00	97.20	96.80	97.90	95.80	97.40	97.60
TiO_2	0.07	0.09	0.04	0.11	0.05	0.03	0.11	0.23	0.06	0.05	–	0.11	0.04	0.09	0.08	0.11
Al_2O_3	0.62	0.63	0.56	1.25	0.21	0.23	0.70	0.51	0.71	0.30	0.30	0.33	0.14	1.14	0.18	0.52
Fe_2O_3	0.49	0.40	0.41	0.37	0.31	0.17	0.47	0.19	0.25	0.15	0.20	0.30	0.23	0.45	0.23	0.34
MnO	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
MgO	0.01	0.02	0.04	–	–	–	–	–	–	–	–	–	–	–	–	–
CaO	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.20	–	–	–	–	–	–	–	–
Na_2O	0.020	0.010	0.030	0.014	0.010	0.010	0.030	0.014	0.010	0.009	–	0.012	0.007	0.008	0.005	0.010
K_2O	0.05	0.10	0.22	0.11	0.02	0.02	0.10	0.08	0.03	0.07	0.10	0.05	0.02	0.05	0.02	0.05
P_2O_5	–	–	0.005	0.020	–	–	0.010	0.005	–	0.003	–	0.005	0.002	0.003	–	0.002
LOI	0.40	0.60	0.20	0.70	0.90	0.30	0.60	0.40	0.70	0.30	0.90	1.30	0.30	0.90	0.40	0.50
Total	**99.06**	**98.75**	**101.31**	**98.27**	**98.50**	**98.66**	**99.42**	**100.93**	**98.16**	**98.88**	**98.70**	**98.91**	**98.64**	**98.44**	**98.32**	**99.13**

SOURCE: after Sanders and McGuinness (2000)

Table 58. Chemical analyses of sand samples (>95% SiO_2) from the GLENBURGH map sheet

GSWA no.	*145667*	*146573*	*147235*	*145665*	*147260*	*146928*	*147177*
				Percentage			
SiO_2	98.00	96.90	96.80	95.50	95.20	95.10	95.10
TiO_2	0.09	0.00	0.13	0.18	0.15	0.12	0.12
Al_2O_3	0.90	1.17	1.41	2.21	1.68	1.97	1.25
Fe_2O_3	1.39	2.86	0.98	2.00	2.80	1.85	1.42
MnO	0.002	0.033	0.007	0.003	0.012	0.009	0.001
MgO	–	0.08	0.09	0.02	0.13	0.13	0.08
CaO	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Na_2O	0.011	0.017	0.02	0.013	0.029	0.026	0.013
K_2O	0.05	0.14	0.17	0.04	0.31	0.23	–
P_2O_5	0.005	0.021	0.016	0.009	0.045	0.024	0.004
LOI	0.14	0.52	1.25	0.92	0.72	1.21	0.26
Total	**100.79**	**101.94**	**101.07**	**101.10**	**101.28**	**100.87**	**98.45**

SOURCE: after Sanders et al. (1998)

Formation is a glauconite-rich clayey siltstone to greensand, but is rarely exposed (Hocking et al., 1982, 1987). The Tumblagooda Sandstone, exposed in the valley of the Murchison River, is a Silurian unit whose thickness exceeds 3000 m. The sandstone varies from red, yellow, and brown to white, is very fine to coarse grained, and is commonly conglomeratic.

Of the 142 samples containing over 95% SiO_2, 16 contained less than 0.5% Fe_2O_3 (Table 57, Fig. 79), and these were taken from the southwestern quarter of the AJANA sheet, close to Winning Group rocks and Tumblagooda Sandstone. The distribution pattern of these samples suggests that there would be large quantities of chemically high-grade sand in the AJANA sheet area. Two of the above samples, GSWA162171 and GSWA162524, assayed 99.7 and 99.3% SiO_2 respectively. Sample GSWA162171 was obtained 7 km north of Mount Curious, and GSWA164524 from 5.5 km northeast of Lake Culcurdoo (Fig. 79). The high-grade sand northeast of Lake Culcurdoo is likely to be eolian sand derived from the Winning Group outcrops to the west. To date, the samples have not been tested for other physical properties, such as particle sizing. Further testing is required for a more realistic assessment of the suitability of the material for high-grade applications such as in the glass industry.

During geochemical mapping of the GLENBURGH 1:250 000 sheet, Sanders et al. (1998) reported chemical analyses of 1019 samples collected from regolith material. Of these, seven collected from the areas covered by the Permian Byro and Wooramel Groups assayed 95–98% SiO_2, 0.98–2.86% Fe_2O_3, and 0–0.18% TiO_2 (Table 58, Fig. 80). Although the chemical grades of these samples are not extremely high, the prospectivity for high-grade silica sand in the area can be significant. The Permian

Table 59. Silica sand resources (published) in Western Australia

Deposit	*Tonnes (Mt)*	*Category*	*Comments*
Kemerton	200	Unknown	Pleistocene Bassendean Sand
Gnangara	61	Inferred	Pleistocene Bassendean Sand (there is additional 75 Mt of low-grade sand)
Wabling Hill	26	Inferred	Pleistocene Bassendean Sand
Bullsbrook	2.6	Demonstrated	Pleistocene Bassendean Sand
Mandogalup	1.3	Unknown	Pleistocene Bassendean Sand
Canning Vale	1.3	Inferred	Pleistocene Bassendean Sand
Total resources for Bassendean Sand	**292.2**		
Mindijup	20	Inferred	Tertiary to Quaternary sand
Crystal Brook	1.1	Indicated	Tertiary to Quaternary sand
Bon Accord	0.85	Indicated	Tertiary to Quaternary sand
Kronkup	0.58	Indicated	Tertiary to Quaternary sand
Marbellup	0.15	Inferred	Tertiary to Quaternary sand
Lake Don	4	Inferred	Tertiary to Quaternary sand
Mount Burges	4.7	Demonstrated	Tertiary to Quaternary sand
Overall total	**323.6**		

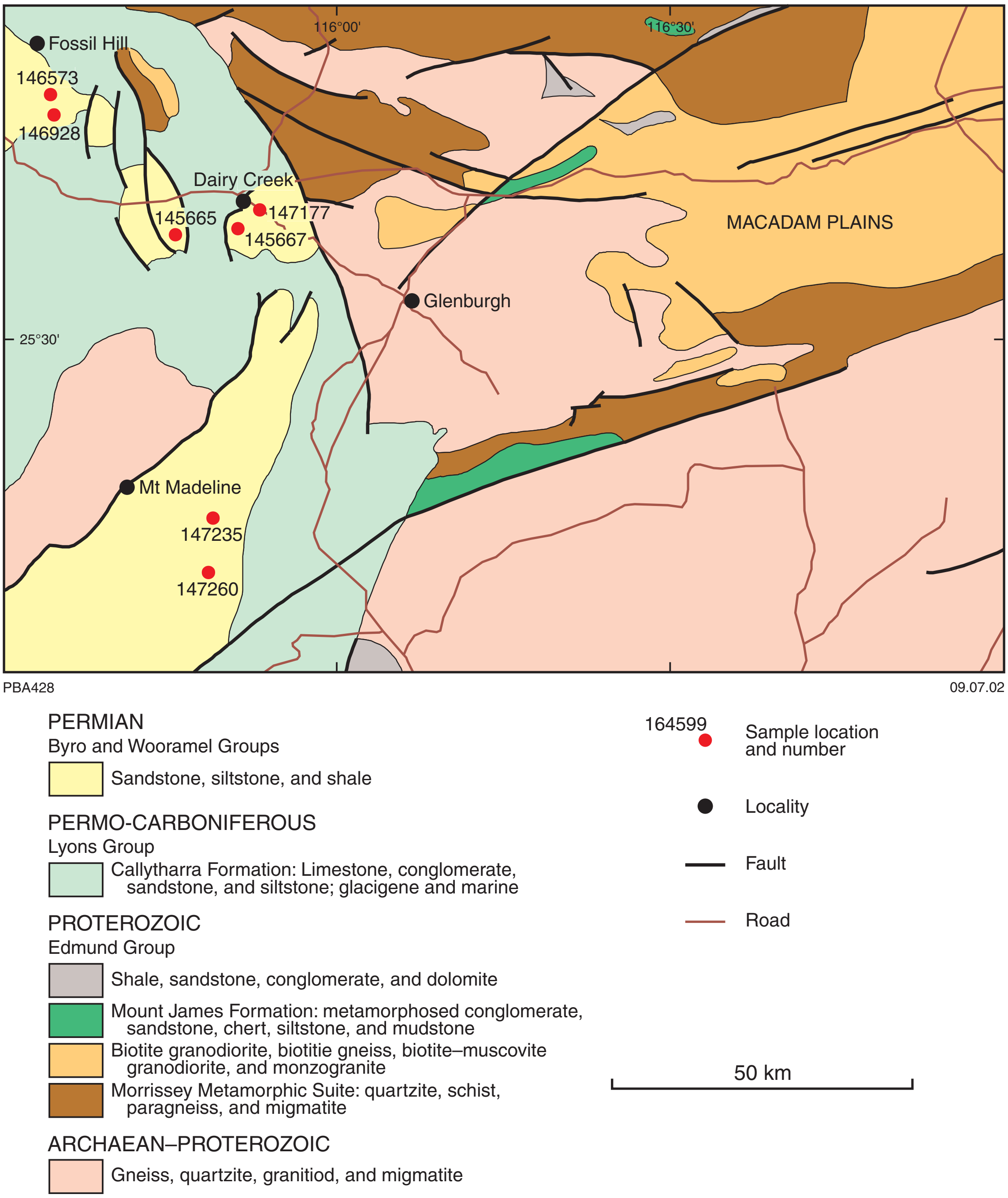


Figure 80. Silica sand localities with >95% SiO_2 in the GLENBURGH 1:250 000 map sheet (after Sanders et al., 1998)

Wooramel Group is a sandy, silty sequence, which in GLENBURGH consists of Moogooloo Sandstone, and Billidee and Keogh Formations. The Permian Byro Group is a fine-grained, locally fossiliferous, shelf sequence consisting of bioturbated siltstone and silty sandstone, with fine-grained calcareous sandstone (Williams et al., 1983a).

Resources and markets

The total resource of silica sand in Western Australia is very large. On the basis of published information, the total resource is estimated at around 324 Mt, of which 292 Mt are in the Bassendean Sand of the Perth Basin (Table 59). The Bassendean Sand estimate does not include the Jandakot deposits, which have no published resource. However, it is known that there are large silica sand resources in the Jandakot area, which are likely to be similar to that of the Gnangara area at around 61 Mt.

Most of the sand produced in the State is exported, without much downstream processing, to Japan, Korea, and other countries in the Asian region. Unimin (formerly ACI) is the only company involved locally in value adding, with the manufacture of clear and coloured container glass. Processing of silica sand in other Western Australian silica sand mines is restricted to washing and sizing, although the sand from these deposits is suitable for high-grade applications such as glass, chemical, and foundry sand industries, and also as filtration sand.

Production from the Gnangara deposit (owned by Rocla Quarry Products) is over 260 000 tpa, with the majority of sales from the deposit being exported to Japan and Korea in the form of bulk shiploads. Depending on the markets, the company can also provide sand in container loads, or dry graded sand in bulker bags, or milled products. Bulk shipments of up to 40 000 t are handled through a loading facility in Kwinana, just south of Fremantle port, with a maximum daily loading rate of 11 000 t. The sand is delivered to the loading facility by road train. The Jandakot mine (owned by the Readymix Group) produces approximately 100 000–120 000 tpa of mostly high-grade silica sand, with a smaller tonnage for the construction industry. A significant proportion of the production is exported to Japan and other Asian destinations. The production of silica sand from the Kemerton deposit (owned by Kemerton Silica Sand Pty Ltd) exceeds 400 000 tpa and is mostly exported to Japan, for use in the container-glass industry and television picture tubes. This market requires both a special high-quality sand containing alumina, and very tight control over the size of grains and the level of impurities. As a step towards diversifying its markets, Kemerton Silica Sand Pty Ltd has recently produced about 10 000 t of sheet-glass grade silica sand. The company also sells a small quantity of its products to local markets, such as Unimin Australia Ltd, for container-glass manufacture. The Mindijup mine (owned by TT Sand Pty Ltd) produces around 100 000 tpa of high-grade silica sand, which is exported to Japan for foundry and glass industries. Other markets are currently being sought in South East Asia.

Chapter 5

Silica rock resources of Western Australia

Commercially important silica rock close to coastal regions and population centres of Western Australia comprises chert, vein quartz, quartzite, and quartz-bearing pegmatite. At present, the only hard-rock mine for silica in Western Australia is near Moora, where Noondine Chert is mined for the production of silicon metal in a plant 300 km to the south at Kemerton, near Bunbury. However, there are other localities in Western Australia that are likely to contain silica rocks suitable for commercial exploitation (Fig. 81).

Following are descriptions of the Moora mine and other commercially prospective areas for hard-rock silica in Western Australia.

Moora

In the 1980s, Barrack Silicon Pty Ltd acquired the Moora Mine from Agnew Clough Ltd, which had carried out extensive exploration programs in the Moora region for high-grade silica suitable for the production of silicon metal. The programs resulted in the identification of a deposit of high-quality silica, 14 km north of Moora, which is 195 km north of Perth. The silica rock identified at the Moora mine is chert, but is often referred to locally as a ‘quartzite’. At the commencement of operations, the chert resources identified in the deposit were considered to be sufficient to sustain a twenty-year project life, assuming an average furnace consumption of 60 000 to 70 000 tpa of chert. The production of chert at the Moora mine began in 1989 and has continued on an annual campaign basis. The current production rate is around 90 000–95 000 tpa.

The Moora mine is currently owned by Simcoa Operations Pty Ltd, which operates two silicon furnaces at Kemerton about 15 km north-northeast of Bunbury. The plant has a current capacity to produce 31 000 tpa of silicon metal and 10 000 tpa of silica fume.

Geology

Chert at the Moora Mine is found within the Moora Group, which outcrops at the western edge of the Yilgarn Craton and is truncated by the Darling Fault at its western margin (Fig. 82). Myers (1990) includes the Moora Group in his description of the Pinjarra Orogen. The rocks in the Moora Group consist of a Proterozoic sequence, broadly comprising a ‘weakly deformed immature fluviatile–alluvial fan–basin margin’, which unconformably overlies the Archaean Yilgarn Craton. The rocks in this sequence are described by Logan and Chase (1961), Playford et al. (1976), Carter and Lipple (1982), and Baxter and Lipple (1985). Stratigraphic units within the Moora Group are given in Table 60.

The chert within the Moora Group is confined to the Coomberdale Subgroup of the Marchagee – Three Springs belt (Fig. 82), which is intersected by a number of northerly trending dolerite dykes of probable Proterozoic age. The Coomberdale Subgroup has a width of 4–15 km, and extends northwards for over 200 km along the western margin of the Yilgarn Craton. The units within the Coomberdale Subgroup are the basal Mokadine Formation, Winemaya Quartzite and Campbell Sandstone and the overlying Noingara Siltstone, Noondine Chert, and Jingemia Dolomite. The Coomberdale Subgroup has not undergone significant deformation or metamorphism, except for the contact metamorphism adjacent to dolerite dykes. Weak to moderate cleavage and minor concentric folding have developed in shales and siltstones. Close to the Darling Fault the folds are increasingly compressed, with steep bedding dips around 80° being recorded; however, some 2 km to the east, dips are almost flat. In the area around the Moora mine, exposed units of the Coomberdale Subgroup are restricted to the Mokadine Formation and Noondine Chert (Fig. 83).

Mineralization

The high-quality chert that is currently mined at Moora, and which is developed predominantly within the Noondine Chert, is a silicified, bedded, carbonate (siliceous limestone–dolomite) unit. Silicification of the chert has been observed to a depth of at least 75 m. The chert, which strikes in a northerly direction with 20–30º westerly dip, consists of predominantly quartz with trace amounts of chlorite, sericite, pyrite, apatite, calcite, and dolomite. Secondary oxides of titanium and iron, together with clays are found within the chert near the surface. Faults and joints within the chert typically contain clays, and local cavities within the chert are filled with quartz gravel.

In December 1991, Simcoa Operations Pty Ltd drilled two diamond holes (MD1 and MD2) within Mining Lease M70/191 to test the thickness of the Noondine Chert in the area. Hole MD2 intersected high-grade chert to a depth of 75 m, below which the rock was found to be carbonate-

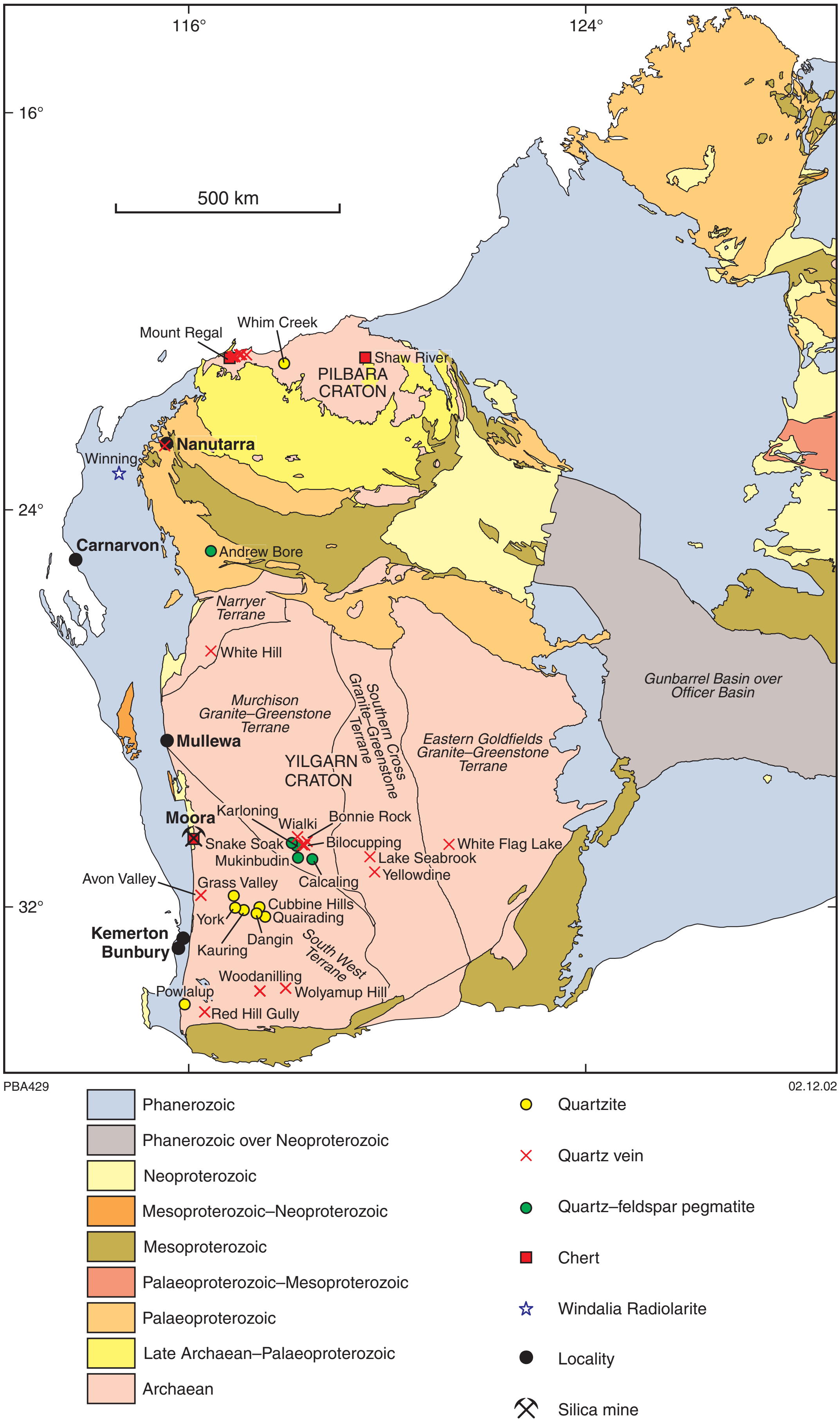


Figure 81. Silica rock resources of Western Australia

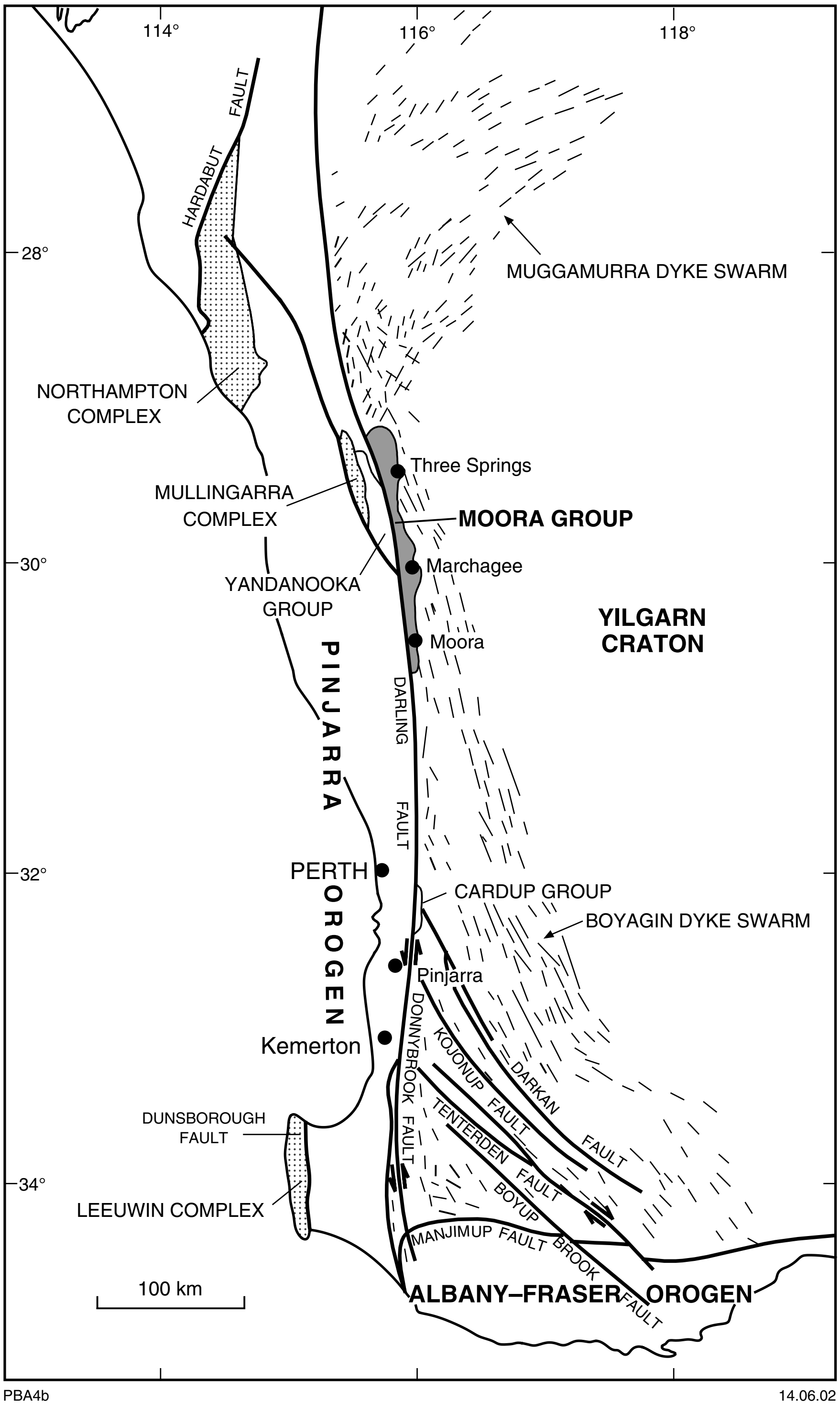


Figure 82. Distribution of the Moora Group (after Myers, 1990)

Table 60. Stratigraphy of the Moora Group

Subgroup	*Formation* MOORA *(1:250 000 sheet)*	*Formation* PERENJORI *(1:250 000 sheet)*	*Previous nomenclature*
Coomberdale		Jingemia Dolomite	Coomberdale Chert Dudawa Beds
	Noondine Chert	Noondine Chert	
	Noingara Siltstone	Noingara Siltstone	
	Winemaya Quartzite	Campbell Sandstone	
	Mokadine Formation	Mokadine Formation	
~ ~ ~ unconformity or disconformity ~ ~ ~			
Billeranga			Billeranga Beds
			Billeranga Group
		Oxley Chert Morawa Lavas	
	Dalaroo Siltstone	Dalaroo Siltstone	
	Capalcarra Sandstone	Neereno Sandstone	
~ ~ ~ unconformity ~ ~ ~			
Archaean basement			

SOURCE: after Baxter and Lipple (1985)

rich (calcite–dolomite) siltstone and fine-grained, banded, stromatolitic limestone.

Evidence from the drillcores suggests that the chert was formed by silicification of Proterozoic stromatolitic limestone/dolomite, with sedimentary banding disrupted by subsequent diagenesis. The carbonate rocks contain approximately 25% quartz, 45% calcium carbonate, and 30% magnesium carbonate. The silicification process is probably related to near-surface Tertiary weathering. The chemical silica front forming chert appears to have invaded the carbonate rocks from surface.

Petrography

Petrographic studies of samples (GSWA145227–37) collected from the mine area, in and around the openpit, are summarized in Tables 61 and 62. Apart from quartz–silica, which is the most dominant mineral, trace minerals identified in the chert include chlorite, carbonate, apatite, sericite, muscovite, tourmaline, and opaques. A sample near the base of drillhole MD2 contains chert enclosed by a carbonate network. In this sample, there are local concentrations of very fine apatite. Textural characteristics of this sample suggest that apatite may have been precipitated with the chert. In the samples collected from the area (GSWA145227–37) it was generally difficult to identify any specific discrete grains or crystals, or composites, which could be regarded as proper accessory minerals.

One sample, GSWA145228 (Fig. 84a,b), shows an apparently inherited sedimentary layering as ultrafine random crystals of chlorite in variable concentration are intricately incorporated within the chert. Some of this material could also be apatite. These impurities (chlorite and possible apatite) would be expected to give slightly elevated assay values for Fe, Mg, Ca, P, Al and possibly Ti, which in fact is confirmed by the assays (Table 63). In almost all other samples, a minor impurity is found as ultrafine material (<5 µm), variably dispersed in different layers. This material, which generally constitutes less than 1% in most samples, cannot be positively identified by optical microscopy although it may include carbonate, sericite, leucoxene, chlorite, or iron oxide.

Petrographic studies of eleven samples (GSWA 145227–37) throughout the area indicate 50–75% cryptocrystalline silica, commonly massive to weakly layered, with some distinctly laminated, especially as seen in hand specimen. The other component (equally abundant to subordinate) is a slightly coarser mosaic of microgranular to microsparry quartz, which is locally much coarser and occurs in irregular stringers and veins, and along the layering in places. These two texturally different but merging forms of quartz have a consistent relationship within samples GSWA 145227, GSWA145233, GSWA145235, and GSWA 145236 (Figs 85–88). The same components are more regularly laminated in GSWA45232 and GSWA145237 (Figs 89–90).

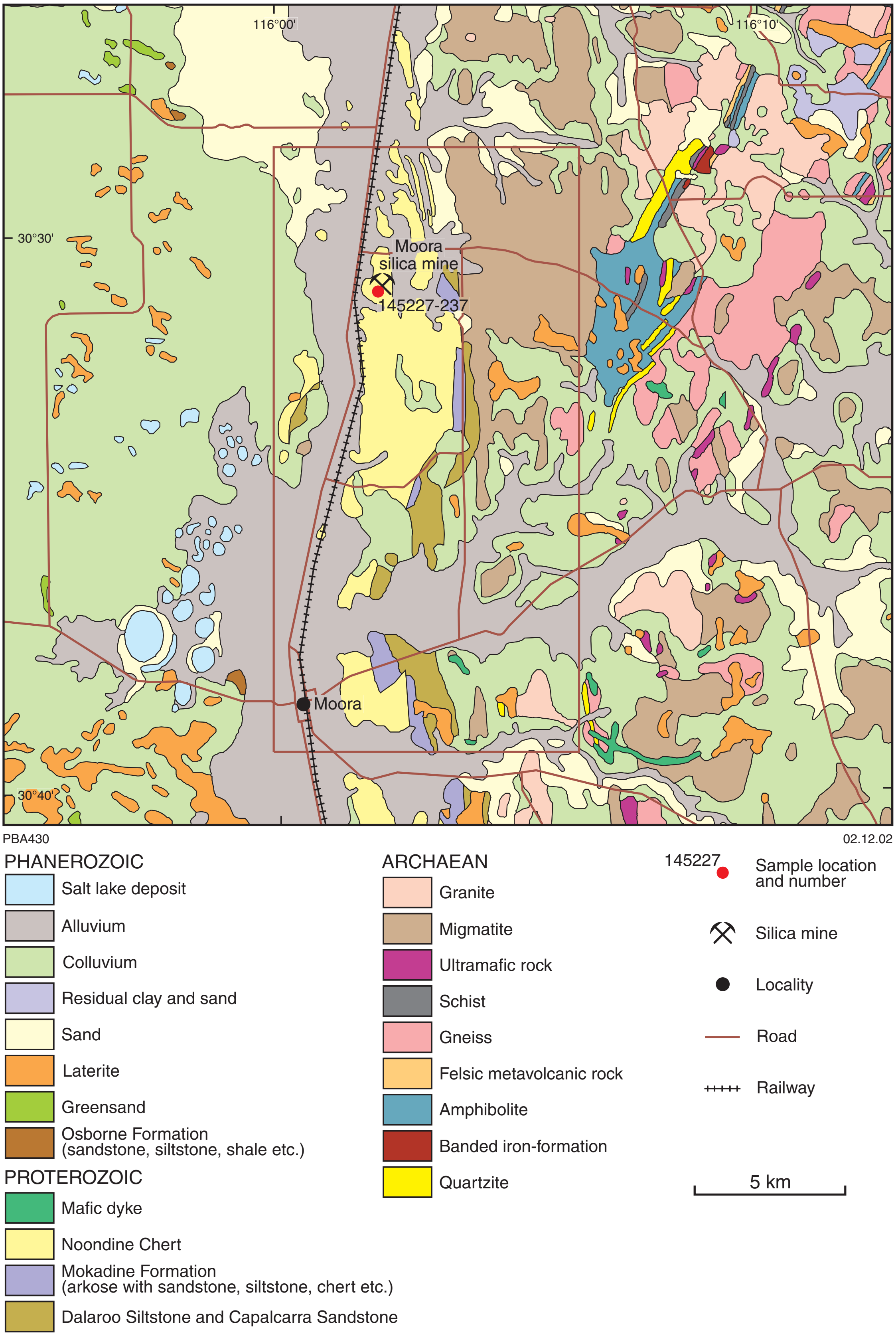


Figure 83. Geology of the Moora area (Low et al., 1982)

Table 61. Summary of test results of chert samples from different locations at the Moora mine area

GSWA no.	*Field description*	*Thermal stability*	*Thermal strength*	SiO_2	Al_2O_3	Fe_2O_3	*MgO*	*CaO*	TiO_2	P_2O_5	*Petrographic summary*
						Percentage					
145227	Typical chert at bottom of pit	73.6	98.5	99.2	0.08	0.06	0.17	0.1	<0.01	0.017	98% quartz with remainder consisting of iron oxide (dust), probable sericite, and possible carbonate
145228	High-phosphorus chert	81.0	98.8	90.1	1.32	0.31	0.33	4.07	0.06	3.05	Up to 90% of the sample consists of ultrafine, cryptocrystalline quartz (chert) with fine, widespread chlorite and extremely fine rutile/anatase/leucoxene. The remaining 10% consist of coarser clearer granular to sparry quartz, as infillings to small voids to 5 mm across, plus quartz stringers (Fig. 84a,b)
145237	Chert — West Ridge (planned pit)	91.6	97.9	99.7	0.05	0.08	<0.01	0.01	<0.01	0.007	Regularly laminated chert with cryptocrystalline silica> microcrystalline quartz intercalated at close but regular intervals. 'Dust' very sparse
145230	High-titanium chert	85.7	96.7	98.5	0.04	0.73	0.02	0.01	0.54	0.013	Chert breccia with minor angular fragments of (clear) chert, within more extensive matrix of clouded chert with some iron staining and apparent quartz-sand grains. Ultrafine clouding material optically indeterminate
145231	High-aluminium chert	93.7	98.2	91.6	2.88	0.75	3.00	<0.01	0.12	0.01	Chert with lenses, and variably continuous irregular bands as primary structures within (disrupted) chemical sediment. Minor silt, rarer sand grains, and dispersed 'dusty' material (?1–2%) of indeterminate composition, but may include a chloritic, sericitic, or iron oxide component
145232	High-quality chert	64.8	98.0	99	0.36	0.17	0.05	0.05	0.01	0.009	Laminated chert, variably of cryptocrystalline to micro-crystalline silica with about 1/3 of layers clouded by ultrafine 'dust' of indeterminate composition, but could include iron oxide, carbonate, sericite, and leucoxene. Local large lens infilled by (zoned) coarse sparry to granular quartz
145235	High-quality chert	99.8	98.9	99.9	<0.01	0.09	0.02	0.03	0.01	0.01	Weakly fine-layered chert with up to 35% veinlets of micro-granular to sparry quartz, partly along layering, also at random. 'Dust' very sparse
145236	Low-iron chert	80.4	98.5	99.4	0.19	0.05	0.03	0.02	0.02	0.023	Weakly layered chert, some bands of laminated crypto-crystalline silica with minor sporadic microcrystalline quartz
145233	Low-phosphorus surface chert	93.2	97.3	99.8	<0.01	0.01	<0.01	<0.01	0.02	0.005	Massive to moderately layered (very milky-white) chert, with minor veinlets of fine granular/sparry quartz, along the layering, some at random. 'Dust' very sparse
145234	High-titanium and low-phosphorus chert	71.2	98.3	98.9	0.52	0.23	0.05	0.01	0.1	0.018	Breccia with numerous small angular ghost-like fragments of chert, incorporated within a massive, fairly homogeneous matrix of ultrafine cryptocrystalline chert. Local weak limonite staining
145229	High-iron chert	99.3	97.9	96.4	1.89	0.51	0.07	0.03	0.12	0.008	Chert breccia, with sparse ultrafine dispersed ?sericite. Breccia matrix (40%) includes medium size quartz sand grains in intricately mixed silica+clay+limonite staining

Table 62. Summary of petrographic descriptions of samples from the drillhole MD2

Drillhole	*Sample depth(m)*	*Minerals(%)*	*Comments*
MD2	81.3	Carbonate portion: Carbonate >89, quartz 3–5, chlorite 1–2, opaques 1 Chert portion: Quartz >94, carbonate 1–2, apatite <1–5	The section consists of portions of a carbonate rock and replacive chert. The contact is interdigitated, resembling a stylolite. Also has opaques, chlorite, and apatite
MD2	89.8	Quartz (major), carbonate (major), apatite (trace to major), opaques <1, muscovite (trace)	Chert enclosed by carbonate network. Areas of concentrations of very fine apatite, suggesting brecciation by their sharp angular chert host. The distinction between phosphatic and non-phosphatic chert is very sharp. The best example of the former is a 3 × 1 mm block, and of the latter, 10 µm fine apatite
MD2	93.4	Quartz 55–60, carbonate 30–40, opaques 2–3, apatite 1, sericite 1, rutile? 1, chlorite <1	Partly composed of chert and partly of carbonate. Chert shows variation in texture with pieces showing different mineralogy. Chert adjacent to the main carbonate development is darker than the main chert farther away. There is another ?front of stylolite type, which appears to be composed of very fine rutile, and lesser opaques. There is one concentration of sulfides (as aggregate 1 mm) in the chert, but having pressure shadows of quartz
MD2	93.8	Carbonate (major), silica/quartz (major), opaques <1	Consists of partly fine chert and partly of coarse carbonate. The former varies from an almost pure coarse chert, to a coarser slightly carbonate-spotted almost mylonitic quartzite. Relation between the quartz and the carbonate is complex, both have undergone deformation, which postdates silica replacement

SOURCE: after Parker (1992)

The other five chert samples petrographically indicate some variation in texture, probably inherited from a primary siliceous chemical sediment and seen as undulating to irregular layering in GSWA145228 (Fig. 84a,b), and possible intra-formational disruption, with minor quartz silt and sand grains, in GSWA145231 (Fig. 91). More advanced and severe brecciation, possibly diagenetic, or even later with follow-up resilicification, occurs in GSWA145229 (Fig. 92) and GSWA145230 (Fig. 93). Sample (GSWA145229) shows abundant quartz sand grains and limonite staining in the matrix.

Quality of chert

Chemical composition

The chert at Moora has variable chemical grades, but the average quality is acceptable for many metallurgical and chemical end-uses in the silicon industry. The typical chert contains <0.10% Fe_2O_3, <0.30% Al_2O_3, <0.03% TiO_2, <0.01% P_2O_5, and around 99.7% SiO_2. Chert with higher percentages of these oxide impurities is generally unsuitable for silicon production, but the quality of some of the impure chert can be blended with high-grade chert in order to increase the quartz resource. Some chert is very pure with oxide impurities <0.03% Fe_2O_3, <0.10% Al_2O_3, <0.003% TiO_2, and <0.003% P_2O_5.

Iron and titanium

Iron and titanium levels vary throughout the mine area. Iron minerals consist of pyrite at depth, which is oxidized to limonite near surface. The percentage of Fe_2O_3 and TiO_2 throughout the mine area varies from 0.01 to 0.20% and 0.001 to 0.10% respectively.

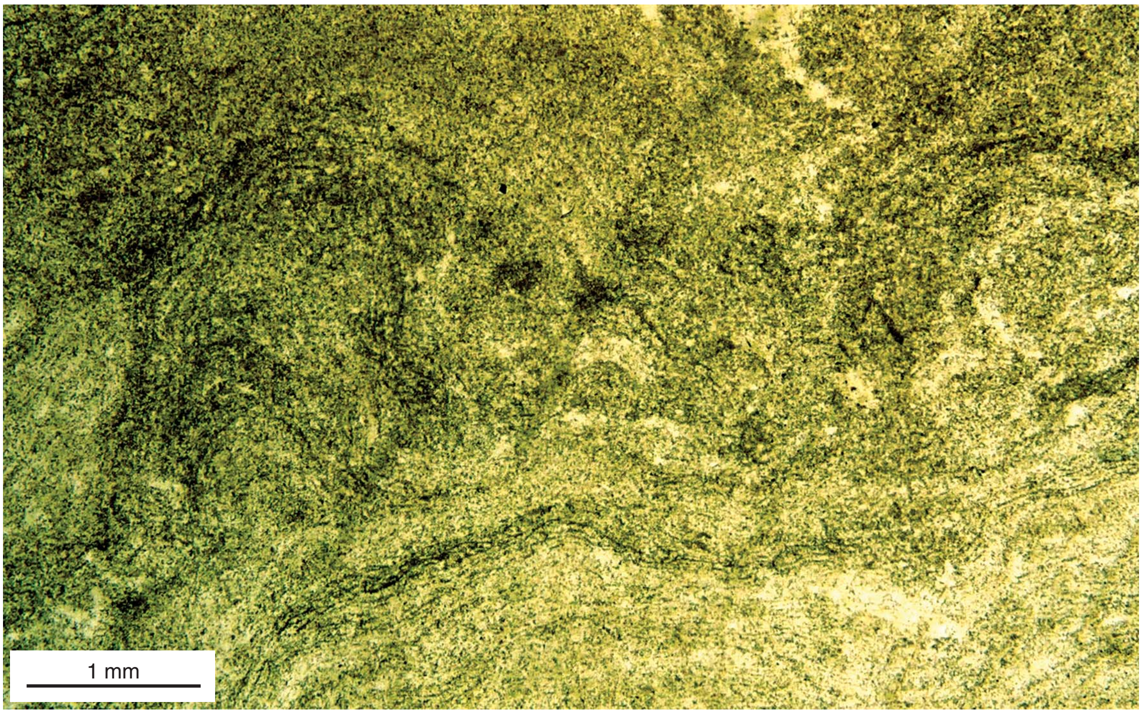
There is an approximate positive correlation between TiO_2 and Fe_2O_3, which suggests that most of the titanium in chert is likely to be found in ilmenite or leucoxene. Lack of more definite correlation between Fe_2O_3 and TiO_2 is likely to be due to the presence of iron in numerous other minerals such as sericite (GSWA145231–32), chlorite (GSWA145231), and clay present as ultrafine material in the chert.

Owing to the ultrafine nature of quartz/silica and associated trace minerals, positive identification of ilmenite, leucoxene, and other trace minerals in these samples by petrographic means is found to be extremely difficult, although in some samples traces of these minerals are found (Fig. 84a,b).

Aluminium and iron

The alumina (Al_2O_3) percentage in chert varies throughout the mine area, ranging from 0.005% to 0.40% according to the presence of clays and chlorite. There is a very approximate and broad positive correlation between Al_2O_3 and Fe_2O_3 in the area. This relationship is possibly due to the presence of both iron and aluminium in minerals such as sericite, chlorite, and clay minerals observed in some samples (Figs 84a,b and 92). Lack of a closer positive relationship can be attributed to the fact that both iron and aluminium can be present as separate minerals (e.g. iron as limonite and aluminium in chlorite).

(a)



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(b)

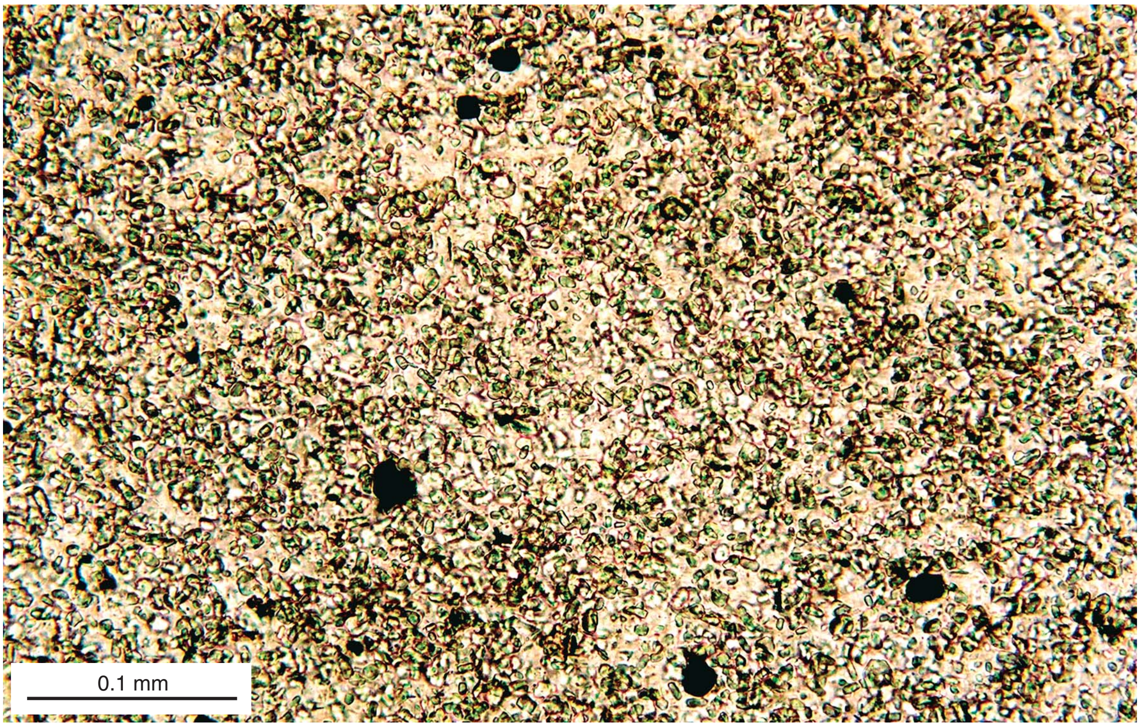

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Figure 84. a) Photomicrograph (ordinary light ×20) showing contorted to undulating extremely fine layering of chlorite in chert (sample GSWA145228: Moora silica mine); b) Photomicrograph detail from Figure 84a showing ultrafine chlorite crystals and opaque minerals (ordinary light ×200)

Table 63. Chemical analyses of chert samples from different locations at the Moora mine area

Sample no.	*145227*	*145228*	*145229*	*145230*	*145231*	*145232*	*145233*	*145234*	*145235*	*145236*	*145237*
						Percentage					
SiO_2	99.2	90.1	96.4	98.5	91.6	99	99.8	98.9	99.9	99.4	99.7
Al_2O_3	0.08	1.32	1.89	0.04	2.88	0.36	<0.01	0.52	<0.01	0.19	0.05
Fe_2O_3	0.06	0.31	0.51	0.73	0.75	0.17	0.01	0.23	0.09	0.05	0.08
MgO	0.17	0.33	0.07	0.02	3.00	0.05	<0.01	0.05	0.02	0.03	<0.01
CaO	0.10	4.07	0.03	0.01	<0.01	0.05	<0.01	0.01	0.03	0.02	0.01
Na_2O	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
K_2O	0.01	0.34	0.27	0.02	0.04	0.07	<0.01	0.16	<0.01	0.07	0.05
TiO_2	<0.01	0.06	0.12	0.54	0.12	0.01	0.02	0.10	0.01	0.02	<0.01
MnO	<0.01	0.02	0.01	0.01	<0.01	0.01	<0.01	0.01	<0.01	<0.01	0.01
P_2O_5	0.017	3.05	0.008	0.013	0.010	0.009	0.005	0.018	0.010	0.023	0.007
BaO	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01
SO_3	<0.01	0.09	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	0.14	0.32	0.59	0.21	1.50	0.13	0.01	0.11	0.02	0.03	0.01
Total	**99.78**	**100.06**	**99.90**	**100.09**	**99.90**	**99.86**	**99.85**	**100.12**	**100.08**	**99.83**	**99.92**
H_2O	<0.01	0.03	0.7	0.87	0.18	0.07	2.87	0.37	0.08	0.02	0.04

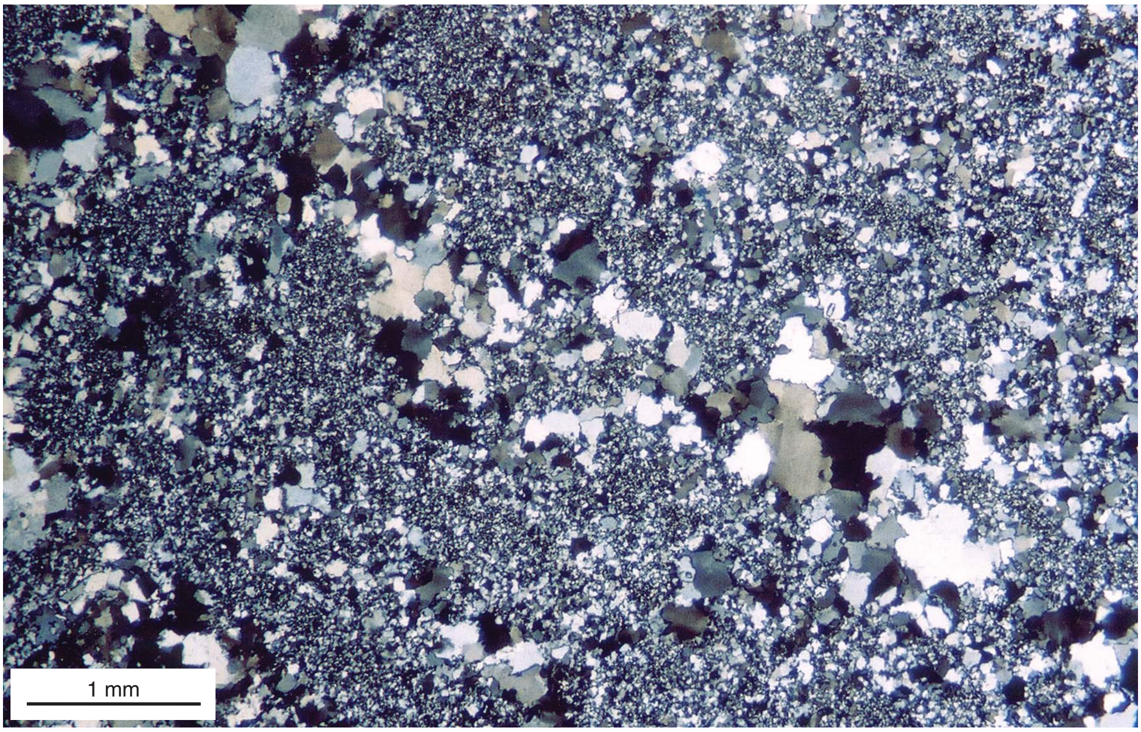

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Figure 85. Photomicrograph (crossed nicols ×20) showing fine chert containing quartz patches and diffuse bedding (sample GSWA145227: Moora silica mine)

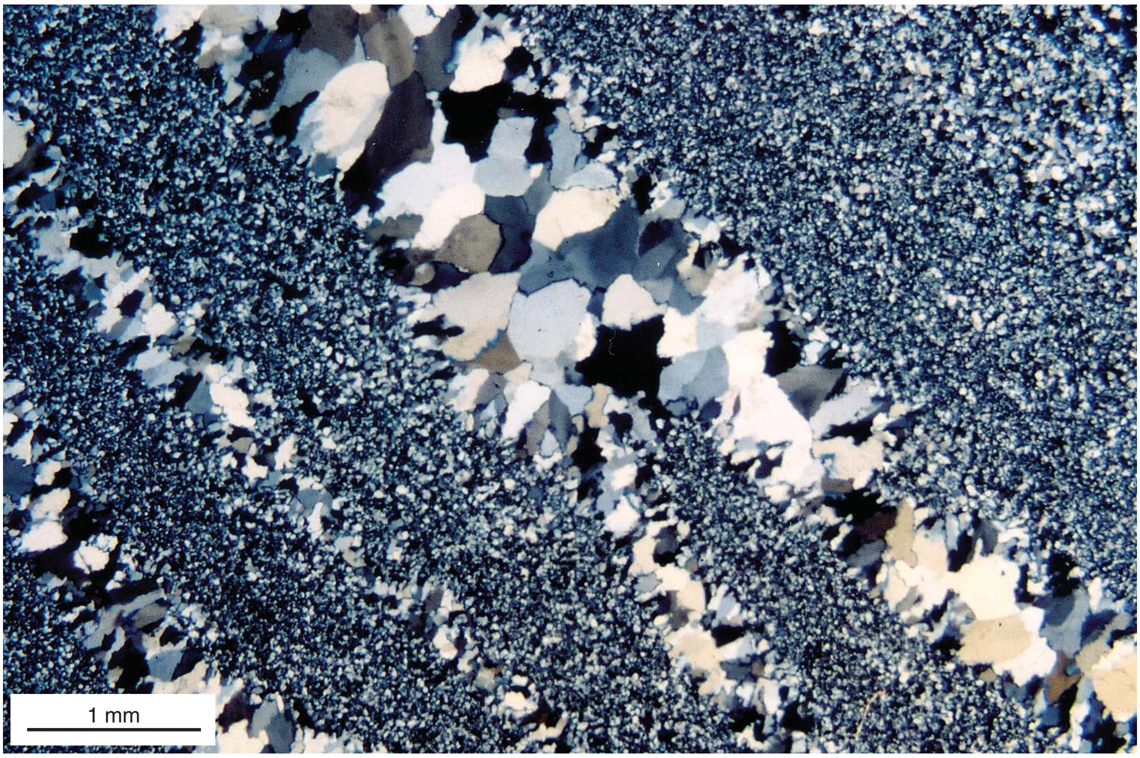

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Figure 86. Photomicrograph (crossed nicols ×20) showing bedded chert, mostly bands of cryptocrystalline silica, with common layer-veins of fine granular to sparry quartz (sample GSWA145233: Moora silica mine)

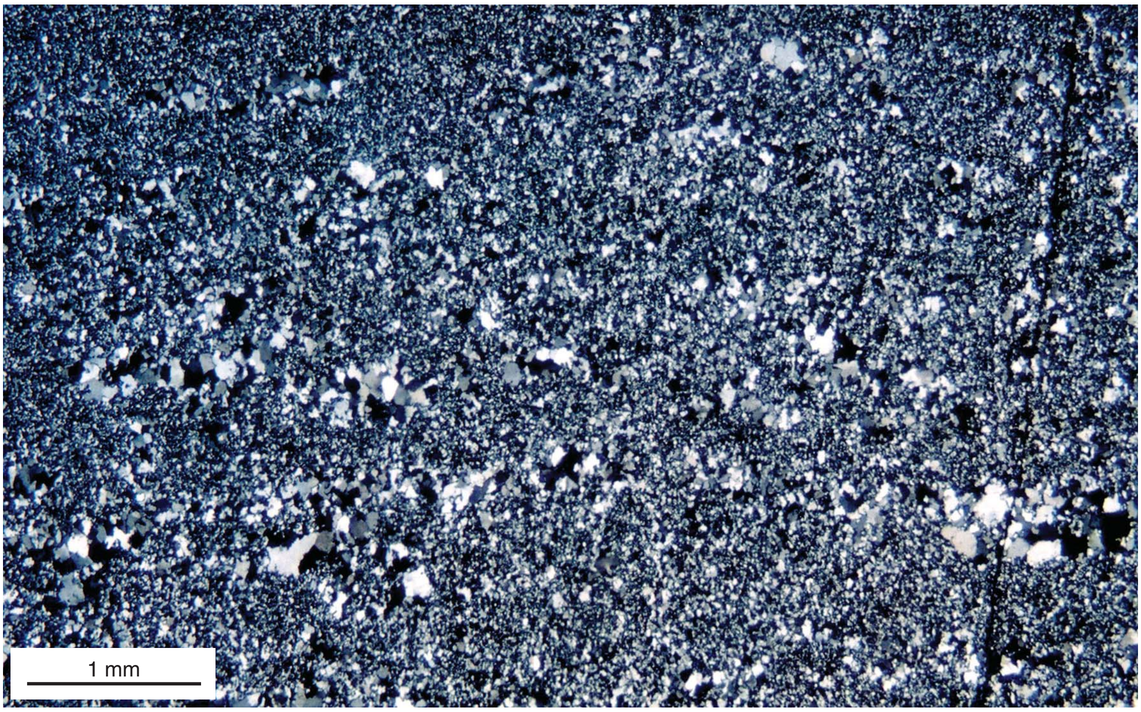

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Figure 87. Photomicrograph (crossed nicols ×20) showing fine-bedded chert (sample GSWA145235: Moora silica mine)

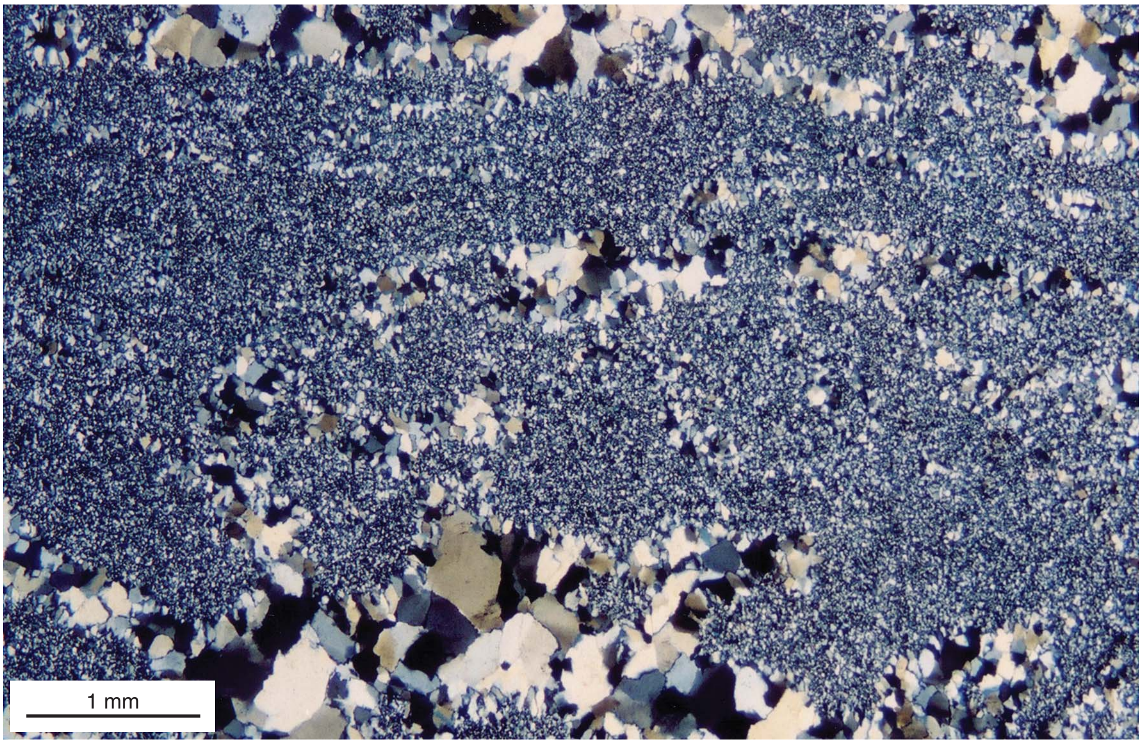

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Figure 88. Photomicrograph (crossed nicols ×20) showing chert with layer-veinlets of microsparry, microgranular quartz (sample GSWA145236: Moora silica mine)

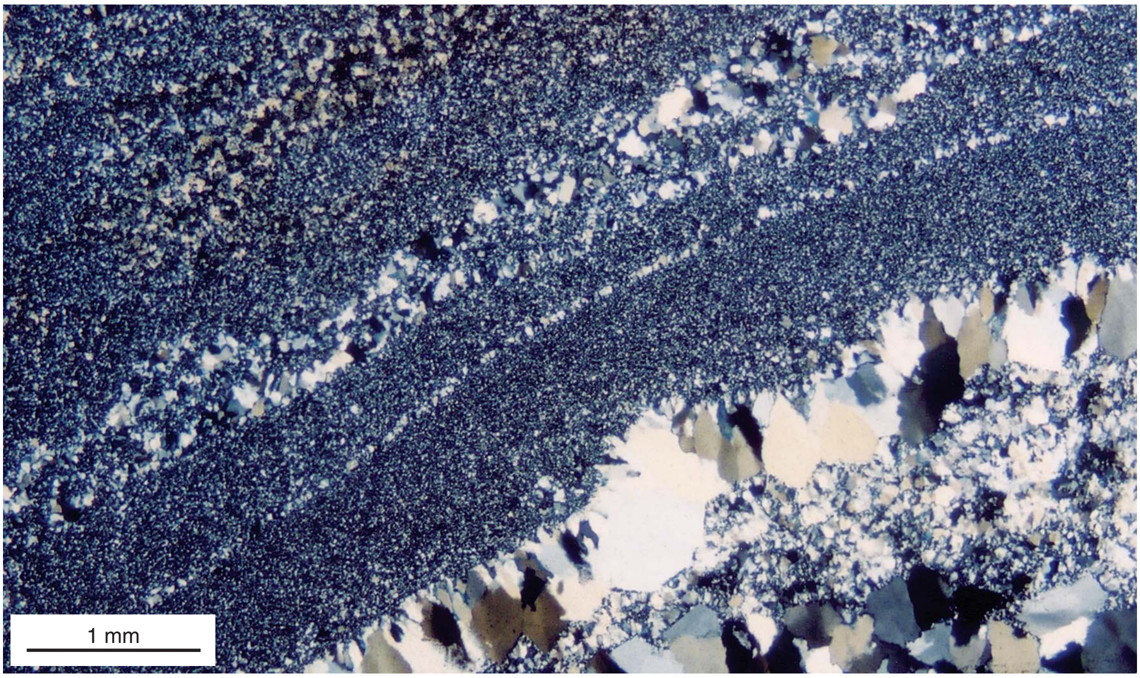

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Figure 89. Photomicrograph (crossed nicols ×20) showing layered-laminated chert (sample GSWA145232: Moora silica mine)

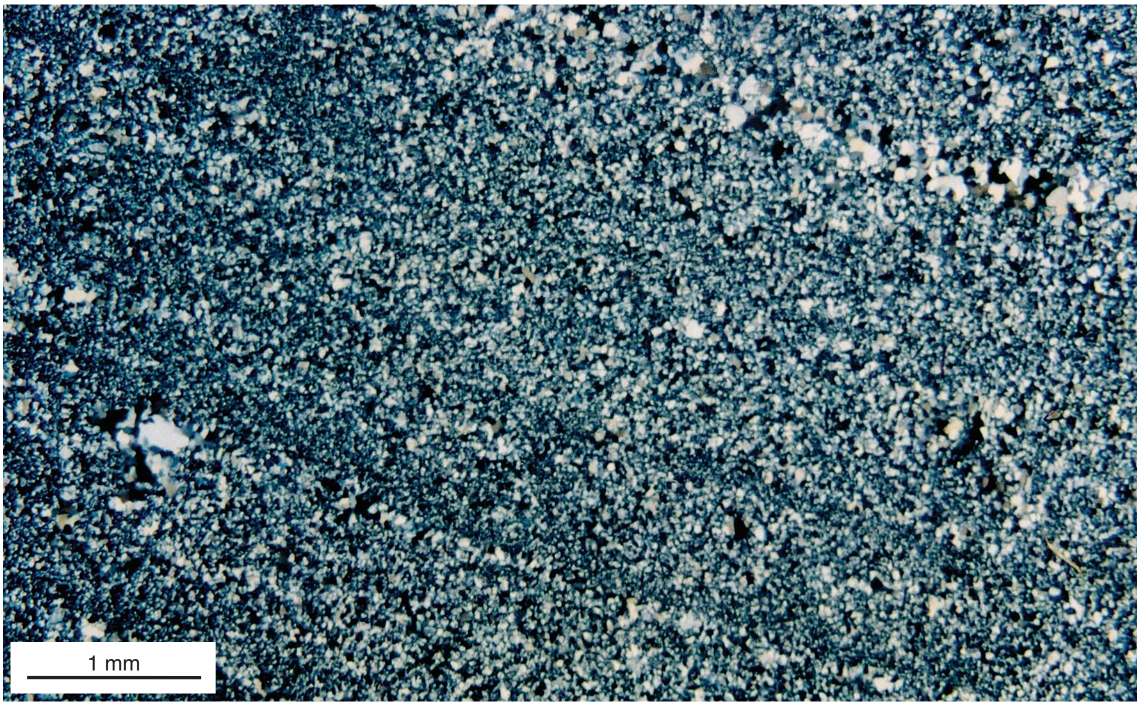

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Figure 90. Photomicrograph (crossed nicols ×10) showing regularly laminated chert (sample GSWA145237: Moora silica mine)

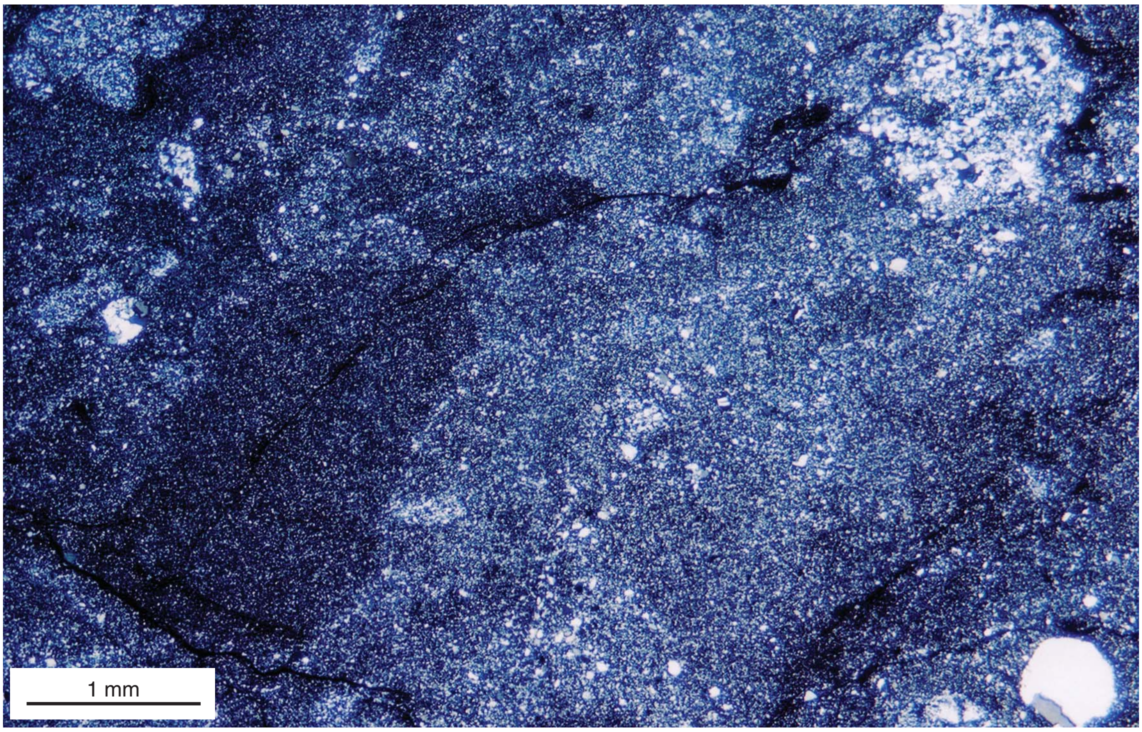

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Figure 91. Photomicrograph (crossed nicols ×20) showing irregular domains within chert, interpreted as 'intraformational disruption' within primary chemical siliceous sediment (sample GSWA145231: Moora silica mine)

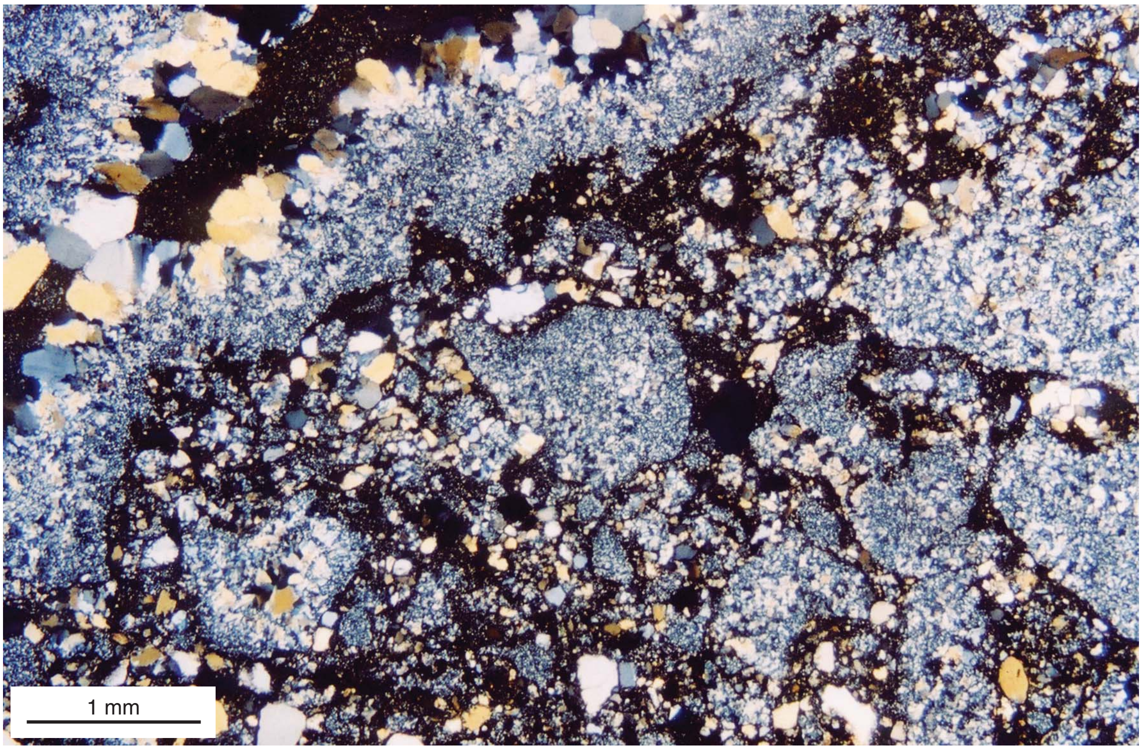

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Figure 92. Photomicrograph (crossed nicols ×20) showing chert breccia. Fragments of randomly distributed chert containing a matrix of intricately mixed silica and ?clay–sericite darkened by limonite staining, also minor scattered quartz sand grains. Vein of sparry quartz in top left corner (sample GSWA145229: Moora silica mine)

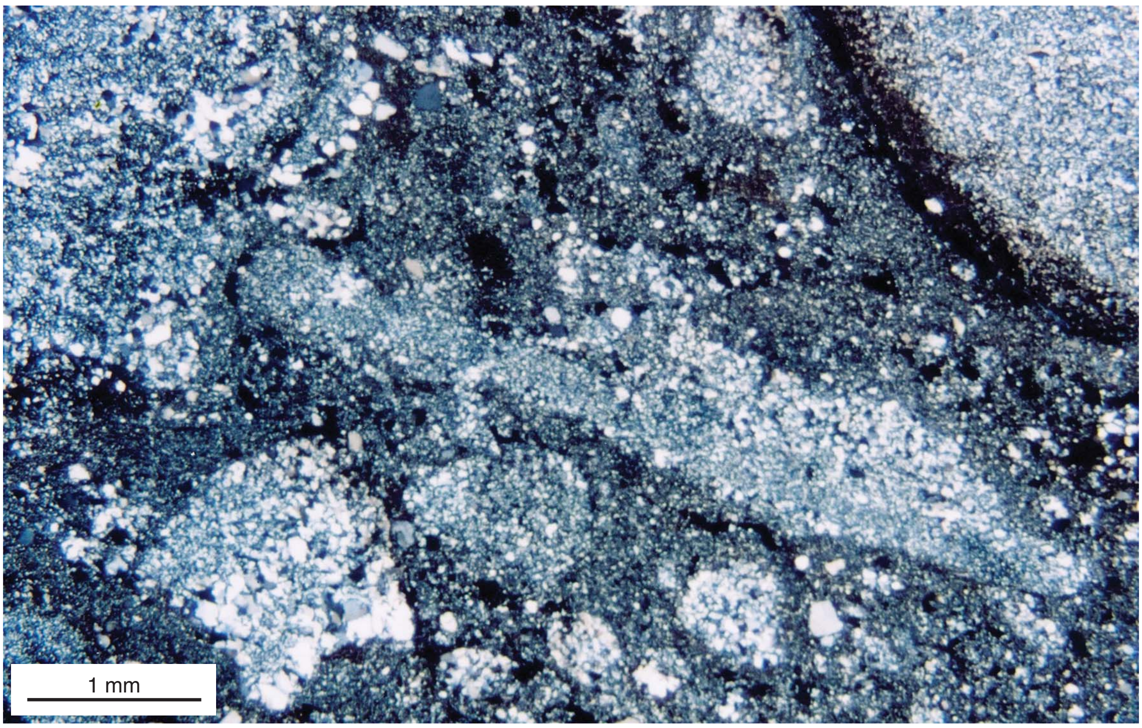

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Figure 93. Photomicrograph (crossed nicols ×20) showing chert breccia fragments in dark matrix of 'clouded chert' (sample GSWA145230: Moora silica mine)

Calcium and magnesium

Calcium and magnesium values vary throughout the mine area and generally increase slightly with depth. Magnesium content tends to be higher at the deeper levels. The strong positive correlation with depth between calcium and magnesium is due to traces of dolomite and chlorite in the chert, and possibly to magnesite. Calcium is also present in other minerals such as apatite (see **Phosphorus and calcium**).

Phosphorus and calcium

The phosphorus content in the chert varies throughout the mine area from 0.001 to 0.030% P_2O_5. Phosphorus and calcium show a very strong positive correlation, suggesting the presence of phosphorus as apatite. Apatite is petrographically identified in some samples, but owing to the ultrafine nature of the chert in other samples (GSWA145227–37, Table 63), positive identification of apatite was found to be difficult. Where the apatite has been leached from the chert by weathering, the phosphorus levels are very low.

Thermal stability and thermal strength

The thermal stability and strength of Moora chert are both high (Tables 64 and 65). According to company sources, thermal stability of the high-grade chert is generally above 95%. For the production of silicon metal, Moora chert is generally superior in terms of thermal strength and stability to quartzite, quartz vein, and quartz pebbles found in different parts of Australia (Parker, 1999).

Resource

The quartz resource at the mine area has been estimated as 2 Mt of high-grade chert (measured resource) at 99.3% silica (Spratt et al., 1989; Wilkinson, 1990). The company has been mining since 1989, and continuing exploration has been successful in delineating additional resources to replace those being mined.

Mining

The chert is mined from an openpit elongated in a north–south direction (Fig. 94). The high-grade ore is selectively mined, and the waste material is dumped separately and later rehabilitated. There are plans for a new pit at the western side of the current pit.

To carry out mining efficiently, an understanding of the distribution of iron, aluminium, titanium, phosphorus, calcium and magnesium (all considered to be trace impurities) in the chert is necessary. Blasthole cuttings are sampled to assist with grade control during mining.

Processing and beneficiation

The mined rock is crushed, washed, and wet screened at a crushing plant at the mine site (Fig. 95). This reduces impurities such as Al_2O_3, Fe_2O_3, and TiO_2 that are present either in the form of clay or as weathered iron oxide minerals, such as limonite. At the mine site, washed and screened chert stockpiles are maintained (Fig. 96).

Silicon metal production

The crushed and screened chert from Moora is transported by railway 300 km south to Picton and then by trucks to Kemerton plant, where there are two 27 MVA submerged-arc electric furnaces for the production of silicon metal. The feedstock for the plant is obtained by blending different grades, depending on customer specification. The manufacture of silicon metal is carried out in the submerged-arc furnaces by the reduction of chert with very low-ash charcoal and wood chip. Raw materials are selected on the basis of chemical purity, size consistency, thermal stability, thermal strength, and smelting characteristics. The chemical reactions involved in this process are discussed in **Chapter 2**.

At the Kemerton plant, the reduction process uses very low-ash charcoal manufactured from jarrah and other timber residues as well as low-ash coal. Prior to smelting, lump chert is mixed with charcoal/coal and

Table 64. Thermal stability test results of chert samples from different locations at the Moora mine area

	Size fraction (mm)					*Cumulative passing*				*Thermal*
GSWA no.	*>19*	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	*stability*
						Percentage				
145227	73.6	24.2	1.8	0.3	0.2	26.4	2.2	0.5	0.2	73.6
145228	81.0	16.4	2.2	0.3	0.1	19.0	2.5	0.4	0.1	81.0
145229	99.3	0.3	0.2	0.1	0.2	0.7	0.4	0.2	0.2	99.3
145230	85.7	12.6	1.1	0.2	0.4	14.3	1.7	0.6	0.4	85.7
145231	93.7	6.1	0.0	0.1	0.1	6.3	0.3	0.3	0.1	93.7
145232	64.8	30.5	4.3	0.3	0.2	35.2	4.8	0.5	0.2	64.8
145233	93.2	5.3	1.1	0.2	0.2	6.8	1.4	0.4	0.2	93.2
145234	71.2	26.1	2.0	0.6	0.2	28.8	2.7	0.7	0.2	71.2
145235	99.8	0.0	0.2	0.0	0.0	0.2	0.2	0.0	0.0	99.8
145236	80.4	18.4	0.9	0.2	0.1	19.6	1.2	0.3	0.1	80.4
145237	91.6	6.6	1.1	0.5	0.2	8.4	1.7	0.7	0.2	91.6

Table 65. Thermal strength test results of chert samples from different locations at the Moora mine

GSWA no.	Size fraction (mm) >19	9.5 – 19.0	4.8 – 9.5	2.0 – 4.8	<2	Cumulative passing 19 mm	9.5 mm	4.8 mm	2 mm	Thermal strength
					Percentage					
145227	68.9	25.2	4.4	0.7	0.8	31.1	5.9	1.5	0.8	98.5
145228	72.8	22.8	3.3	0.4	0.8	27.2	4.5	1.2	0.8	98.8
145229	75.3	21.0	1.6	0.8	1.2	24.7	3.6	2.1	1.2	97.9
145230	57.2	34.1	5.4	1.4	1.9	42.8	8.8	3.3	1.9	96.7
145231	70.8	24.0	3.4	0.8	1.1	29.2	5.3	1.8	1.1	98.2
145232	29.7	59.2	9.1	1.0	1.0	70.3	11.1	2.0	1.0	98.0
145233	87.4	6.6	3.2	0.6	2.1	12.6	5.9	2.7	2.1	97.3
145234	69.5	24.6	4.3	0.9	0.8	30.5	5.9	1.7	0.8	98.3
145235	76.0	19.7	3.3	0.3	0.7	24.0	4.3	1.1	0.7	98.9
145236	77.7	19.7	1.1	0.7	0.7	22.3	2.6	1.5	0.7	98.5
145237	74.8	20.0	3.1	1.0	1.1	25.2	5.2	2.1	1.1	97.9

some wood chip. In the furnace, smelting is achieved by an electric arc operating at a temperature in excess of 3000ºC. The Kemerton plant, considered to be one of the most efficient in the world, produces different chemical grades of silicon depending on customer requirements. The plant has a capacity to produce around 31 000 tpa of silicon metal, which is about 4% of world production (Department of Resources Development, 1999).

In addition to the standard products of silicon smelting, the byproduct silica fume has a strong market in the concrete industry, and is now considered to be a separate product. Up to 10 000 tpa of silica fume is extracted from furnace off-gases for use in the manufacture of high-strength or corrosion-resistant concrete and industrial refractories. Other byproducts of the process that are value-adding to Simcoa's operations include charcoal fines and dust, which are used to make barbecue briquettes (Department of Resources Development, 1999). The plant operates on a 24-hour basis to maintain maximum efficiency in the production process while achieving substantial energy savings. The packaging of silica products is automated and efficient.


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Figure 94. Openpit of Moora silica mine (looking west, 16 August 2000)

PBA492

Figure 95. Crushing plant at Moora mine


PBA493

Figure 96. Photograph of chert stockpiles — Moora mine

Markets

The products from the silicon plant at Kemerton are used in diverse metallurgical and chemical applications, requiring generation of products with varying specifications. Simcoa Operations is regarded as a premium supplier of silicon for both the metallurgical market, where it is used in the production of aluminium alloys, and the chemical market, which uses silicon as the raw material in the production of silicones and semi-conductors (Department of Resources Development, 1999). Simcoa has been able to supply these products without major problems to the satisfaction of many customers. At present, approximately 10–20% of production is sold to the domestic market, with the remainder being exported to the United States, Europe, Japan, India, and a number of other countries.

Prospectivity

Reconnaissance sampling by the author from various localities in the State has identified a number of areas of silica rocks with suitable chemical composition and thermal stability and strength as potential raw material for silicon metal production. The main rock types and localities are quartz–feldspar pegmatites at Karloning and Mukinbudin; quartz veins in the Karratha and Nanutarra regions; and chert at Shaw River (Figs 97 and 98). Information obtained at other localities indicates quartz veins at Bonnie Rock, White Flag Lake and White Hill, and a quartz–feldspar pegmatite body at Snake Soak may also be prospective areas for high-grade silica rocks.

Following are descriptions of these and other silica rocks in the State.

Other occurrences within Noondine Chert

The Noondine Chert outcrops intermittently for about 165 km north of Moora. Maximum width of the unit is 5 km, but outcrop width rarely exceeds 100 m. The chert is invariably hard to very hard. At Gunyidi Siding, about 11 km south of Marchagee (Fig. 82), a large quartz vein is found on farmland.

Quality of the surface layer of the Noondine Chert appears to deteriorate progressively towards the north, owing to the development of thicker lateritic profiles. Outcrops of Noondine Chert within the nature reserves and parks, particularly around Watheroo, are covered by thick vegetation.

A medium- to coarse-grained, feldspathic quartz arenite is found near Three Springs. The rock is somewhat similar to Donnybrook Sandstone, and contains a feldspathic matrix, suggesting a high percentage of aluminium. The arenite was therefore considered to be unsuitable for use as raw material in the silicon metal production (Parker, 1999).

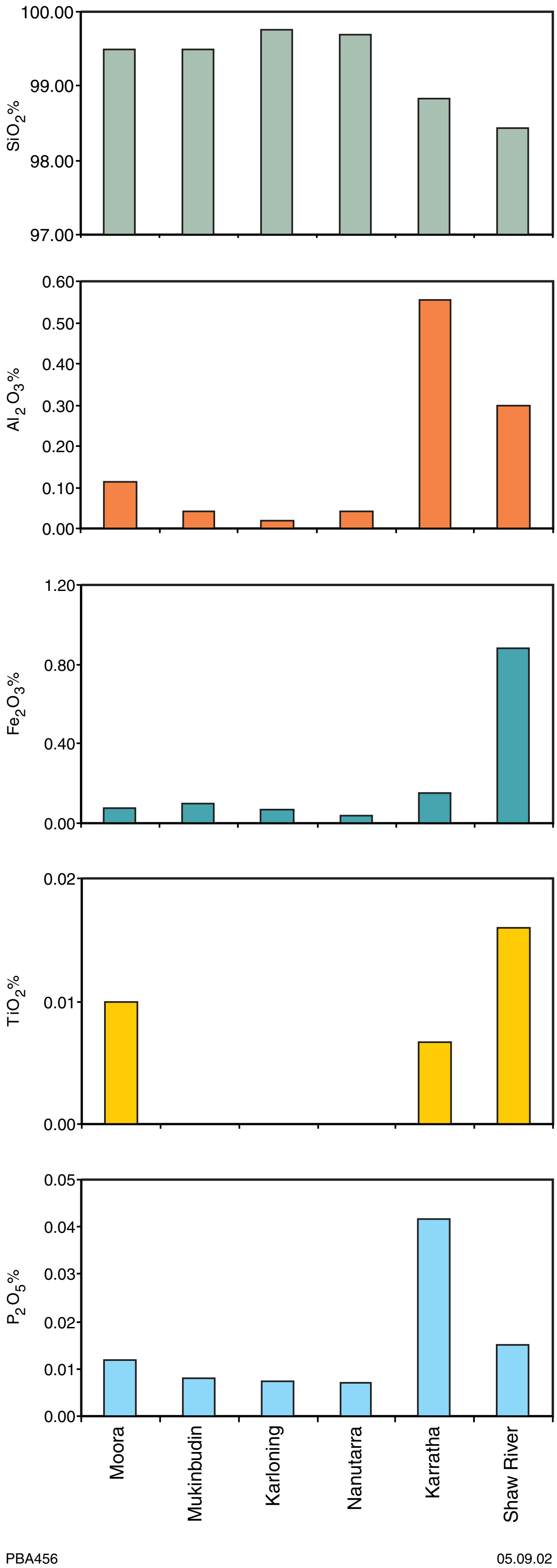


Figure 97. Average chemical trends of silica rocks from various localities of Western Australia

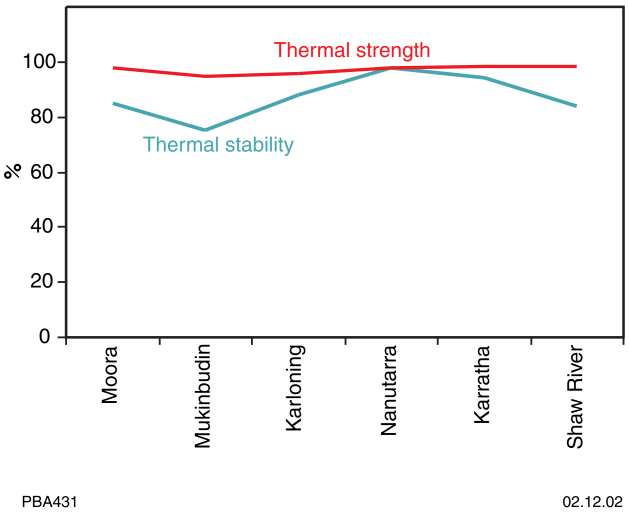


Figure 98. Average thermal stability and thermal strength of silica rocks from various localities of Western Australia

Yilgarn Craton

Localities for quartzite, pegmatite, and quartz veins are distributed throughout the Yilgarn Craton, with the main concentrations being in the South West Terrane and the Murchison Granite–Greenstone Terrane (Fig. 81). These occurrences were examined and sampled to investigate the suitability of these materials for use as metallurgical-grade silica raw material.

Quartzite

Quartzite and metamorphosed orthoquartzites are found as massive to flaggy bands in the Jimperding Gneiss Complex situated in the central western sector of the South West Terrane (Figs 58 and 81). These quartzites consist of interlocking grains of quartz with minor amounts of muscovite, fuchsite (chrome-muscovite), feldspar, sillimanite, and garnet (Wilde and Low, 1978). Samples from the following localities were tested for chemical composition and thermal strength to assess the suitability of the material for use as raw material for metallurgical-grade silicon.

Quairading

Approximately 11 km southeast of Quairading (Fig. 99), there is a prominent quartzite ridge that is mostly exposed on the south side of the Beverley Road between Quairading Road and Sunny Vale Road turnoffs. The rock has well-developed, closely spaced vertical joints, and there are traces of mica and greenish fuchsite. The band of quartzite is about 75 m wide at the road cutting, and extends approximately north–south with steep easterly dips. The outcrop is mostly in the form of boulders and pebbly material scattered along the ridge.

Petrographic studies of sample GSWA164573, from the easterly edge of the quartzite band, indicate that it consists almost entirely of massive, very coarse quartz mosaic, with individual quartz grains optically continuous to 10 mm diameter. The grains have very irregular and commonly sutured intergranular contacts, and most possess quite complex internal strain fabric (including composite stress lamellae) and fluid inclusions (Fig. 100a,b). The sets of stress lamellae have different orientation in adjacent grains. The accessory minerals present are 2–3% muscovite flakes (some altered to chlorite), and 1–2% minute acicular and partially broken fibre-like crystals (mostly <3 µm), possibly of rutile and/or sillimanite, as random inclusions in quartz. The muscovite is probably a metamorphosed minor pelitic component. Zircon crystals (<1%) are scattered sparsely as inclusions within quartz and rarely on intergranular contacts. Another sample (GSWA164574), from the westerly edge of the quartzite band, is essentially the same as GSWA164573, and is composed almost entirely of massive very coarse, irregular and intricately interlocking quartz grains showing typical exaggerated grain growth, and with internal stress fabric. These grains enclose abundant fluid inclusions, but contain considerably fewer ultrafine acicular inclusions of possible rutile and/or sillimanite than in GSWA164573. There are rare to trace single zircon grains (<100 µm) and rare, scattered, randomly oriented small flakes of muscovite. These rocks are classified as metaquartzites.

The two samples (GSWA164573–74) assayed 97.70–99.10% SiO_2, 0.30–0.92% Al_2O_3, 0.19–0.45% Fe_2O_3, 0.02–0.05% TiO_2, 0.02% CaO, 0.01% MgO, and 0.008% P_2O_5 (Table 66). Some of the impurities (e.g. Fe_2O_3) are rather high and SiO_2 percentage is somewhat low for metallurgical- and chemical-grade silicon metal production. The average thermal stability and thermal strength of the samples are 93.8 and 92.0 respectively, and are very close to acceptable grade for use in high-temperature furnaces (Tables 67 and 68).

Cubbine Hills

Approximately 2.5 km north of Cubbine Hills (Fig. 99), there are some scattered pebbles of ‘quartzite’, and the extent of the occurrence appears to be small. A thin section of a sample (GSWA164575) indicates primary, undeformed, homogeneous allotriomorphic granular aggregate of microcline crystals, mostly ranging in size from 1 to 3 mm (average approximately 2 mm) with rare coarse (≤12 mm) microcline phenocrysts. Potash feldspar forms about 65% of the rock, with the rest composed of irregular allotriomorphic quartz grains, some as small blebby inclusions within the potash feldspar. However, most quartz grains are coarser at about 1–3 mm and are part of the essential rock-forming aggregate. Intergranular contacts are commonly marked by a very narrow rim (0.01 mm) of apparent recrystallized feldspar. Minor small irregular grains of plagioclase are present but minor. The microcline has a diffuse clay-clouding and sparse, extremely fine ?albite-exsolution inclusions (incipiently perthitic). On the basis of petrography, this rock is classified as an aplite (typically leucocratic and of granitic composition).

The sample (GSWA164575) assayed 96.9% SiO_2, 1.38% Al_2O_3, 0.63% Fe_2O_3, 0.04% TiO_2, 0.06% CaO,

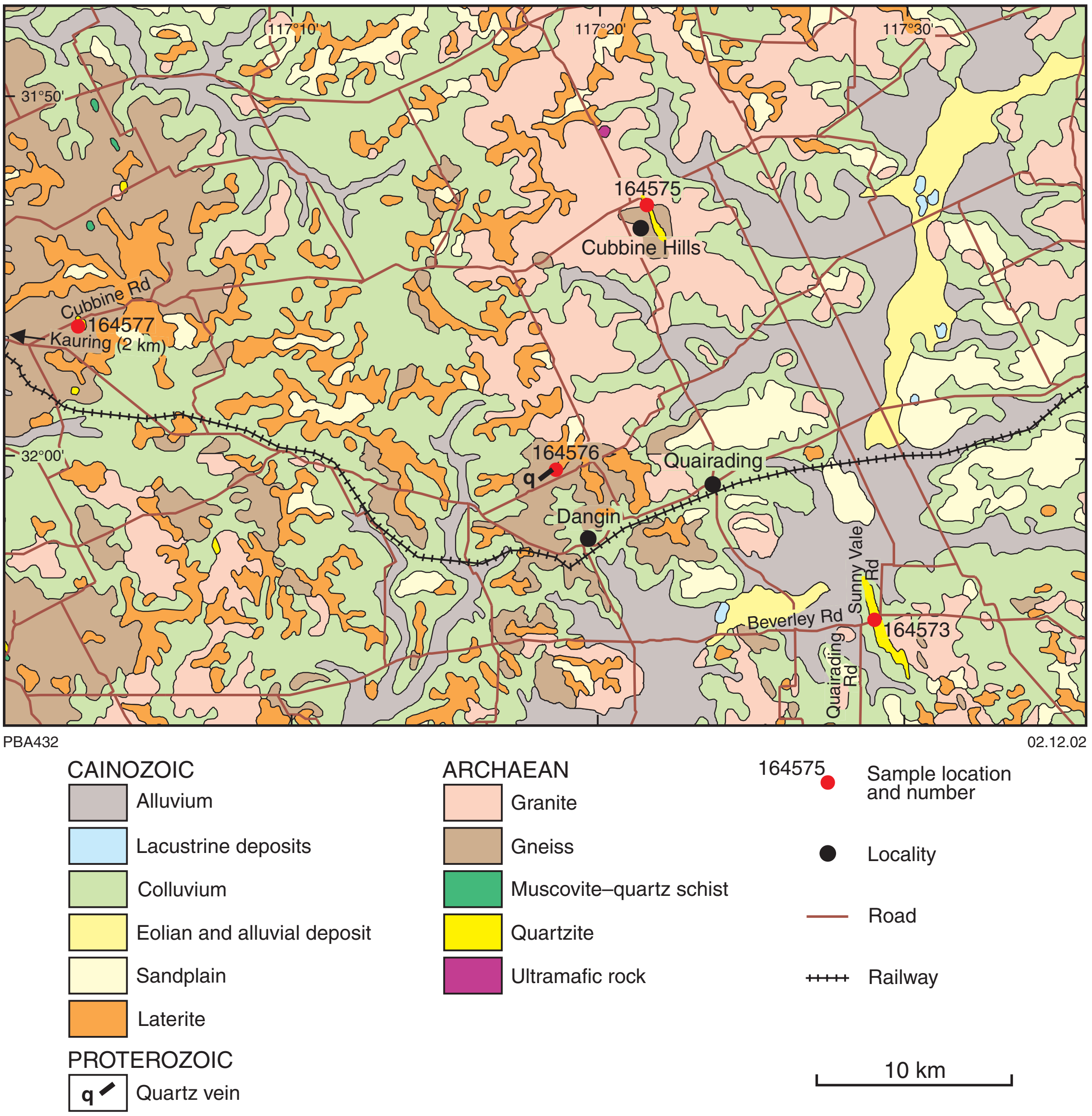


Figure 99. Regional geology around Kauring, Cubbine Hills, Dangin, and Quairading (after Muhling and Thom, 1985a)

0.04% MgO, and 0.011% P_2O_5 and appears to be unsuitable for the production of silicon metal for high-grade applications (Table 66). Moreover, thermal stability of the sample is 68.7% and thermal strength is 57.3%, which are too low for high-temperature furnaces (Tables 67 and 68).

Dangin

Approximately 4.5 km north-northwest of Dangin (Fig. 99), along Toapin Road, there are scattered pebbles of quartzite distributed on both sides of the road. A thin section of a sample (GSWA164576) from this quartzite indicates intricately interlocking inequigranular quartz grains, of variable size (2–12mm), with very irregular but not specifically sutured intergranular boundaries. These grains contain abundant minute fluid inclusions. Accessory small flakes of muscovite, rare altered potash feldspar, and rare discrete crystals of zircon up to 0.1 mm in size are disseminated. The accessory minerals compare with those in metaquartzite samples GSWA164573–74, about 11 km southeast of Quairading, and described earlier.

Sample GSWA164576 is white and assayed 99% SiO_2, 0.64% Al_2O_3, and 0.05% Fe_2O_3 (Table 66). The thermal stability of the sample is reasonably good (94.9%) but the thermal strength is too low (69.6%) for high-grade applications (Tables 67 and 68). Furthermore, the surface extent of the quartzite appears to be too small for commercial exploitation.

Kauring

A pinkish white quartzite outcrop is present on a hillock, approximately 2.5 km along the Cubbine Road from the turnoff to Kauring (Fig. 99). The outcrop is on the south side of the road and extends for some 30 m along a north-northeast direction.

Table 66. Chemical analyses of quartzite from the Quairading, Cubbine Hills, Dangin, Kauring, and Mount Hardy regions

GSWA no.	*164573*	*164574*	*164575*	*164576*	*164577*	*164578*
			Percentage			
SiO_2	99.10	97.70	96.90	99.00	99.40	98.60
Al_2O_3	0.30	0.92	1.38	0.64	0.24	0.57
Fe_2O_3	0.19	0.45	0.63	0.05	0.08	0.27
MgO	0.01	0.01	0.04	<0.01	<0.01	<0.01
CaO	0.02	0.02	0.06	<0.01	<0.01	0.01
Na_2O	<0.01	0.02	0.26	<0.01	<0.01	0.02
K_2O	0.07	0.34	0.06	0.02	0.03	0.13
TiO_2	0.02	0.05	0.04	0.03	0.03	0.03
MnO	0.01	0.01	0.01	0.01	<0.01	0.01
P_2O_5	0.008	0.008	0.011	0.006	0.003	0.010
BaO	<0.01	0.01	<0.01	<0.01	<0.01	<0.01
SO_3	<0.01	0.02	0.01	0.01	<0.01	<0.01
LOI	0.15	0.25	0.50	0.30	0.08	0.22
Total	**99.88**	**99.81**	**99.90**	**100.07**	**99.86**	**99.87**
H_2O	<0.01	<0.01	0.10	0.04	0.01	0.02

NOTE: 164573–74: Beverley Road, 11 km southeast of Quairading; 164575: south side of Cubbine Road, Cubbine Hills; 164576: 4.5 km northwest of Dangin; 164577: Cubbine Road, 3 km northeast of Kauring; 164578: 1.5 km north of Mount Hardy

A thin section of a sample (GSWA164577) from the above outcrop is very similar to the previously described sample GSWA164576 from the Dangin area, and has coarse but inequigranular stressed quartz, with irregular and intergranular contacts. There are trace–accessory flakes of muscovite (≤250 µm in length) and discrete grains of zircon (≤100 µm in length) (Fig. 101).

Sample (GSWA164577) has 99.4% SiO_2, 0.24% Al_2O_3, 0.08% Fe_2O_3, 0.03% TiO_2, <0.01% CaO, <0.01% MgO and 0.003% P_2O_5, indicating that the quartzite is of sufficiently high quality for high-grade applications (Table 66). The thermal stability of the sample is 99.6%, which is very good for silicon metal production, but the thermal strength 88.2% is slightly low for such use (Tables 67 and 68).

York (Mount Hardy)

Quartzite is found in a number of localities east of York (Fig. 102) interbanded with gneisses of the Jimperding metamorphic belt. Samples were collected as part of this investigation some 10 km east of York, where quartzite pebbles from a quartzite band are scattered on the north side of Station Road near Mount Hardy.

A thin section of a sample (GSWA164578) of this pebbly quartzite indicates up to 85% massive coarse quartz mosaic with very irregular intricately interlocking quartz grains, optically continuous up to 12 mm in diameter, and interpreted as typical of exaggerated metamorphic grain growth. Also, as in other quartzites described above, the grains are stressed with internal 'blocky' stress lamellae evident in crossed nicols. Accessory minerals present are zircon, opaque oxides, and muscovite. The sample has abundant trails and disseminations of minute fluid inclusions (Fig. 103a,b). The remaining 15% (approximate) of the thin section consists of subhedral to euhedral single potash-feldspar crystals (0.5–3 mm), mostly as single isolated crystals and only rarely in very small clusters. Some of these feldspar crystals are accompanied by lesser muscovite and altered to clay–sericite, partly leached out to form voids.

Chemical analysis of the sample (GSWA164578) indicates 98.6% SiO_2, 0.57% Al_2O_3, 0.27% Fe_2O_3, 0.03% TiO_2, 0.01% CaO, <0.01% MgO and 0.01% P_2O_5, suggesting that the material is reasonably high grade (Table 66). The thermal stability of the sample is 98.6%, which is very good for silicon metal production, and the thermal strength of 91.9% is also acceptable for such applications (Tables 67 and 68).

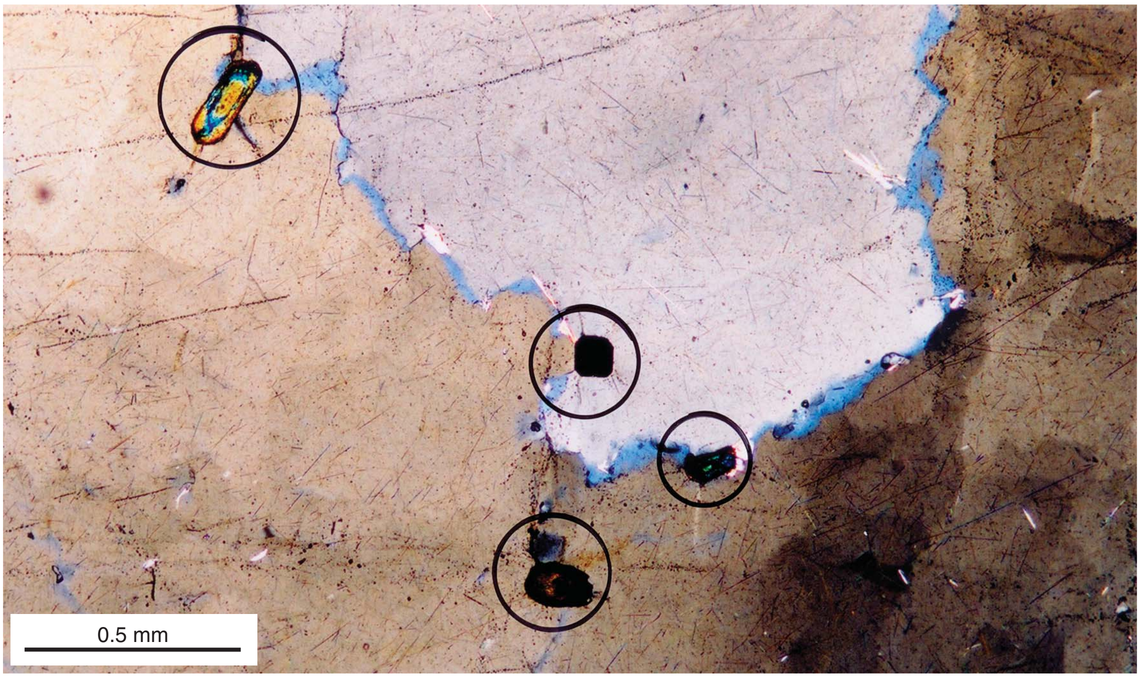
Grass Valley

Scattered pebbles of white quartzite, stained with iron oxide, are found in a paddock approximately 5 km east of Grass Valley, at the end of Leeming Road (Fig. 102). Quartzite is not widespread and is interbanded with granitic gneiss. A sample (GSWA164581) assayed 88.8% SiO_2 and 5.95% Al_2O_3 (Table 69), indicating that it is of too low a quality for industrial applications.

Powlalup

A band of Archaean quartzite is exposed on the south side of Maidment Road, approximately 5 km west of Powlalup in the Balingup area (Fig. 104). The quartzite band, on the south side of the road, strikes in a southwesterly direction. The outcrops are generally covered with bush and thick vegetation and therefore the extent of the quartzite band is difficult to determine. Some portions appear to be weathered and ferruginous. Two samples (GSWA164527–

(a)



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(b)

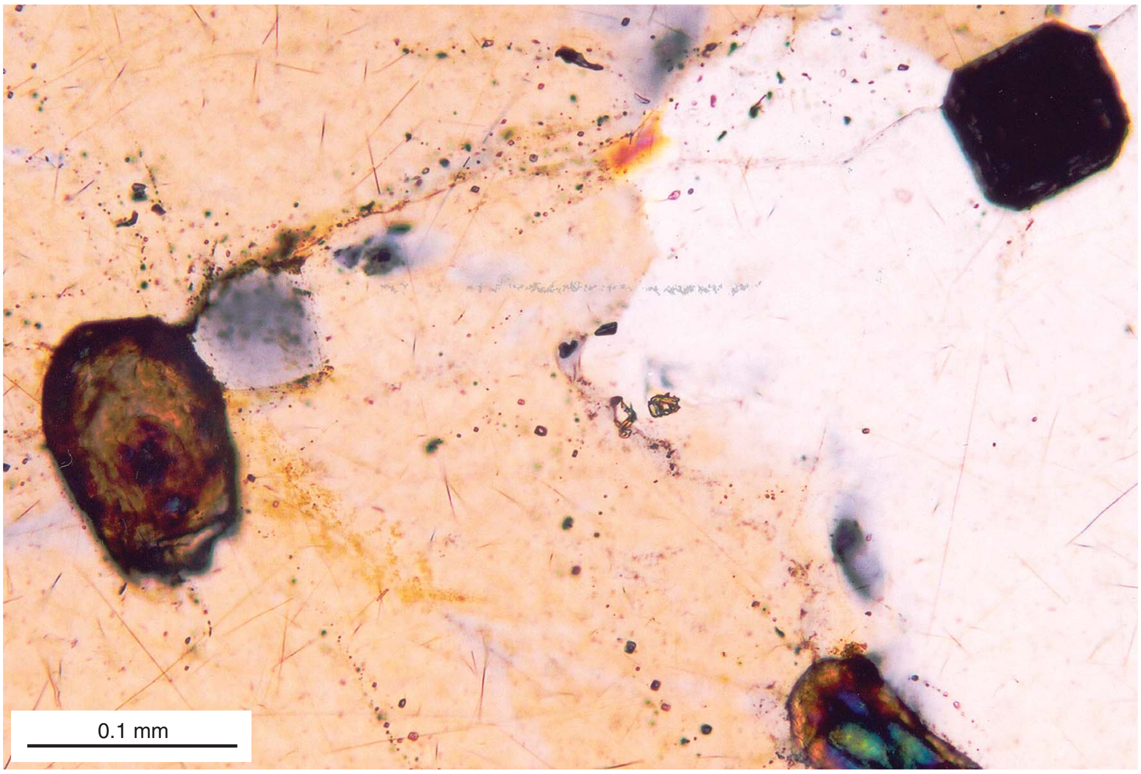

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Figure 100. a) Photomicrograph (crossed nicols x50) showing coarse quartz in metaquartzite with scattered microfibres and dust-like fluid inclusions, and trace zircon (sample GSWA164573: Quairading); b) Higher magnification (crossed nicols x200) of Fig. 100a showing details of three zircon crystals and dust-like fluid inclusions (sample GSWA164573: Quairading)

Table 67. Thermal stability of quartzite from the Quairading, Cubbine Hills, Dangin, Kauring, and Mount Hardy regions

GSWA no.	*Locality*	*Size fraction (mm)*					*Cumulative passing*				*Thermal stability*
		>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	
						Percentage					
164573	Quairading (11 km southeast; Beverley Road)	95.2	2.2	1.8	0.5	0.4	4.8	2.6	0.8	0.4	95.2
164574	Quairading (11 km southeast; Beverley Road)	92.3	3.3	3.5	0.5	0.4	7.7	4.4	0.9	0.4	92.3
164575	Cubbine Hills (south side of Cubbine Road)	68.7	20.9	6.1	2.6	1.7	31.3	10.4	4.3	1.7	68.7
164576	Dangin (4.5 km north-northwest)	94.9	1.7	0.8	1.5	1.1	5.1	3.4	2.6	1.1	94.9
164577	Kauring (3 km northeast; Cubbine Road)	99.6	0.0	0.0	0.2	0.2	0.4	0.4	0.4	0.2	99.6
164578	Mount Hardy (1.5 km north)	98.6	0.0	0.7	0.4	0.3	1.4	1.4	0.7	0.3	98.6

Table 68. Thermal strength of quartzite from the Quairading, Cubbine Hills, Dangin, Kauring, and Mount Hardy regions

GSWA no.	*Locality*	*Size fraction (mm)*					*Cumulative passing*				*Thermal strength*
		>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	
						Percentage					
164573	Quairading (11 km southeast; Beverley Road)	33.1	39.7	16.8	5.5	4.9	66.9	27.2	10.4	4.9	89.6
164574	Quairading (11 km southeast; Beverley Road)	30.5	53.8	10.0	2.9	2.8	69.5	15.7	5.7	2.8	94.3
164575	Cubbine Hills (south side of Cubbine Road)	29.3	8.3	19.7	21.3	21.5	70.7	62.4	42.7	21.5	57.3
164576	Dangin (4.5 km north-northwest)	69.6	5.3	10.5	8.5	6.0	30.4	25.1	14.5	6.0	85.5
164577	Kauring (3 km northeast; Cubbine Road)	43.2	29.0	15.9	6.3	5.5	56.8	27.8	11.8	5.5	88.2
164578	Mount Hardy (1.5 km north)	51.9	34.2	5.8	2.6	5.5	48.1	13.9	8.1	5.5	91.9

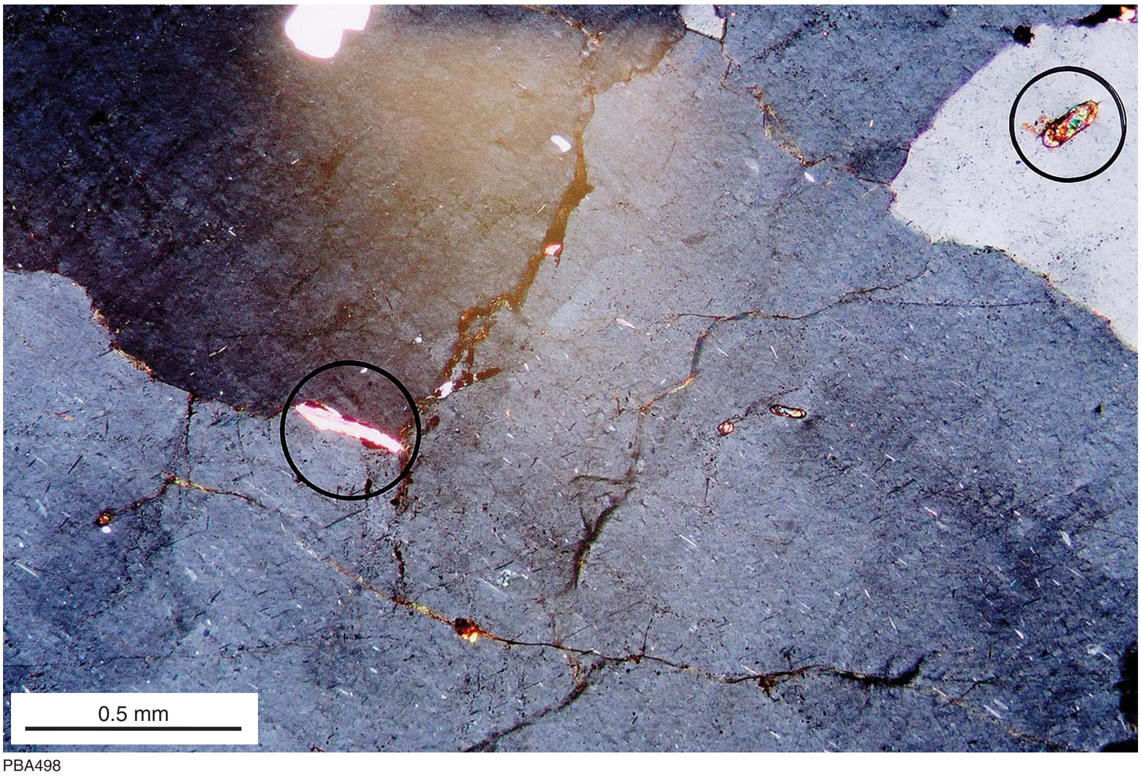


Figure 101. Photomicrograph (crossed nicols ×50) of quartzite showing coarse quartz mosaic, trace inclusion of zircon, muscovite, and disseminated fibrous crystals (sample GSWA134577: Kauring)

28), approximately 1.5 km apart, were collected for testing.

A thin section of sample GSWA164527 indicates an inequigranular mosaic of commonly elongated quartz grains that range in size from about 0.5 to 3 mm. Intergranular contacts are notably irregular and moderately sutured, as may be expected in a metaquartzite. There is a minor randomly scattered intergranular porosity forming 10–12% of the whole rock, which possibly represents a former mineral that has been completely altered and leached out. This mineral may have been feldspar. The other sample (GSWA164528) is metaquartzite, is similar to GSWA164527, and consists of an inequigranular medium to coarse mosaic of quartz grains, with irregular and partly sutured intergranular contacts and minor intergranular voids. The whole aggregate has more of a preferred orientation/elongation than exists in GSWA164527. The sample also contains minor scattered flakes of muscovite (2–3%) up to 1 mm in size.

The two samples (GSWA164527–28) assayed 98.4–99.5% SiO_2, 0.07–0.54% Al_2O_3, 0.03–0.62% Fe_2O_3, 0.02–0.03% TiO_2, 0.02–0.05% CaO, <0.01% MgO and 0.011–0.012% P_2O_5 (Table 69), indicating moderately high grade quartzite. The average thermal stability and thermal strength of the samples are respectively 99.7 and 94.1%, thus the quartzite is of high quality and suitable for use in silicon metal production (Tables 70 and 71). The extent of the deposit is uncertain as most of the outcrops are covered with thick vegetation.

Wolyamup Hill

Bands of quartzite on the north and south sides of Warren Road (DUMBLEYUNG 1:250 000 geological sheet) do not outcrop prominently but are present as scattered pebbles on the north side of the road, approximately 2 km northwest of Wolyamup Hill (Fig. 105). The quartzite is associated with granitic rock exposures on the north and south sides of the road, but the quantity of quartzite available at this location appears to be small.

In hand specimen, the quartzite is coarse to extremely coarse, granular, and massive. In thin section, sample GSWA164571 consists almost entirely of irregular grains of stressed quartz, mostly 5–10 mm in size, with abundant microscopic trails of fluid inclusions. Intergranular contacts are very irregular. Several irregular grains of microcline (0.5–5 mm), forming 5–7% of the whole rock, are randomly dispersed within the coarse quartz aggregate. Microcline grains are clouded by clay–sericite, and are accompanied by sparse, fine flakes of muscovite. There is also separately developed sparse fine muscovite, which is altered to limonite-stained clay–sericite. The thin section suggests the rock to be metaquartzite, with original possible pelitic impurities metamorphosed to potash feldspar and muscovite, or possibly inherent ex-detrital potash feldspar.

Sample GSWA164571 assayed 98.40% SiO_2, 0.44% Al_2O_3, 0.32% Fe_2O_3, 0.03% TiO_2 and 0.008% P_2O_5 (Table 69), indicating reasonably high grade quartzite. The

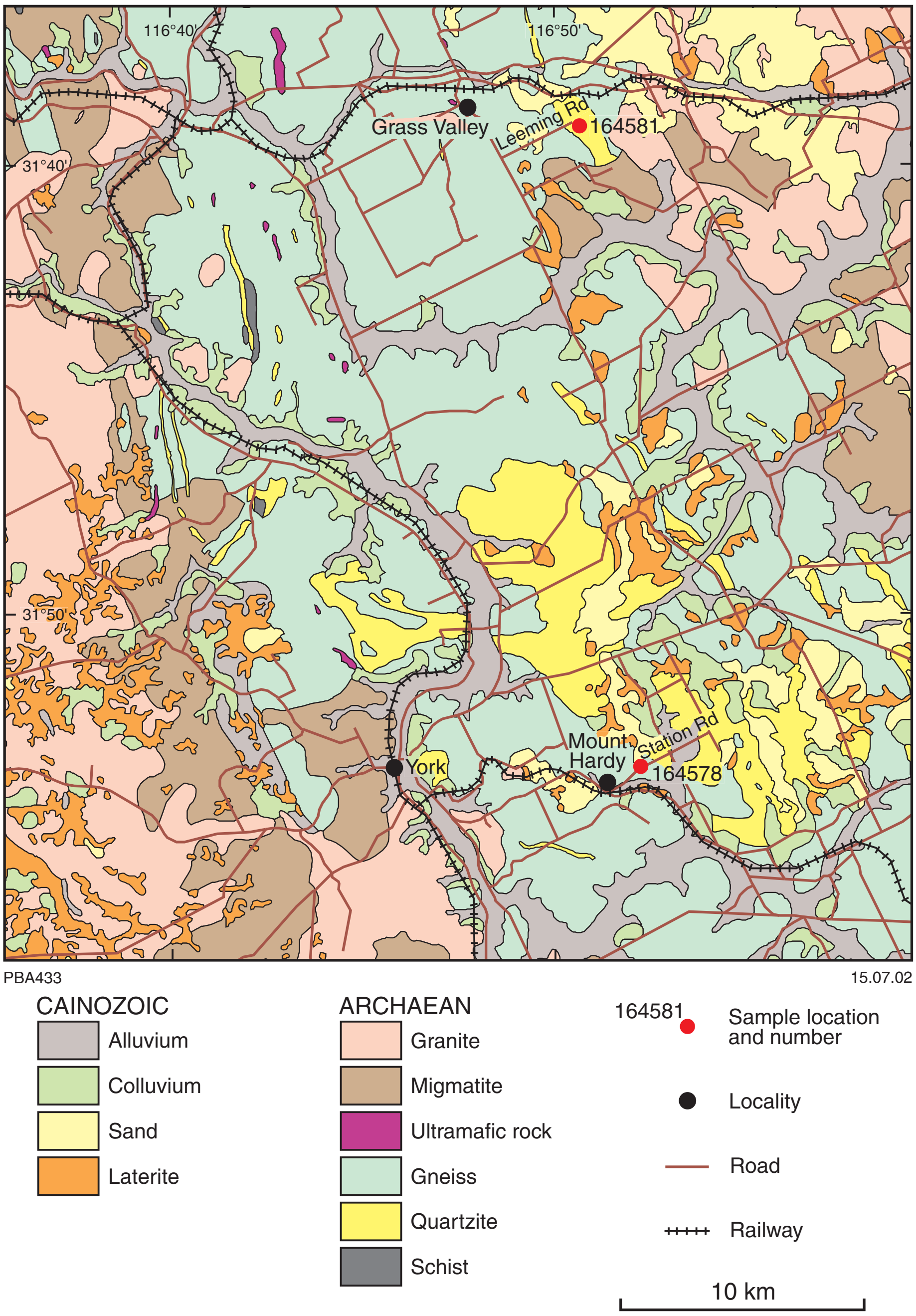
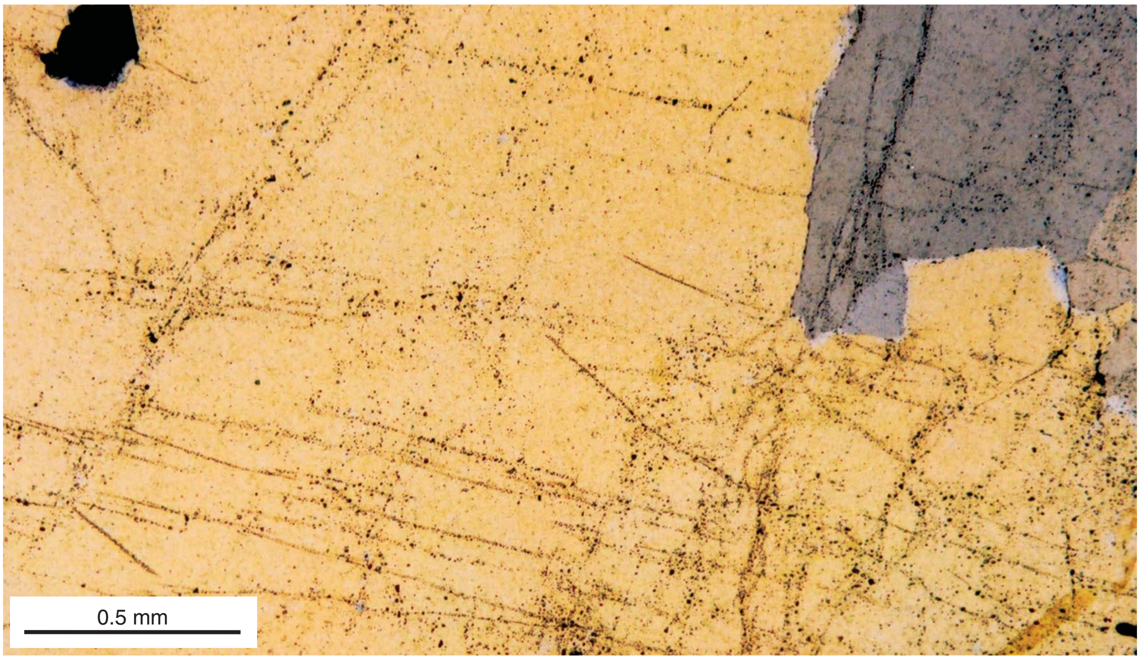


Figure 102. Geology around York (Mount Hardy) and Grass Valley (after Low et al., 1978)

(a)



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(b)

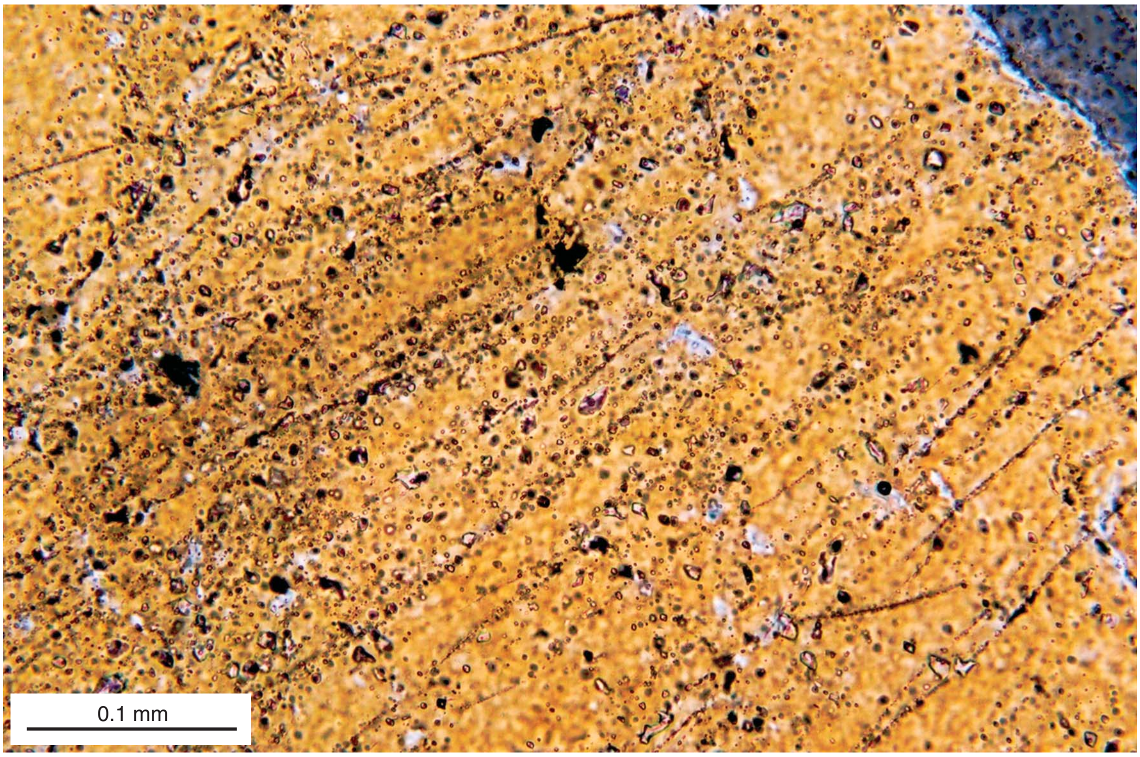

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Figure 103. a) Photomicrograph (crossed nicols ×50) showing abundant fluid inclusions in coarse quartzite, also a single inclusion of opaque oxide grain (sample GSWA164578: York, Mount Hardy); b) Higher magnification (crossed nicols ×200) of Figure 103a showing trails of crowded fluid inclusions (sample GSWA164578: York, Mount Hardy)

Table 69. Chemical analyses of quartzite from the Grass Valley, Powlalup, and Wolyamup Hill regions

GSWA no.	*164581*	*164527*	*164528*	*164571*
		Percentage		
SiO_2	88.80	99.50	98.40	98.40
Al_2O_3	5.95	0.07	0.54	0.44
Fe_2O_3	0.22	0.03	0.62	0.32
MgO	0.01	<0.01	<0.01	0.02
CaO	0.10	0.05	0.02	0.14
Na_2O	1.35	<0.01	<0.01	0.04
K_2O	3.20	0.02	0.08	0.19
TiO_2	0.02	0.02	0.03	0.03
MnO	<0.01	0.01	0.01	0.01
P_2O_5	0.007	0.012	0.011	0.008
BaO	0.14	<0.01	<0.01	<0.01
SO_3	<0.01	0.06	0.01	0.04
LOI	0.22	0.08	0.32	0.23
Total	**100.02**	**99.85**	**100.04**	**99.87**
H_2O	0.14	0.06	0.47	<0.01

NOTE: 164581: Leeming Road, Grass Valley
164527–28: Maidment Road, Powlalup
164571: 2 km northeast of Wolyamup Hill

thermal stability of the sample is good with a value of 91.6%, but the thermal strength of 71.6% is too low for use in silicon metal production (Tables 70 and 71).

Pegmatite

Proterozoic pegmatite intruding Archaean granite is known in a number of localities in the southwestern region of the Yilgarn Craton. Some of these pegmatites in the Mukinbudin area, including Mukinbudin, Karloning, Snake Soak and Calcaling, have been mined (or held under mining leases) to obtain quartz and feldspar (Fig. 81). Following are descriptions of these deposits.

Mukinbudin

A quartz–feldspar pegmatite 6.5 km west of Mukinbudin was investigated by a number of companies for its economic potential (Fig. 106). In 1970, the area was investigated for its quartz potential by Watts Griffis and McOuat (Australia) Pty Ltd. From around 1975 to date, interest in the deposit has been mainly for its feldspar potential, and ownership has changed a number of times. Companies that held the property at various times after Watts Griffis and McOuat (Australia) Pty Ltd include Snowstone Pty Ltd, Magnet Industries Pty Ltd, Matlock Mining NL, and Commercial Minerals Ltd (a subsidiary of Normandy Industrial Minerals Ltd). The current owner of the deposit is Unimin Australia Ltd, who purchased the deposit from Normandy Industrial Minerals Ltd in 2000.

Exploration history

In 1970, 31 percussion holes (total metres unknown) were drilled by Watts Griffis and McOuat (Australia) Pty Ltd to assess the quartz resource in the eastern area of the property. From 1985 to 1998, the area was drilled fairly extensively by each of Matlock Mining and Commercial Minerals to assess the feldspar resource available (Thynne, 1991; Martin, 1997, 1999). The drilling included:

- 40 percussion holes (totalling 708 m);
- 114 reverse-circulation holes (totalling 2207 m);
- 17 diamond holes (totalling 883 m);
- 14 reverse-circulation/diamond holes (totalling 965 m of reverse-circulation and 101 m of diamond drilling).

Geology

The deposit consists of five discrete pegmatite bodies, and the relationships between these pegmatites are difficult to establish due to the surface soil cover. The pegmatites consist of coarsely crystalline albite, microcline, biotite, and quartz. In one of the openpits, the pegmatite appears to be subvertical with relatively pure albite and perthitic microcline occurring as subhorizontal zones 1–5 m thick surrounding a quartz core. The quartz core, as seen on the surface, has a width of 10–15 m and trends 210–260º (Shackleton, 1993). Quartz also forms four large quartz ‘blows’ surrounded by granite, some of which rise about 6 m above the surrounding plain, which is almost entirely covered with soil and vegetation.

The large quartz bodies at the eastern sector of the lease area are surrounded by, and separated by, a quartz–feldspar granite. Along the margins of the quartz bodies, small pods of feldspar can be seen, along with stringers and veinlets of white mica, and rare pods of biotite. The veins of white mica can be up to 30 cm wide and may extend about one metre into the granite. The feldspar pods at the margins of quartz are small in size and are composed of sodic plagioclase. The quartz in the deposit is massive, milky, and of high purity. However, the quartz contains small stringers of white mica in places, and is iron stained at the surface. Minor quantities of clear or colourless quartz have been reported from the deposit.

Resource and quality

Based on 31 percussion holes drilled in 1970, the resource of quartz available in the eastern sector of the deposit was estimated at 319 000 t averaging 98.8% silica (Coles, 1975a). This resource was later re-estimated based on drilling investigations by both Matlock Mining and Commercial Minerals, but the results remain confidential (Guy, 1988; Shackleton, 1993).

A sample (GSWA164585) of white translucent quartz collected from dumps south of the openpit assayed 99.5% SiO_2, 0.04% Al_2O_3, 0.10% Fe_2O_3, <0.01% TiO_2, 0.01% CaO, <0.01% MgO and 0.008% P_2O_5, indicating that it is of excellent quality, chemically, for high-grade applications (Table 72). The thermal strength of the sample is 94.6%, which is close to acceptable levels for use in the silicon metal production, but the thermal stability of 75.2% is too low for such high-grade uses. (Tables 73 and 74).

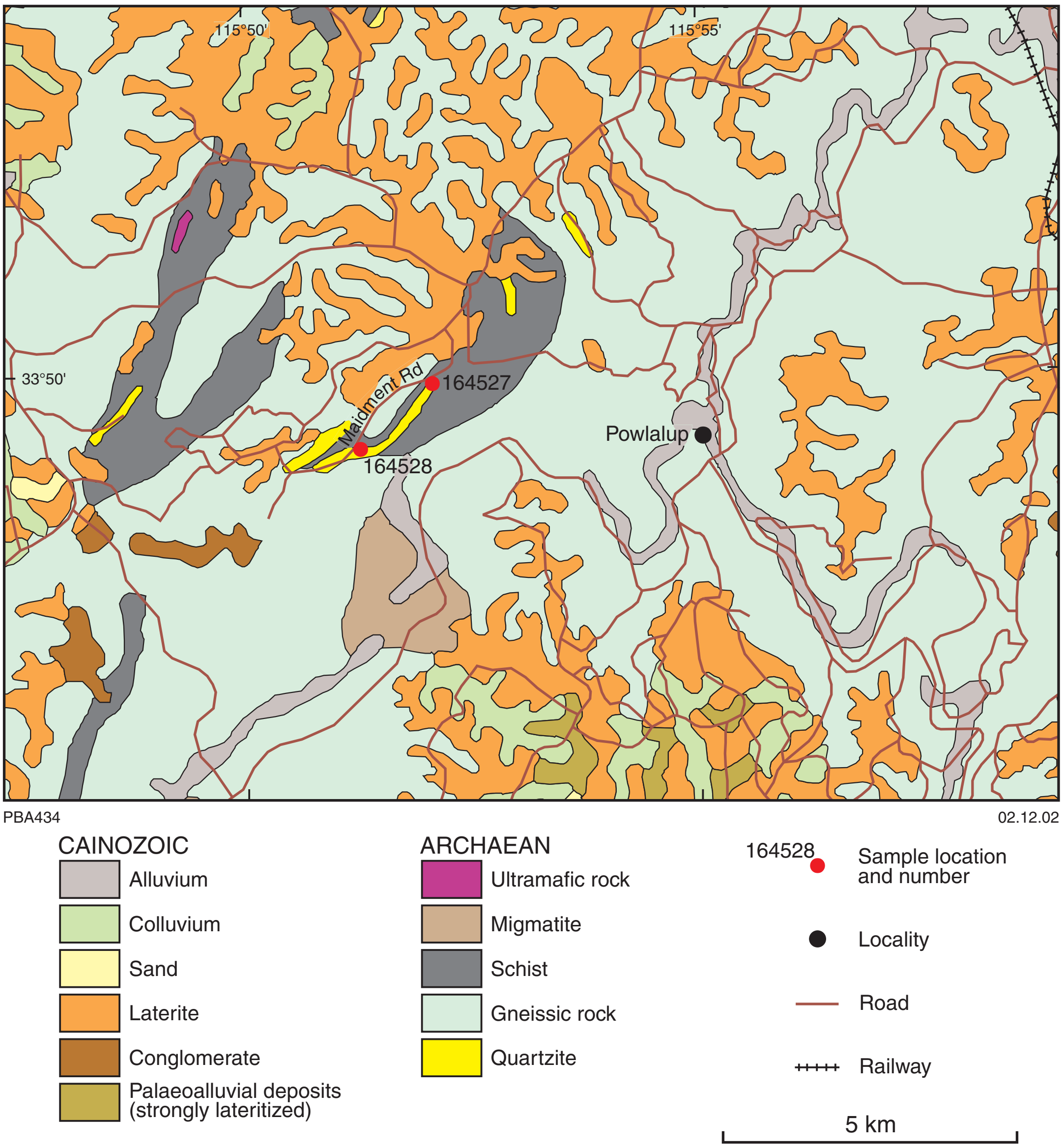

Figure 104. Geology around Powlalup (after Wilde and Walker, 1982)

Production

During 1970–90, there was sporadic production of 56 977 t of quartz from this deposit for use in gardens both as building and decorative stone. Some quartz produced during 1970–79 was exported to Japan. There is no reported production of quartz from the deposit since 1990 and the production pits of quartz at the eastern side of the deposit have been rehabilitated.

The existing openpits are for feldspar but contain some potential for high-purity quartz. The mine, which is currently on care and maintenance, consists of three openpits (two of which contain water), waste stockpiles, crushed feldspar stockpiles, a dry-crushing plant, offices, workshop, and front-end loader.

The deposit is more important for its feldspar resource, production of which amounted to 54 285 t from 1990 to 1999. There is also reported production of 244 t of kaolin from this pegmatite during 1975 to 1978.

Several northerly striking quartz veins outcrop each side of the road to Trayning, about 10 km south of Mukinbudin. However, the veins are narrow and do not appear to contain a resource sufficiently large for commercial development (Parker, 1999).

Karloning

A pegmatite at 4.5 km west-southwest of Karloning (Fig. 107) was investigated in 1970 by Watts Griffis and McOuat (Australia) Pty Ltd for quartz and feldspar (Coles, 1975b). In 1975, Snowstone Pty Ltd carried out further investigation of the deposit for both quartz and feldspar. The deposit was mined by Imdex Ltd (Mining Lease M70/780, now expired). The deposit is now held by

Table 70. Thermal stability of quartzite from the Powlalup and Wolyamup Hill regions

GSWA no.	*Locality*	*Size fraction (mm)*					*Cumulative passing*				*Thermal*
		>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	*stability*
							Percentage				
164527	Powlalup (Maidment Road)	99.9	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	99.9
164528	Powlalup (Maidment Road)	99.4	0.2	0.1	0.1	0.2	0.6	0.4	0.3	0.2	99.4
164571	Wolyamup Hill (2 km northeast)	91.6	5.5	1.7	0.5	0.7	8.4	2.9	1.2	0.7	91.6

Mr B. J. Adams and Mr G. S. Hepple, under Prospecting Licence P70/1322.

Geology

The pegmatite formed on the northeastern side of a large quartz blow surrounded by Archaean granite (Fig. 108). Several smaller quartz bodies are found to the northeast of the large quartz blow. The outcrops and veins of quartz trend in a northwesterly direction, and have joints developed in the directions of 065º and 330º. The quartz is milky white and is iron stained on the surface. Drilling indicates that some of the quartz bodies are not very thick and are underlain by feldspar, which inturn is underlain by granite that shows effects of shearing. The outer margins of the feldspar bodies are more potassic, whereas the inner parts are more sodic. The granite farther away from the pegmatite is less sheared and more even grained than that at the contact zone.

The quarry, mined for feldspar, has dimensions of about 50 × 50 m and is about 10 m deep. Waste stockpiles surround the pit, and there are some stockpiles of crushed feldspar. The rocks in the pit consist of granite (biotite adamellite), and pegmatite, with the latter consisting largely of potassium feldspar with minor quartz. Quartz, which is milky white, translucent, pure and overlain by feldspar, is exposed at the south wall of the quarry. This quartz band rises about 5 m from the pit floor. The waste dumps at the quarry contain a significant quantity of quartz.

To the west of the quarry, there is a large (100 × 50 m) outcrop of quartz, which is part of the quartz–feldspar pegmatite. The outcrop forms a small hill which rises to about 20 m above the surrounding area. The quartz outcrop consists of slightly iron-stained crystalline quartz.

Quality

In thin section, two samples (GSWA164586–87) indicate massive coarse quartz as a compact mass of irregular grains with intricate, partly sutured interlocking contacts, mostly with internal elongate stress fabric oriented differently in adjacent grains. Trails of ultrafine fluid inclusions form both along and across the stress lamellae. There are rare inclusions of very small (0.15 mm) muscovite (sericite) flakes and potash feldspar (Fig. 109).

Chemical analyses of typical quartz samples (GSWA 164586–87) from the deposit indicate high-purity material with high SiO_2 (99.7–99.8%) and low levels of Fe_2O_3 (0.01–0.04%), Al_2O_3 (0.02%), TiO_2 (<0.01%), and P_2O_5 (0.006–0.009%) (Table 72). The quartz in the outcrop shows very little variation in mineralogy and therefore is likely to be chemically consistent.

The two samples (GSWA164586–87) have average thermal stability and thermal strength values of 88.15 and 95.9% respectively (Tables 73 and 74). Another sample, collected by Parker (1999) indicates a thermal stability of 99.5% and a thermal strength of 94.1%. These results suggest that this quartz is suitable for use in silicon metal production.

Resource

An estimate of the deposit’s resources, based on 20 percussion holes (totalling 302 m), is approximately 150 000 t of quartz averaging 98.7% SiO_2 and 50 000 t of feldspar (Coles, 1975b). The resource under the current JORC (Joint Ore Reserves Committee, 1999) code probably falls within the inferred category.

Parker (1999) stated that the deposit has potential for a smaller (about 100 000 t) high-grade quartz resource of

Table 71. Thermal strength of quartzite from the Powlalup and Wolyamup Hill regions

GSWA no.	*Locality*	*Size fraction (mm)*					*Cumulative passing*				*Thermal*
		>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	*strength*
							Percentage				
164527	Powlalup (Maidment Road)	94.0	1.4	0.4	0.3	3.9	6.0	4.6	4.2	3.9	95.8
164528	Powlalup (Maidment Road)	73.8	14.3	4.4	2.5	5.1	26.2	12.0	7.6	5.1	92.4
164571	Wolyamup Hill (2 km northeast)	0.0	36.9	34.7	17.0	11.4	100.0	63.1	28.4	11.4	71.6

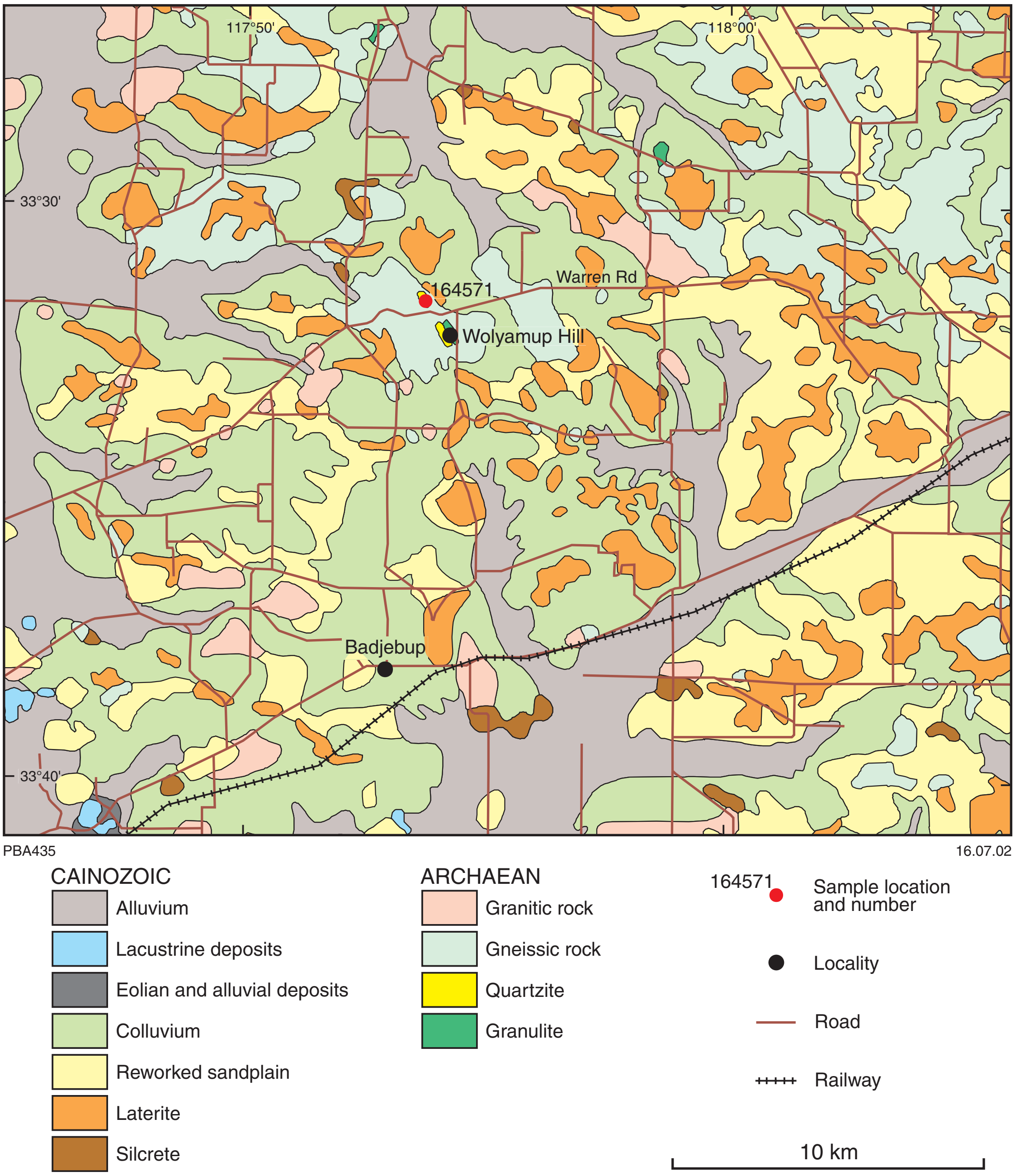

Figure 105. Geology around Wolyamup Hill (after Brakel et al., 1985)

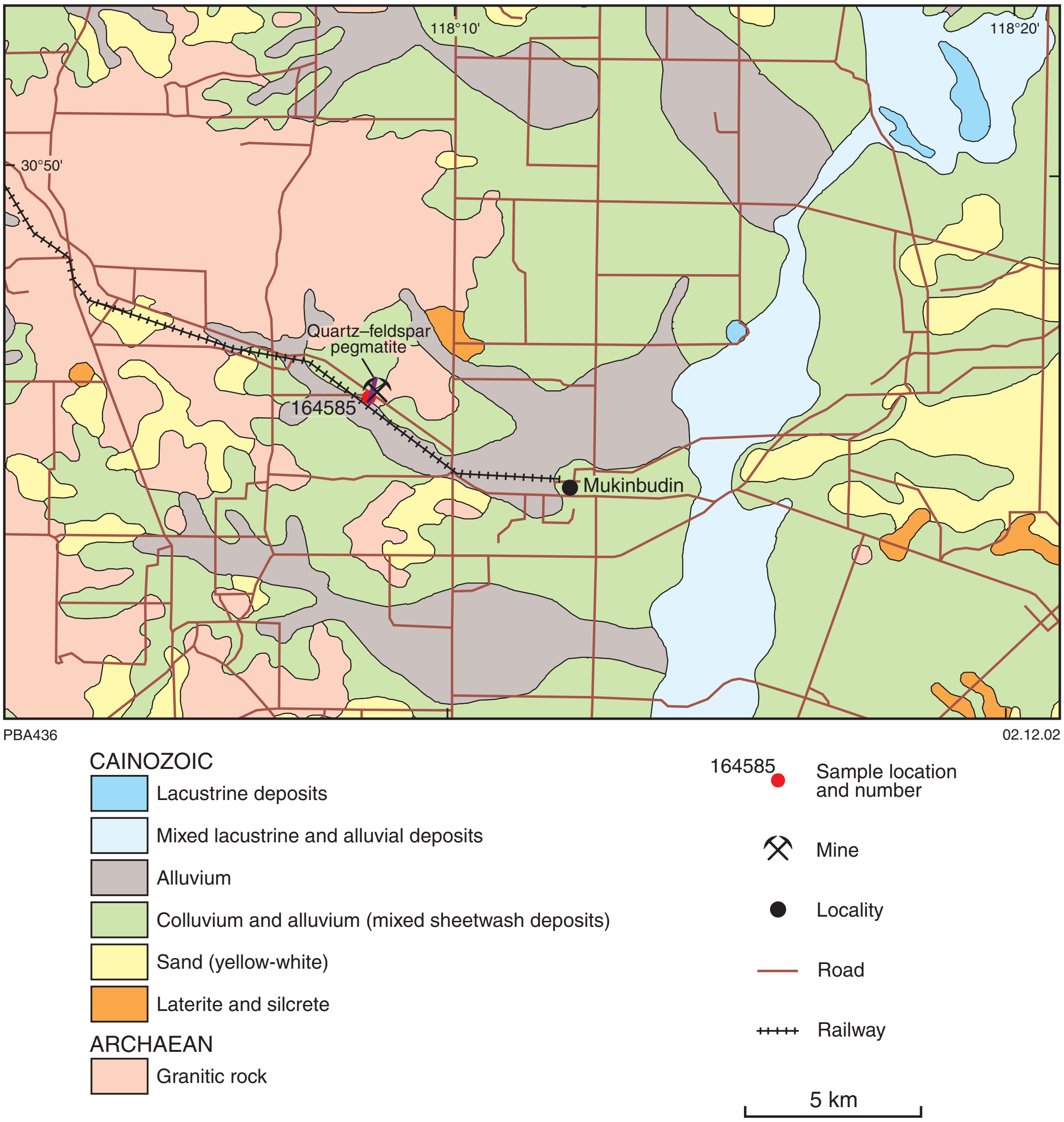

Figure 106. Geology around Mukinbudin feldspar–quartz mine (after Blight et al., 1983)

Table 72. Chemical analyses of quartz from the Mukinbudin and Karloning pegmatites

GSWA no.	*164585*	*164586*	*164587*
		Percentage	
SiO_2	99.50	99.80	99.70
Al_2O_3	0.04	0.02	0.02
Fe_2O_3	0.10	0.04	0.10
MgO	<0.01	<0.01	<0.01
CaO	0.01	<0.01	0.02
Na_2O	<0.01	<0.01	0.01
K_2O	0.01	0.01	0.02
TiO_2	<0.01	<0.01	<0.01
MnO	0.01	<0.01	0.01
P_2O_5	0.008	0.006	0.009
BaO	<0.01	<0.01	<0.01
SO_3	<0.01	<0.01	<0.01
LOI	0.08	0.05	0.06
Total	**99.76**	**99.93**	**99.95**
H_2O	0.02	0.01	0.01

NOTE: 164585: Mukinbudin
164586–87: Karloning

Table 73. Thermal stability of quartz from Mukinbudin pegmatite

GSWA no.	*Locality*	*Size fraction (mm)*					*Cumulative passing*				*Thermal*
		>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	*stability*
						Percentage					
164585	Mukinbudin	75.2	14.1	8.3	1.5	0.8	24.8	10.7	2.3	0.8	75.2
164586	Karloning	96.9	1.6	0.9	0.3	0.2	3.1	1.5	0.5	0.2	96.9
164587	Karloning	79.4	18.5	1.1	0.5	0.6	20.6	2.1	1.0	0.6	79.4

Table 74. Thermal strength of quartz from Mukinbudin pegmatite

GSWA no.	*Locality*	*Size fraction (mm)*					*Cumulative passing*				*Thermal*
		>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	*strength*
						Percentage					
164585	Mukinbudin	46.0	45.5	3.0	3.7	1.7	54.0	8.4	5.4	1.7	94.6
164586	Karloning	73.8	17.9	4.4	2.1	1.8	26.2	8.3	3.9	1.8	96.1
164587	Karloning	79.5	12.5	3.8	2.2	2.1	20.5	8.1	4.3	2.1	95.7

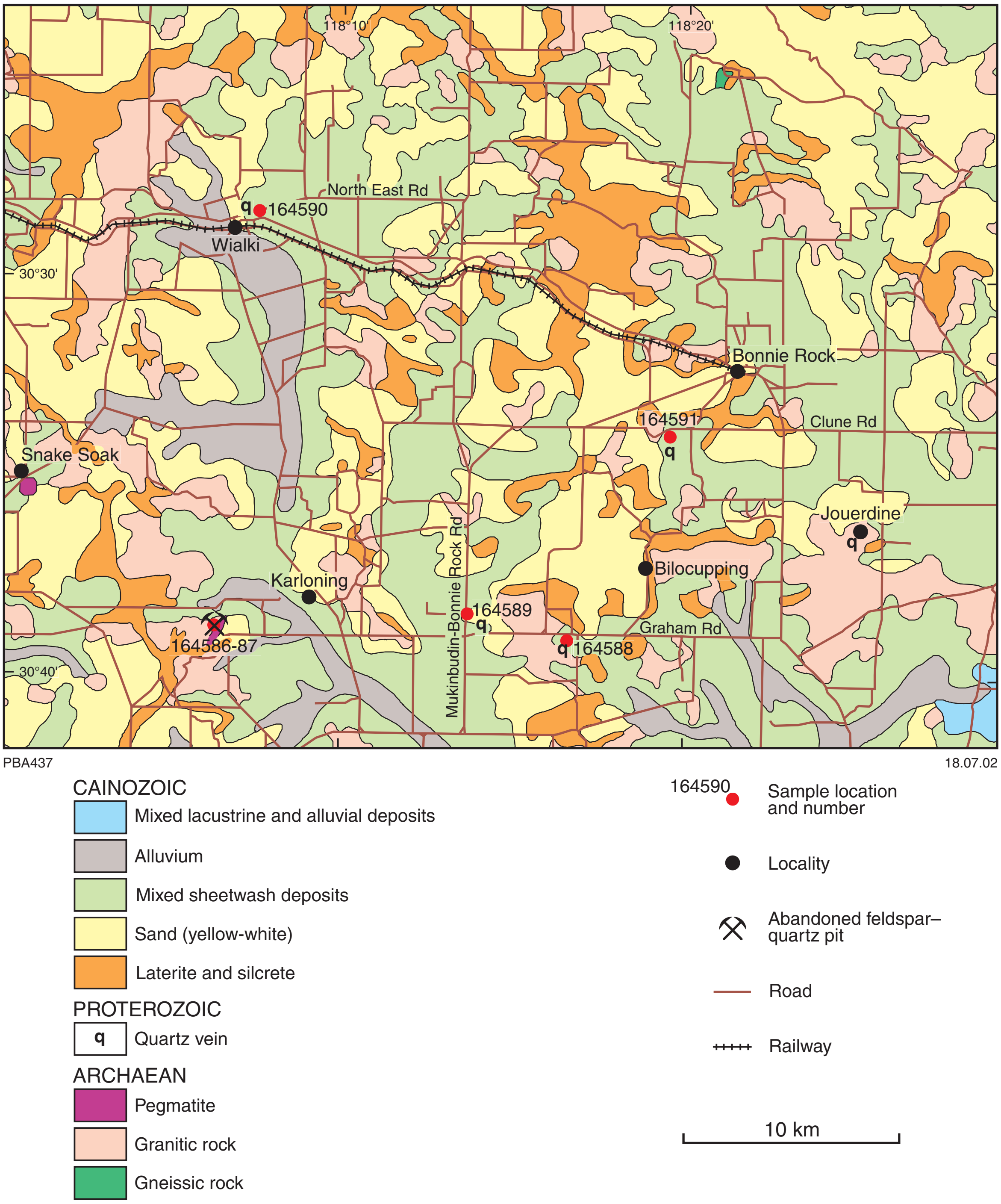

Figure 107. Geology around Karloning, Snake Soak, Bilocupping, Bonnie Rock, and Wialki (after Blight et al., 1983)

PBA501

Figure 108 Photograph of massive quartz in feldspar–quartz pegmatite at Karloning openpit

very low iron, alumina, titania, and phosphorus. Dry crushing, using a mobile crusher, would be possible as there is little clay in the deposit.

Snake Soak

A quartz–feldspar pegmatite deposit 1 km south of Snake Soak (35 km north-northwest of Mukinbudin) (Figs 81 and 107) is considered to have the potential to produce about 200 000 t of moderately high purity quartz within 15–20 m of the surface (Parker, 1999). This deposit represents one of the largest outcrops of quartz within Western Australia (excluding Moora). The deposit is covered by three Mining Leases 70/1048–50, held by the group Unimin Australia Pty Ltd and Messrs B. J. Couper, R. J. Jones, and P. A. Sachse.

The quartz at the surface contains 0.012–0.018% Fe_2O_3, 0.044–0.052% Al_2O_3, 0.003–0.005% TiO_2, and 0.001–0.002% P_2O_5 and also has acceptable thermal characteristics for use as raw material for silicon metal production (Table 75). According to Parker (1999), this quartz deposit has potential for use in the production of silicon metal. Although a resource has not been formally estimated and reported, Parker (1999) stated that the resource has potential to produce about 200 000 t of high-grade quartz. A drillhole sample from 25 m depth, however, indicates higher Fe_2O_3 (0.295%) and alumina (0.461%) than the surface samples (Parker, 1999).

Calcaling

A feldspar–quartz pegmatite deposit at Calcaling (Fig. 110), about 315 km northeast of Perth, was mined during 1995–97 by Imdex Minerals Ltd (Imdex) to extract feldspar. Mining was subsequently stopped owing to a

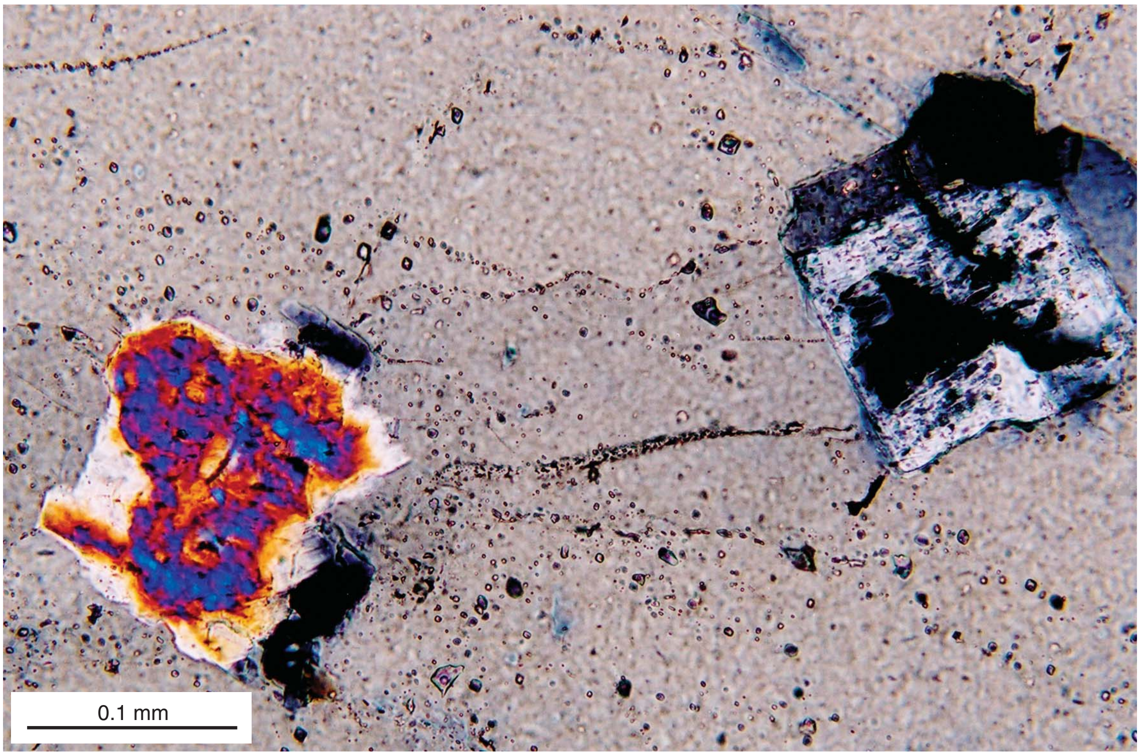

Figure 109. Photomicrograph of Karloning quartz (crossed nicols ×100) showing fluid inclusions, accessory muscovite (coloured) and potash feldspar (grey-altered) in coarse quartz (sample GSWA164586)

combination of low prices, high transport costs, and a lack of feldspar reserves. Imdex have relinquished all mining tenements. The area is now covered by Mining Lease M70/1008 held by Messrs A. J. Jones and R. J. Jones, and Ms R. M. Rivers.

At this location, there is some 1000 t of quartz dumped on the surface adjacent to the openpit. The quartz is very pure but very brittle; it is mixed with about 2–3% feldspar and thus relatively contaminated (Parker, 1999). Test results of samples from this deposit indicate both high- and low-grade quartz (Table 76).

Quartz veins

Quartz veins intruding Archaean granite basement rocks are common in many localities around the Yilgarn Craton (Fig. 81), particularly in the South West Terrane and the Southern Cross Granite–Greenstone Terrane. Many veins identified from the maps were too thin and had surface extensions too limited to be considered as an economic source of quartz. The following section gives test results and descriptions of some veins that appeared to contain high-quality quartz or appreciable surface extensions, and which were sampled by the author. Also included is openfile information available from MPR and other sources. The following occurrences are not described in any priority order.

Bilocupping

Intruding Archaean granitic rock and gneiss in the Bilocupping area (about 30 km northeast of Mukinbudin) are a number of quartz veins of small to moderate size (Figs 81 and 107); however, most of them appear to be not large enough for commercial exploitation.

A prominent northeasterly trending quartz vein on the south side of Graham Road, 4.5 km southwest of Bilocupping, is about 3–4 m wide (sample GSWA 164588), and has vertical jointing (Fig. 111). From exposures at a road cutting, the vein is seen to be intruding granitic rock. Another vertically jointed quartz vein by the side of Mukinbudin–Bonnie Rock Road (Fig. 107) and trending in an east–west direction is about 3–4 m wide (sample GSWA164589). The extent of both quartz veins is uncertain as outcrop is not continuous along the strike directions.

A thin section of sample GSWA164588 indicates that about 60% of quartz is more or less sparry vein quartz, with a size range of about 0.5–2 mm. The remainder consists of coarser (2–5 mm) grains. The textural characteristics suggest that the vein is hydrothermal in origin. The primary crystalline aggregate shows localized dislocation along a network of brittle single fractures and narrow (2 mm) corridors of brecciation (Fig. 112). Minor recrystallization and possible later stage quartz is found along simple fractures. Minor limonite-stained clay–

Table 75. Test results of pegmatite at Snake Soak

Locality	*Thermal stability*	*Thermal strength*	*Fe_2O_3*	*Al_2O_3*	*TiO_2*	*CaO*	*MgO*	*P_2O_5*
				Percentage				
Snake Soak 1. Quartz blow (P70/1244)	85.5	89.2	0.018	0.052	0.005	0.012	0.002	0.002
Snake Soak 2 Quartz blow (P70/1244)	97.4	90.8	0.012	0.044	0.003	0.004	0.001	0.001
Snake Soak Drillhole 25 m (P70/1244)	–	–	0.295	0.461	0.013	0.014	0.007	0.002

SOURCE: after Parker (1999)

sericite (7%) of uncertain origin is found in very small clusters scattered along disruption zones.

A thin section of sample GSWA164589 shows features similar to those of GSWA164588, but the primary vein quartz is coarser overall, and brittle fracturing more extensive and more complex. The primary hydrothermal vein quartz aggregate consists of vaguely sparry/prismatic crystals (commonly 5 mm but up to 20 mm in size), typically with dispersed minute fluid inclusions. The extensive fracturing between, and to a lesser extent through, primary crystals and associated micro-brecciation is largely occupied by microcrystalline quartz. Subparallel stringers and earlier sealed stringers through some very coarse crystals indicate multiple crack and seal events. Some microsparry quartz, partly healing fractures, may have a late-stage epithermal genesis, and minor small patches of decussate sericite conceivably has the same genesis. Subparallel ‘crack and seal’ microveinlets/laminae occur through several of the earlier very coarse quartz crystals (Fig. 113).

Sample GSWA164588 assayed 99.00% SiO_2, 0.34% Al_2O_3, 0.10% Fe_2O_3, 0.01% TiO_2, and 0.01% P_2O_5, indicating that the quartz is high-grade (Table 77). The other sample (GSWA164589) assayed 98.90% SiO_2, 0.42% Al_2O_3, 0.23% Fe_2O_3, 0.01% TiO_2 and 0.011% P_2O_5, indicating that the quartz is moderately high grade (Table 77). The samples GSWA164588–89 had average thermal stability and thermal strength values of 94.5 and 95.8% respectively, indicating that the quartz is suitable for use in the production of silicon metal (Tables 78 and 79).

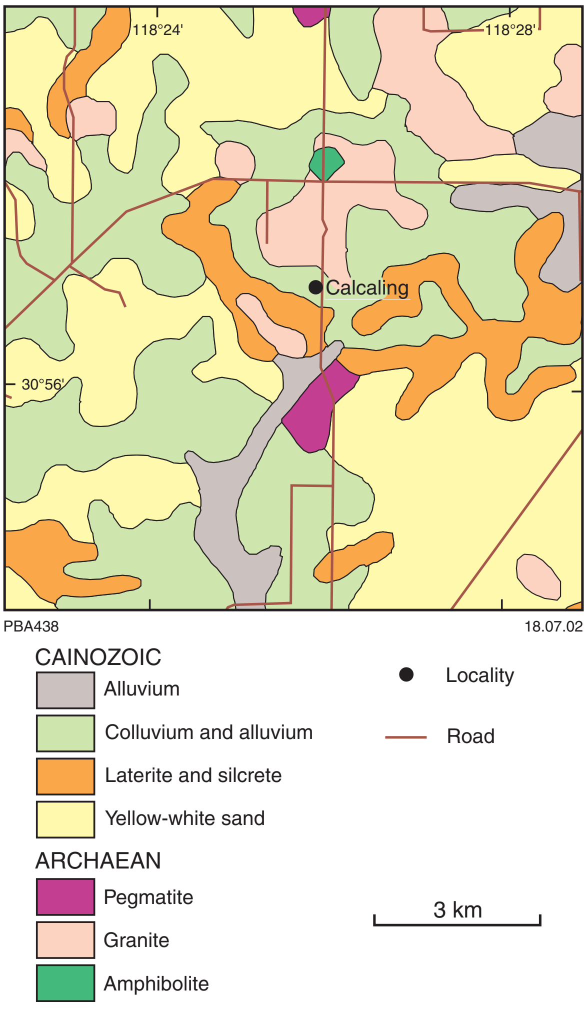

Figure 110. Geology around Calcaling pegmatite (after Blight et al., 1983)

Bonnie Rock (Jouerdine)

There is a prominent ridge containing quartz veins at Jouerdine, approximately 9.5 km southeast of Bonnie Rock (Fig. 107). One major quartz vein in the ridge strikes approximately 200º and has a width ranging from a few metres to more than 15 m. There are also parallel quartz veins having widths of 2 m or more. The surrounding area consists of sporadic granite outcrops and quartz scree material. In 1986, the resource in the main quartz vein was estimated at 289 000 t (probably of inferred status) based on seven drillholes to a depth of 9 m each and a strike length of 900 m (Ronk, 1986). The holes were drilled into the main quartz vein using an air-track drill but locations are not given. The chemical composition of 21 samples (3 m composite samples from the seven drillholes) had 94.1–98.8% SiO_2, 0.56–3.11% Al_2O_3, and 0.05–0.6% Fe_2O_3. The quartz is considered to be suitable for use as decorative cladding. The resource has been subsequently upgraded but details remain confidential.

A quartz vein is also exposed at the south side Clune Road, approximately 4 km southwest of Bonnie Rock (Fig. 107). The vein is about 10–15 m wide and the

Table 76. Test results of pegmatite at Calcaling

Locality	*Thermal stability*	*Thermal strength*	*Fe_2O_3*	*Al_2O_3*	*TiO_2*	*CaO*	*MgO*	*P_2O_5*
				Percentage				
Calcaling Quartz Vein 1	99.2	96.4	0.081	0.340	0.007	0.014	0.007	0.004
Calcaling Quartz Vein 2	98.5	87.9	0.037	0.332	0.002	0.007	0.005	0.002
Calcaling mine quartz dump	64.1	79.6	0.017	0.062	0.004	0.015	0.01	0.003

SOURCE: after Parker (1999)

PBA503

Figure 111. Outcrop of quartz vein at Bilocupping

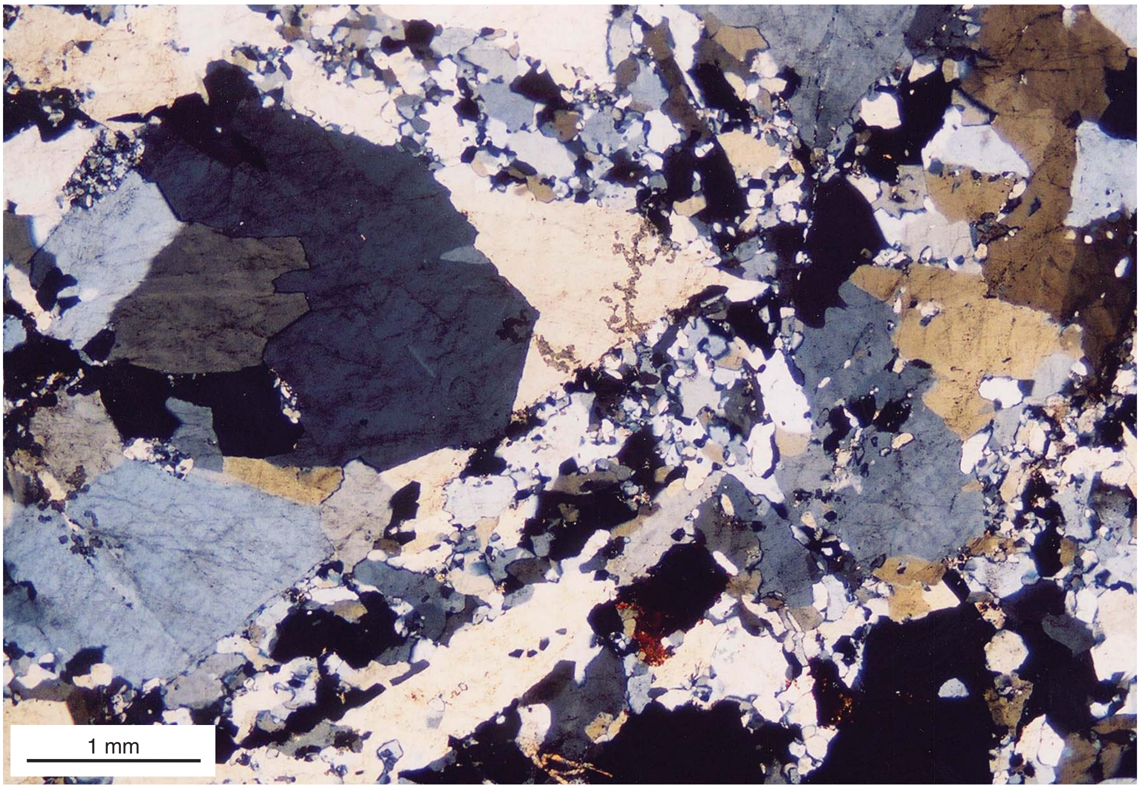

Figure 112. Photomicrograph (crossed nicols ×20) showing aggregate of coarse randomly interlocking quartz crystals with narrow zones of brecciation (sample GSWA164588: Bilocupping)

outcrop extends to about 100 m southwards, but it does not appear to extend to the north side of the road. A thin section of a sample (GSWA164591) from this quartz vein indicates that at least 85% consists of primary hydrothermal quartz crystals, mostly subhedral/sparry, ranging in size from 2 to 10 mm. These crystals are randomly interlocked. The quartz crystals are stressed with internal 'ghost-like' textures indicating early fractures subsequently healed in situ (crack and seal). However, later and more random fractures are commonly occupied by mobilized or possible epithermal microcrystalline/microsparry quartz (Fig. 114). Minor interstitial areas between original crystals are infilled by the same ?epithermal microcrystalline quartz. Sparse, minute inclusions of sericite are present in many of the primary quartz crystals, and sparse, coarser sericite has formed in the later vein quartz.

Sample GSWA164591 assayed 99.30% SiO_2, 0.20% Al_2O_3, 0.06% Fe_2O_3, <0.01% TiO_2 and 0.002% P_2O_5, indicating that the quartz is high grade (Table 77). The thermal stability and thermal strength values of the sample are 99.7 and 95.7% respectively, and indicate possible potential of the material for use in the production of silicon metal (Tables 78 and 79).

Wialki

A prominent outcrop of quartz vein is found near North East Road, approximately 1.5 km northeast of Wialki (Fig. 107). The vein, which is exposed on both sides of the road, is about 20 m wide and strikes in a north-northeasterly direction.

A thin section of a sample (GSWA164590) of this quartz vein indicates an intricately interlocking, quite coarse (≤6 mm) mass of sparry hydrothermal vein-quartz crystals. These crystals commonly exhibit internal zoning defined by variable concentrations of fluid-inclusion 'dusting', which commonly reflect incipient pyramidal terminations to prismatic quartz (Fig. 115a). Locally, these sparry crystals are commonly oriented in rows, with overall banded 'cockade' or 'comb-like' texture. In other parts, there are smaller (≤1 mm) sparry crystals distributed in a random manner, with interstitial micro/crypto-crystalline quartz (Fig. 115b).

Sample GSWA164590 assayed 98.9% SiO_2, 0.46% Al_2O_3, 0.13% Fe_2O_3, <0.01% TiO_2 and 0.013% P_2O_5, indicating that the quartz is moderately high grade (Table 77). The thermal stability and thermal strength values of the sample are 96.7and 98.0% respectively, indicating that the material has excellent thermal properties for use in the production of silicon metal (Tables 78 and 79).

Red Hill Gully

A quartz vein is found at Red Hill Gully (15 km east-southeast of Bridgetown), at the end of a track (towards

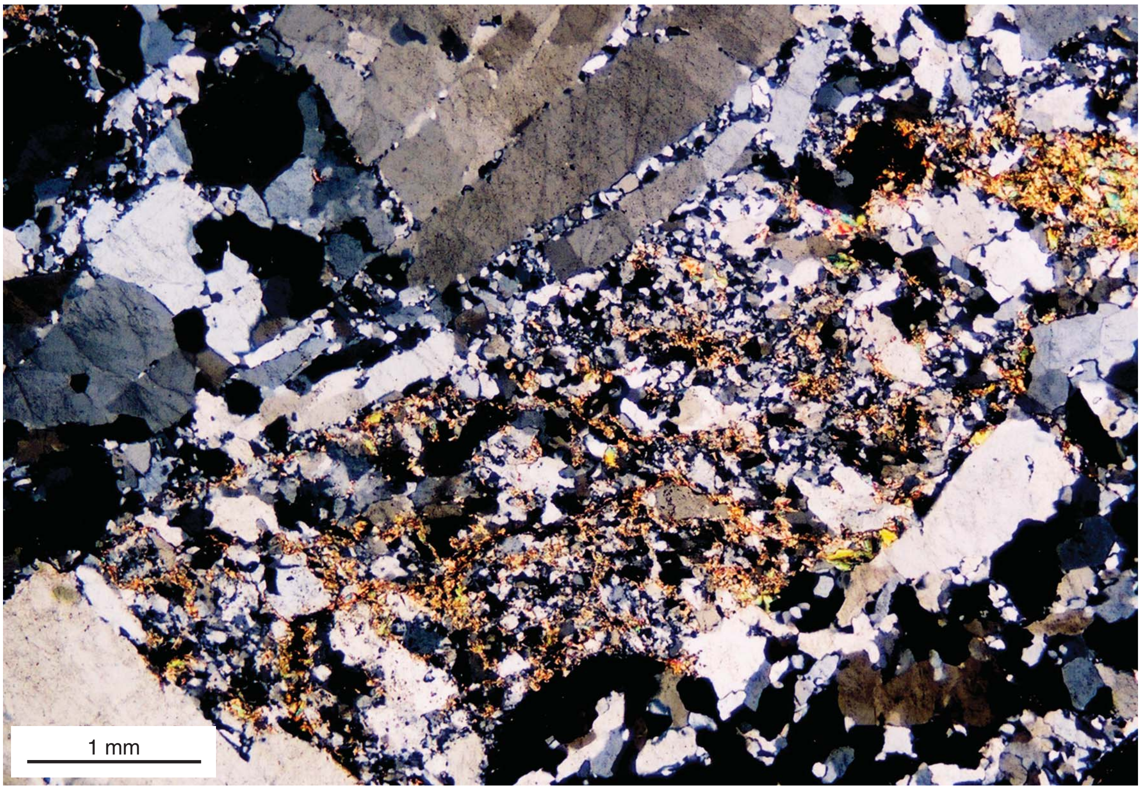

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Figure 113. Photomicrograph (crossed nicols ×20) showing early coarse hydrothermal quartz that has been stressed and fractured, and permeated by later crystalline quartz with associated sericite (sample GSWA164589: Bilocupping)

Table 77. Chemical analyses of quartz veins from Bilocupping, Bonnie Rock, Wialki, Red Hill Gully, and Woodanilling

GSWA no.	*164588*	*164589*	*164591*	*164590*	*164537*	*164572*
			Percentage			
SiO_2	99.00	98.90	99.30	98.90	99.10	98.60
Al_2O_3	0.34	0.42	0.20	0.46	0.13	0.59
Fe_2O_3	0.10	0.23	0.06	0.13	0.32	0.21
MgO	0.01	0.02	<0.01	<0.01	<0.01	0.02
CaO	0.02	0.01	0.01	0.03	0.03	0.06
Na_2O	0.01	<0.01	0.01	0.02	<0.01	0.03
K_2O	0.06	0.09	0.05	0.06	0.02	0.11
TiO_2	0.01	0.01	<0.01	<0.01	0.03	0.01
MnO	0.01	<0.01	<0.01	0.01	0.01	0.02
P_2O_5	0.010	0.011	0.002	0.013	0.007	0.006
BaO	0.01	<0.01	<0.01	0.01	<0.01	<0.01
SO_3	<0.01	<0.01	<0.01	<0.01	0.02	<0.01
LOI	0.17	0.18	0.12	0.18	0.16	0.40
Total	**99.75**	**99.87**	**99.75**	**99.81**	**99.83**	**100.06**
H_2O	0.05	0.03	0.02	0.03	0.24	0.01

NOTE: 164588: Graham Road, Bilocupping
164589: Mukinbudin–Moondon Road, Bilocupping
164591: Clune Road, Bonnie Rock
164590: Wialki
164537: Red Hill Gully
164572: Orchard Road, 6 km southwest of Woodanilling

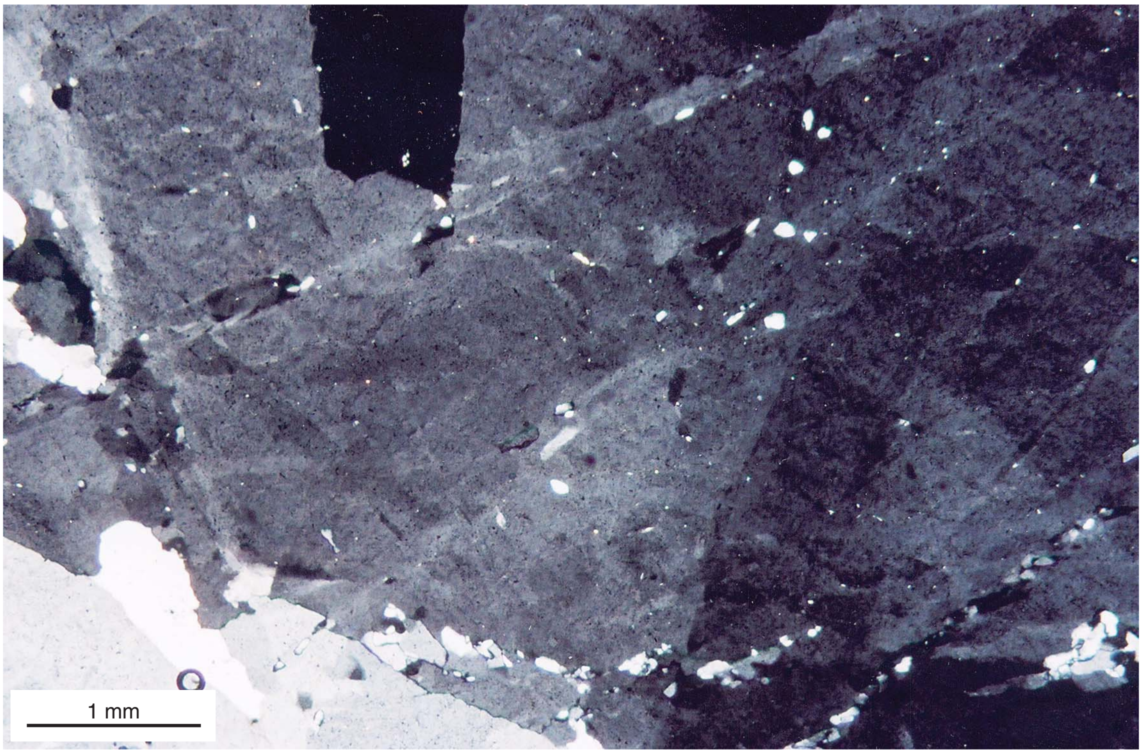

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Figure 114. Photomicrograph (crossed nicols ×20) showing a large quartz grain with 'ghost-like' apparent relict cracks, completely healed. Later microfractures filled with extremely fine microsparry quartz (sample GSWA164591: Bonnie Rock, Clune Road)

Red Hill Gully) off Carbunup Brook Road (Fig. 116). The vein is exposed in the form of pebbles on the west slope of a steep ridge elongated in an approximately north–south direction. The vein appears to be small at the locality of sampling and the quantity available would be small. However, a sample (GSWA164537) assayed 99.10% SiO_2, 0.13% Al_2O_3, 0.32% Fe_2O_3, 0.03% TiO_2, and 0.007% P_2O_5 (Table 77). The thermal stability of the sample is 84.6%, which is too low for use in the silicon metal production, but the sample has a high thermal strength value of 97.2% (Tables 78 and 79).

A thin section of sample GSWA164537 displays a metamorphic mosaic of equigranular quartz. Individual grains have a fairly consistent average size of about 0.5 mm, with intergranular contacts commonly sutured. Streaky lenticular laminae through this mosaic, however, are finer grained, and incorporate minor, partly bifurcating, schistose foliae (Fig. 117). These characteristics objectively tend to favour an interpretation of metaquartzite, but do not exclude possible recrystallized (and sheared?) vein quartz. Accessory minerals were not present.

Woodanilling

A quartz vein is exposed approximately 6 km west-southwest of Woodanilling, along Orchard Road (Fig. 118). The vein strikes northeasterly and is more exposed on the south side of the road. Quartz derived from the vein is distributed within a zone about 50 m wide. The western margin of the quartz vein has an intrusive contact with the granite. The quartz is white and massive and a thin section from sample (GSWA164572) shows that at least 80% consists of a texturally complex aggregate of interlocking coarse to very coarse hydrothermal, sparry to granular vein-quartz crystals. Some quartz crystals are distributed randomly, although many are arranged in bands exhibiting a 'cockade' texture. The crystals are densely clouded with minute fluid inclusions, which commonly define internal pyramidal zones (Fig. 119). Locally, a coarse hydrothermal vein quartz is overprinted by microfractures, and also by a breccia corridor up to 6 mm wide. These structures are infilled by later generation microsparry microgranular quartz, which is probably epithermal.

Sample GSWA164572 assayed 98.6% SiO_2, 0.59% Al_2O_3, 0.21% Fe_2O_3, 0.01% TiO_2 and 0.006% P_2O_5, indicating moderately high grade quartz (Table 77). The thermal stability and thermal strength values of the sample are 96.1 and 92.2% respectively, and can be considered to be within acceptable levels for use in the production of silicon metal (Tables 78 and 79).

Avon River Valley

In 1988, Omen Pty Ltd sampled a quartz vein that cut across the Avon River valley (approximately 50 km northeast of Perth) to determine the quality and quantity of quartz available as possible feedstock for a silicon smelter project. The quartz vein strikes east–west, has a

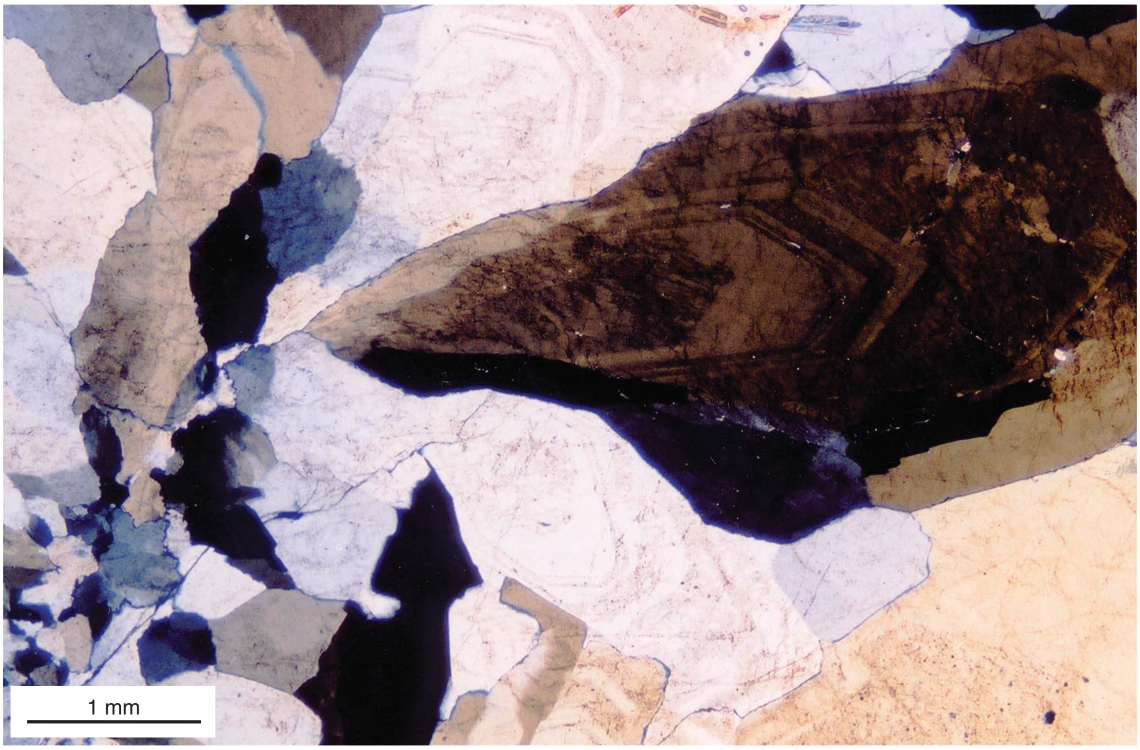
Table 78. Thermal stability test results of quartz veins from Bilocupping, Bonnie Rock, Wialki, Red Hill Gully, and Woodanilling

GSWA no.	*Locality*	*Size fraction (mm)*					*Cumulative passing*				*Thermal stability*
		>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	
						Percentage					
164588	Bilocupping (Graham Road)	98.7	0.6	0.5	0.1	0.1	1.3	0.7	0.2	0.1	98.7
164589	Bilocupping (Mukinbudin–Moondon Road)	90.3	6.7	1.9	0.8	0.3	9.7	2.9	1.0	0.3	90.3
164591	Bonnie Rock (Clune Road)	99.7	0.0	0.0	0.1	0.2	0.3	0.3	0.3	0.2	99.7
164590	Wialki	96.7	3.2	0.0	0.0	0.0	3.3	0.1	0.1	0.0	96.7
164537	Red Hill Gully	84.6	14.0	0.8	0.2	0.3	15.4	1.4	0.5	0.3	84.6
164572	Woodanilling (6 km southwest; Orchard Road)	96.1	2.9	0.2	0.4	0.3	3.9	0.9	0.7	0.3	96.1

Table 79. Thermal strength test results of samples from Bilocupping, Bonnie Rock, Wialki, Red Hill Gully, and Woodanilling

GSWA no.	*Locality*	*Size fraction (mm)*					*Cumulative passing*				*Thermal strength*
		>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	
						Percentage					
164588	Bilocupping (Graham Road)	94.0	3.0	1.9	0.5	0.6	6.0	3.0	1.0	0.6	99.0
164589	Bilocupping (Mukinbudin–Moondon Road)	46.4	32.3	13.9	4.4	3.0	53.6	21.3	7.4	3.0	92.6
164591	Bonnie Rock (Clune Road)	69.2	21.2	5.3	2.3	2.0	30.8	9.6	4.3	2.0	95.7
164590	Wialki	88.1	6.8	3.1	0.7	1.3	11.9	5.1	2.0	1.3	98.0
164537	Red Hill Gully	85.1	10.0	2.0	0.7	2.1	14.9	4.9	2.8	2.1	97.2
164572	Woodanilling (6 km southwest; Orchard Road)	70.5	15.0	6.7	3.1	4.7	29.5	14.5	7.8	4.7	92.2

(a)



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(b)

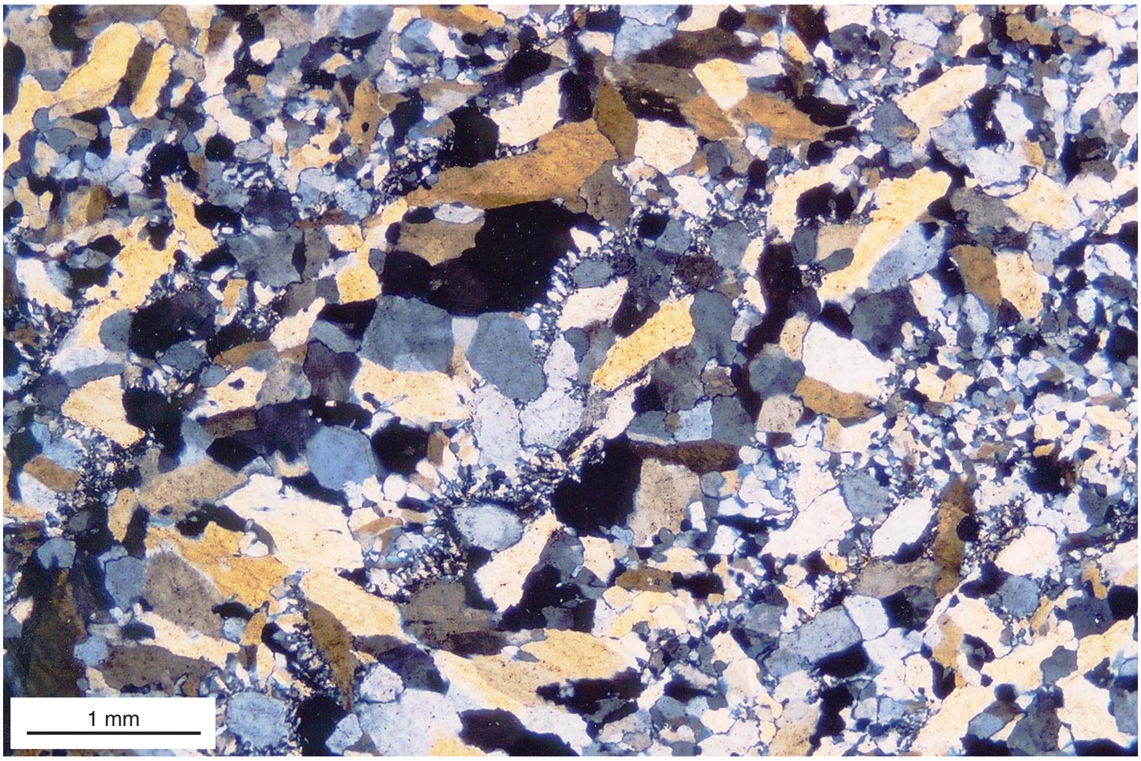

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Figure 115. a) Photomicrograph (crossed nicols ×20) showing coarse hydrothermal sparry quartz, with internal zones defined by fluid inclusions (sample GSWA164590: Wialki); b) Different area of Figure 115a thin section (crossed nicols ×20) showing finer interstitial micro/cryptocrystalline quartz (GSWA164590: Wialki)

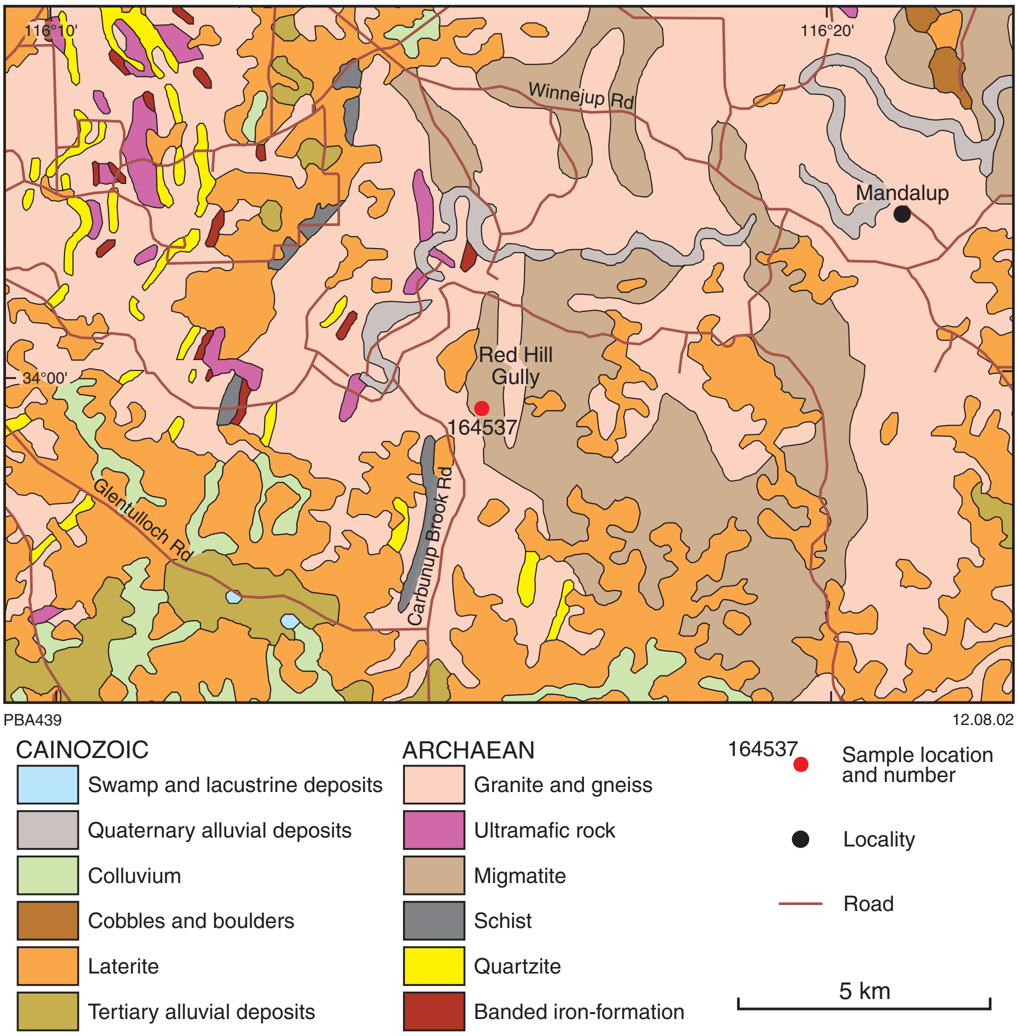

Figure 116. Geology around Red Hill Gully (after Lowry et al., 1983; Wilde and Walker, 1984a)

nearly vertical dip, and is some 200 m wide with a length of approximately 1.5 km (Fig. 120). The results of sample tests are not given (Omen Pty Ltd, 1988).

Yellowdine

A large quartz vein outcrops about 10 km north of Yellowdine (30 km east of Southern Cross; Fig. 121), some 400 km east of Perth. The vein strikes north–south and is shown on the SOUTHERN CROSS 1:250 000-scale geological map as outcropping in three zones over a length of about 600 m. The vein appears to be up to 10 m wide. Parker (1999) noted that one drillhole inclined at 60° to the west had intersected 30 m of quartz. This equates to a true thickness of about 12 m. The quartz is fairly coarse grained and shatters when hit with a hammer. No information is available on the company involved or the time of drilling.

Surface samples collected along the strike of the vein by Mr Lloyd Hirst (a haulage contractor) indicate high-purity quartz. Some of the cuttings from the hole are very pure quartz. Surface samples contain low to moderate levels of alumina, which is consistent with the presence of small quantities of feldspar observed in the outcrop. Parker (1999) stated that traces of epidote were observed in drill cuttings, which is consistent with locally higher levels of calcium. However, no information is available on any chemical analyses. According to Parker (1999), the prospect is significant in terms of size and has acceptable chemical characteristics with moderate thermal characteristics.

Lake Seabrook

In 1971, Barrier Exploration NL carried out a survey to determine resources of silica at a quartz blow known as Quartz Hill, near Lake Seabrook (Fig. 122). The resource was estimated at about 16.3 Mt (Morton, 1972). A planned drilling program to determine the overall quality of quartz and a follow-up feasibility study was not carried out, and the resource is probably not of ‘inferred’ status under the current JORC code as no grade estimate exists. The main exploration program was for ultramafic hosted nickel–copper sulfides and gold in an Archaean sequence of serpentinized ultramafic rocks, metabasalt, and metasedimentary units.

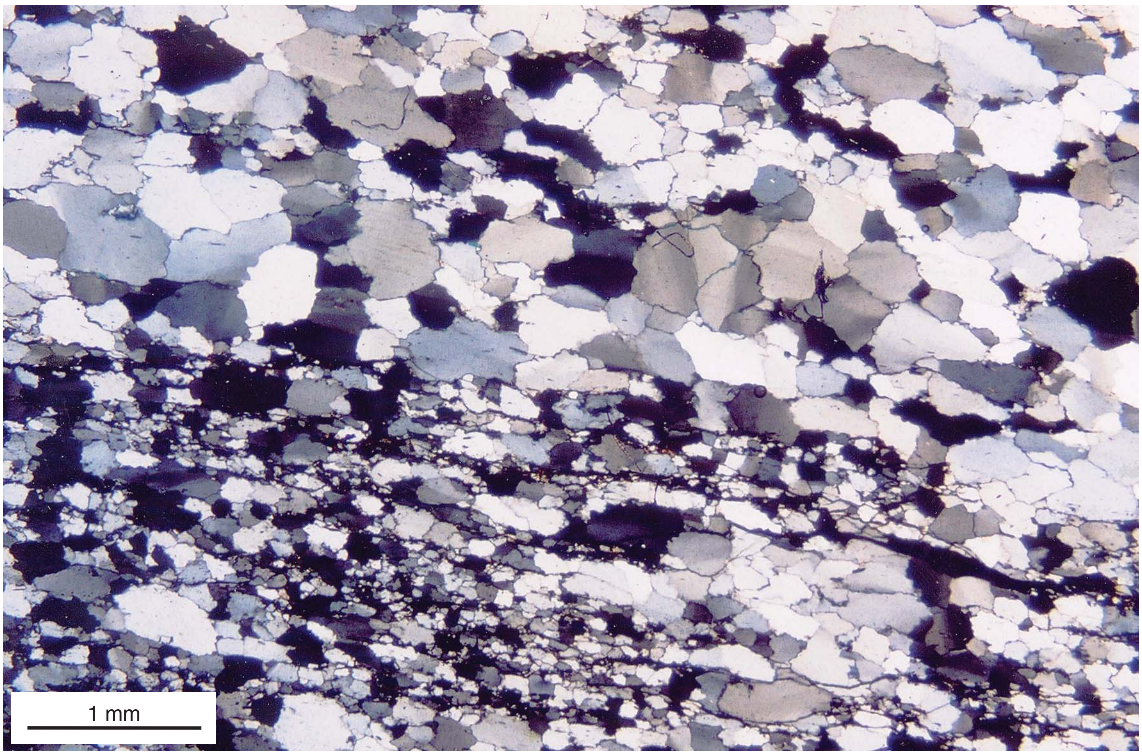

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Figure 117. Photomicrograph (crossed nicols ×20) showing quartzite with layers of different average grain size within the quartz mosaic (sample GSWA164537: Red Hill Gully)

White Flag Lake

During 1981–86, Western Mining Corporation (WMC) carried out exploration for quartz at White Flag Lake, located 24 km northwest of Kalgoorlie in the Ora Banda greenstone belt (Fig. 123). The quartz outcrop adjacent to White Flag Lake was tested for volume and purity with a view to its future use as a converter flux in WMC's nickel smelter at Kalgoorlie. Twenty samples were analysed and the results indicated that SiO_2 ranged from 98 to 99% and that the only significant impurity was Al_2O_3 with values ranging from 0.4 to 1.6%. The resource available was estimated at 400 000 m^3 at 98–99% SiO_2 (Western Mining Corporation Limited, 1986). In 1987, an exploratory hole was drilled to intersect the quartz vein at a depth of approximately 100 m. The first 39 m of the hole was drilled by reverse-circulation percussion and the remaining 101 m by diamond drilling. Samples from the drillhole indicated that the quality of quartz deteriorated with depth, with SiO_2 averaging 75% at 100 m. It was concluded that the tonnage available was insufficient for long-term requirements, and also that due to developments at the smelter, lump quartz was no longer required for the fluxing process (Western Mining Corporation Limited, 1986, 1988, 1989).

White Hill

A quartz vein at White Hill, approximately 6 km north-northwest of Mount Murchison and 220 km north-northeast of Mullewa (Figs 81 and 124), was explored by Mr B. McNab in 1990–91 for possible high-grade quartz. The vein strikes north-northeast and outcrops through an alluvial plain of unconsolidated silt and sand in sheetwash sediment. The vein extends for approximately 1.2 km and has an average width of 5 m. At the southern end, the quartz vein is some 15 m above the ground level and gradually tapers off to ground level within about 500 m. The quartz vein probably intrudes the granitoid rocks that are exposed in areas to the south. The tonnage of quartz above the ground was estimated at 172 125 t with another 30 000 t of weathered quartz on the breakaway areas of the hill (McNab, 1991). A composite of 60 rock-chip samples of the quartz vein collected by McNab (1991) along the crest line assayed 99.9% SiO_2, 0.002% Ti, and 0.001% P.

Pilbara Craton

Prominent quartz veins, chert, and quartzite sequences of the Pilbara Craton are known within about 120 km of Karratha and Port Hedland. Occurrences are indicated on the GSWA 1:250 000 geological series maps of PORT HEDLAND and ROEBOURNE, and in the 1:50 000 urban geology map of KARRATHA (Kriewaldt et al., 1964; Biggs, 1979; Hickman and Gibson, 1981; Hickman and Smithies, 2000). Prominent chert formations are known approximately 20 km east of Shaw River, quartz veins are found within 20 km of Karratha, and there are quartzite occurrences some 10 km south of Whim Creek (Fig. 81).

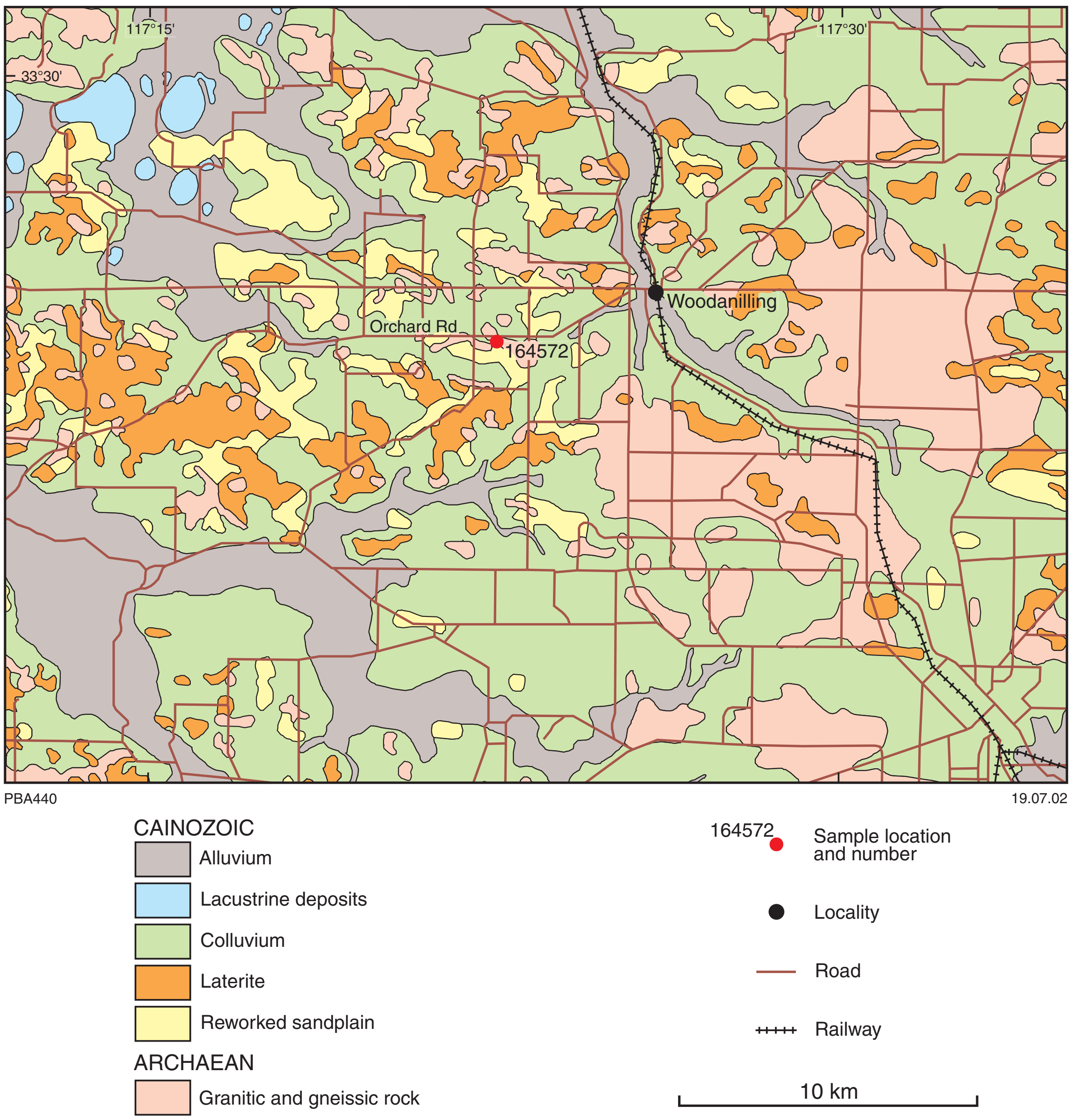

Figure 118. Geology around Woodanilling (after Brakel et al., 1985)

Following are descriptions of some of these silica rock occurrences, which were sampled by the author to test for their suitability as sources of material for the production of silicon metal.

Chert

Shaw River

There are prominent outcrops of Archaean chert on both sides of the road about 23 km southeast of Shaw River along the Port Hedland – Marble Bar Road.

Prominent ridges of chert outcrop in north-northwest and southwest directions (Fig. 125). The chert is exposed as banded, massive, white chert (Fig. 126) and also as grey and white bands with well-defined parallel layering (Fig. 127). The chert is associated with an Archaean sequence containing rhyolite to dacite lava and felsic schist, basalt, and sandstone. Quaternary gravel deposits are common along the western side of the sequence (Hickman and Gibson, 1981).

Petrography

Petrographic studies of five samples (GSWA145206–10) collected from the ridges north and south of the road (Fig. 125) confirm the material as chert that consists of somewhat banded and laminated cryptocrystalline to microcrystalline (lesser) quartz. Very fine quartz is present in variable concentration within the inherently more extensive ultrafine cherty quartz, and is interpreted

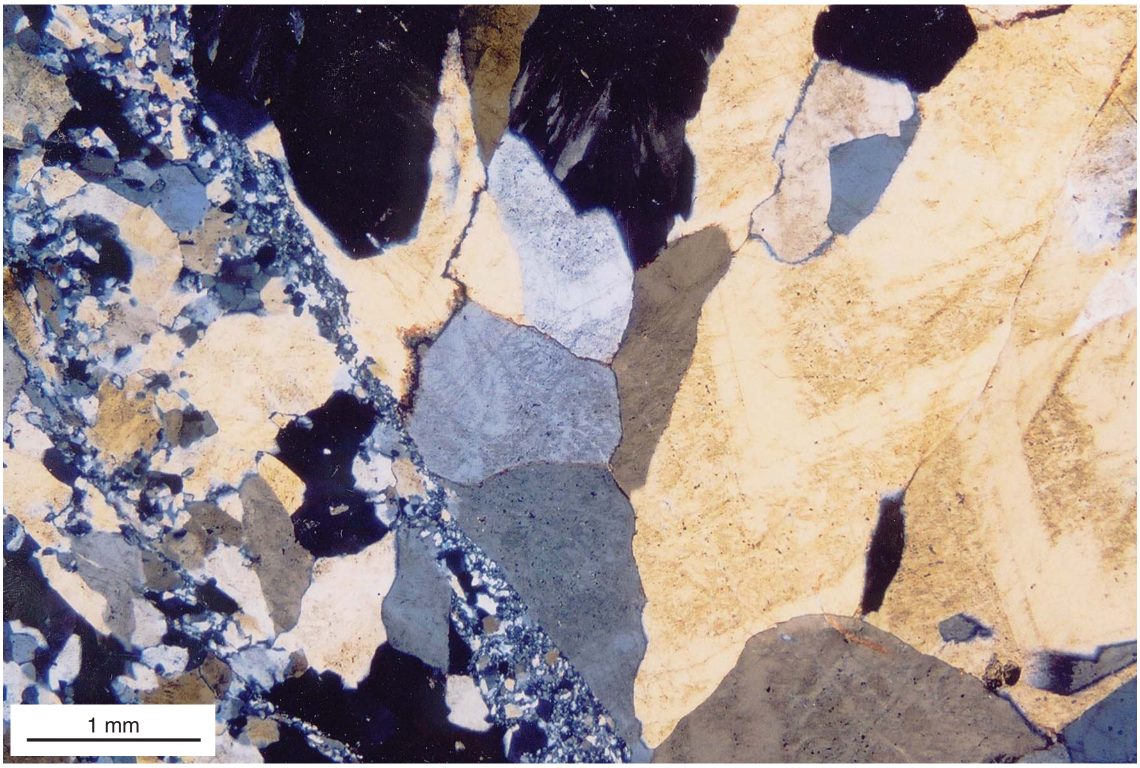

Figure 119. Photomicrograph (crossed nicols ×20) showing coarse early sparry hydrothermal quartz, with fluid inclusions defining a zoned internal crystal structure (sample GSWA164572: Woodanilling)

as recrystallization in situ with some local incipient secondary silicification. Samples GSWA145206–07 have stringers and veinlets of microcrystalline quartz, mostly cutting across the prevailing layering, but some along inherited layering and bedding. In samples GSWA145208–10, quartz veins are much wider and more abundant, and in GSWA145209 these fill disruptions with or without what may be oxidized pyrite. In GSWA145208, wide veins of coarse sparry quartz are conformable along selective shear planes, and these appear to post-date crosscutting veins of coarse quartz. In GSWA145210, a wide vein has sparry pyramidal 'cockade-textured' quartz lining the margins and surrounding a central core of chalcedony with fine colloform zoning, all of which suggest an epigenetic origin rather than localized recrystallization and mobilization. Following are more detailed descriptions of the samples.

Sample GSWA145206 is milky white chert from a ridge of banded chert on the north side of the Port Hedland – Marble Bar Road. The chert ridge (Fig. 128) trends north-northwesterly, and the chert has well-developed steep (70°) easterly dipping joints. The ridge is approximately 200 m long and approximately 50 m wide and rises to about 5 m above surrounding ground level. A thin section of this sample indicates almost 100% quartz consisting of predominantly ultrafine cryptocrystalline silica with individual grain size mostly less than 20 µm. The only other mineral phase is iron oxide (<1%), which occurs as limonite and also rare stylolites of secondary iron oxide along some layers. Up to about 15% of the total quartz forming this rock occurs as stringers and veins (width 0.5–1.5 mm) crosscutting the chert layering at a fairly high angle (Fig. 129). The fabric of some of these veins spreads into the internal fabric of the layers they cut. Sample GSWA145207, from the same ridge, is milky white chert with lenses of dark grey siliceous material. A thin section of this sample shows laminated chert layers up to 10 mm thick with some closely spaced siliceous laminations about 2 mm thick. Approximately 50% of these layers and laminae consist of homogeneous ultrafine cryptocrystalline chert (Fig. 130a), with the other 50% consisting of slightly coarser, irregularly elongated to relatively random quartz micromosaic (Fig. 130b). Some quartz with this internal micromosaic fabric, however, forms disconformable (partly crosscutting) domains, which may be dislocated primary bands, subsequently rehealed within the body of the chert. Several stringers and veinlets of quartz are randomly crosscutting. In sample GSWA145207, there is rare secondary iron-oxide as sparse microscopic stylolites and local dust-like disseminated material. Also trace minute oxidized pyrite or magnetite crystals are seen in some bands. There are trace microfoliae of sericite.

A ridge of chert at the south side (Fig. 131) of the Port Hedland – Marble Bar Road is about 300 m long and 75 m wide and extends to about 10 m above ground level. The ridge trends north-northwesterly. The chert is very

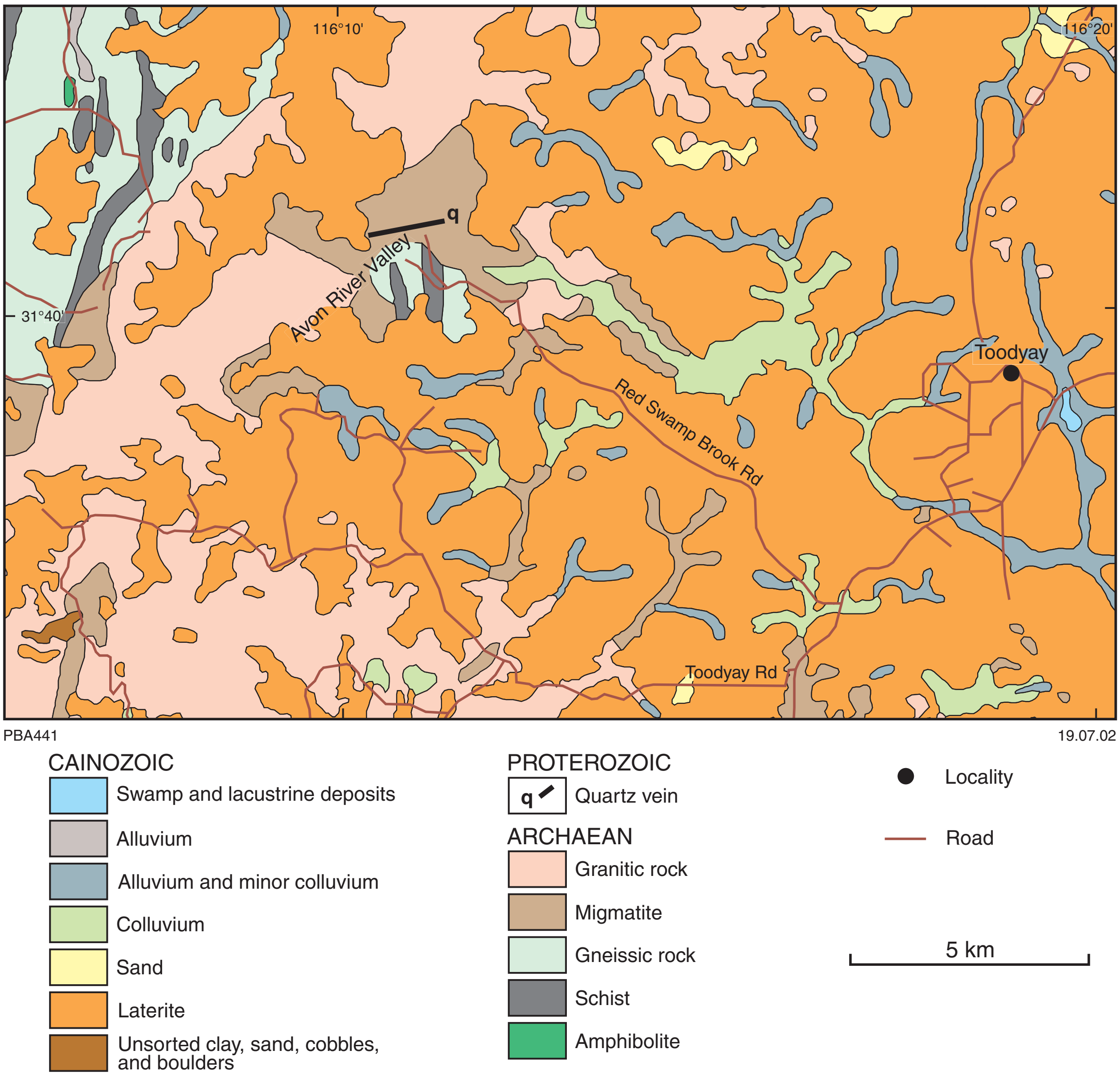

Figure 120. Geology around Avon River Valley (after Low et al., 1978)

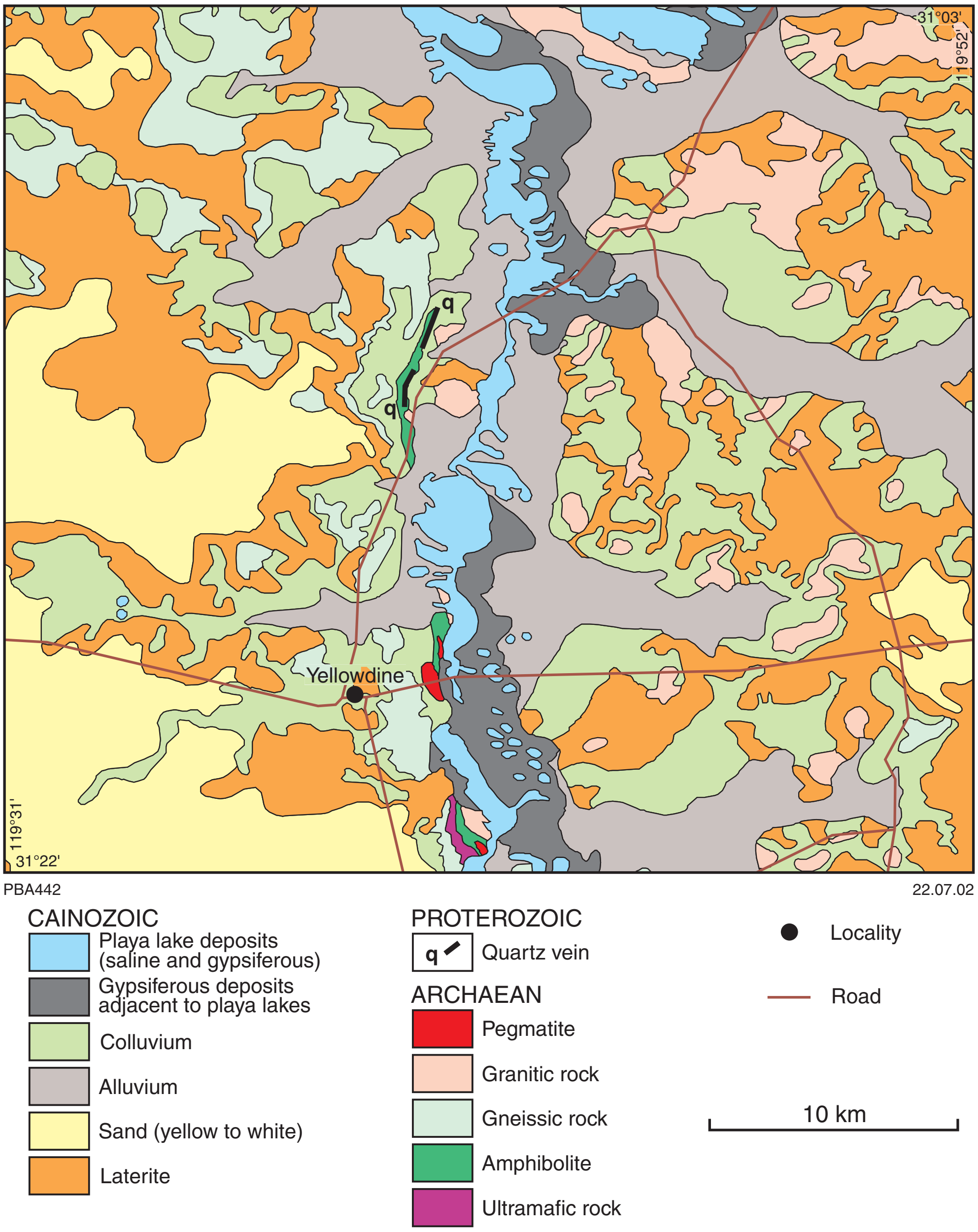

Figure 121. Geology around Yellowdine (after Gee, 1981)

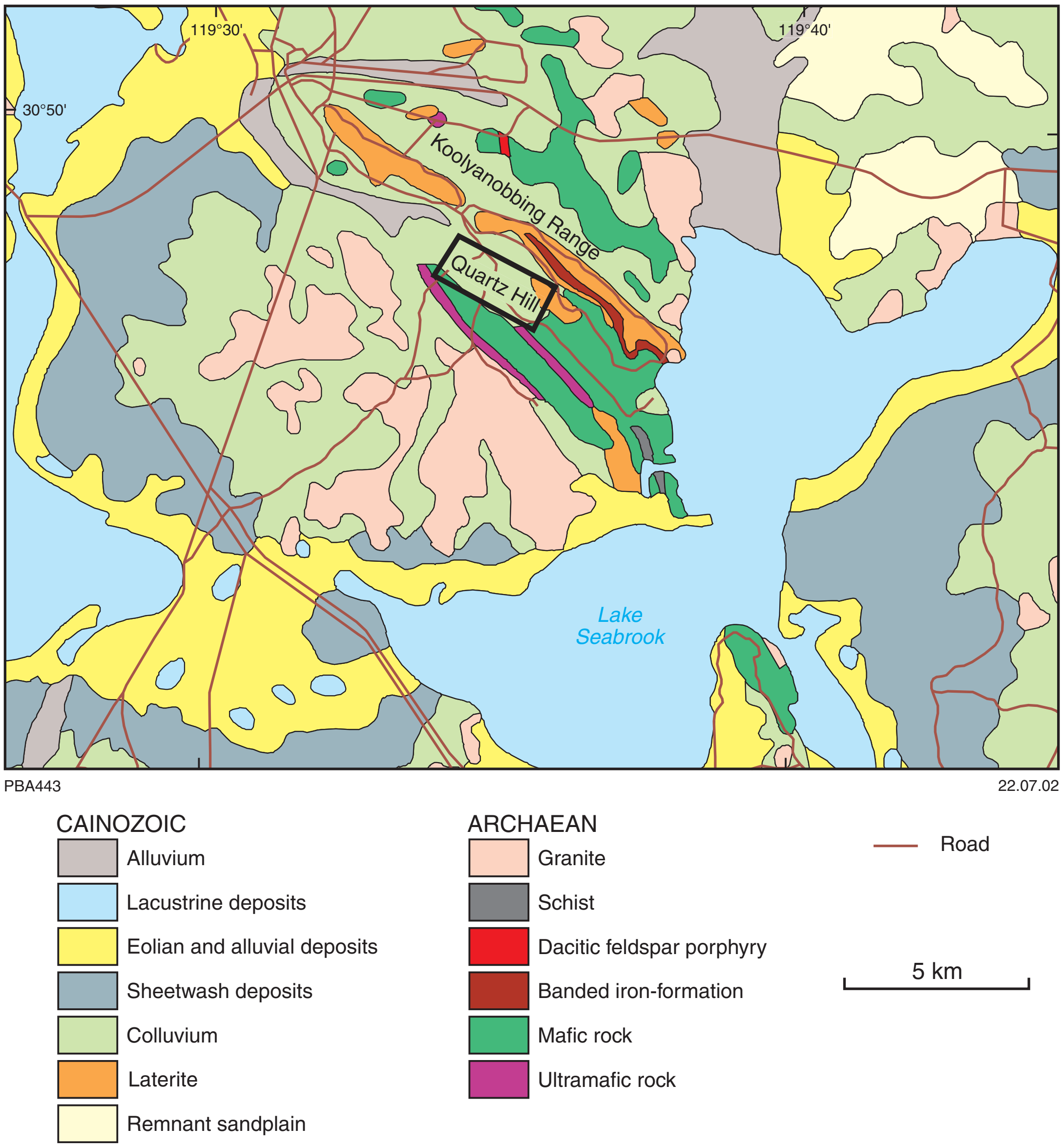

Figure 122. Geology around Lake Seabrook (after Chin et al., 1983)

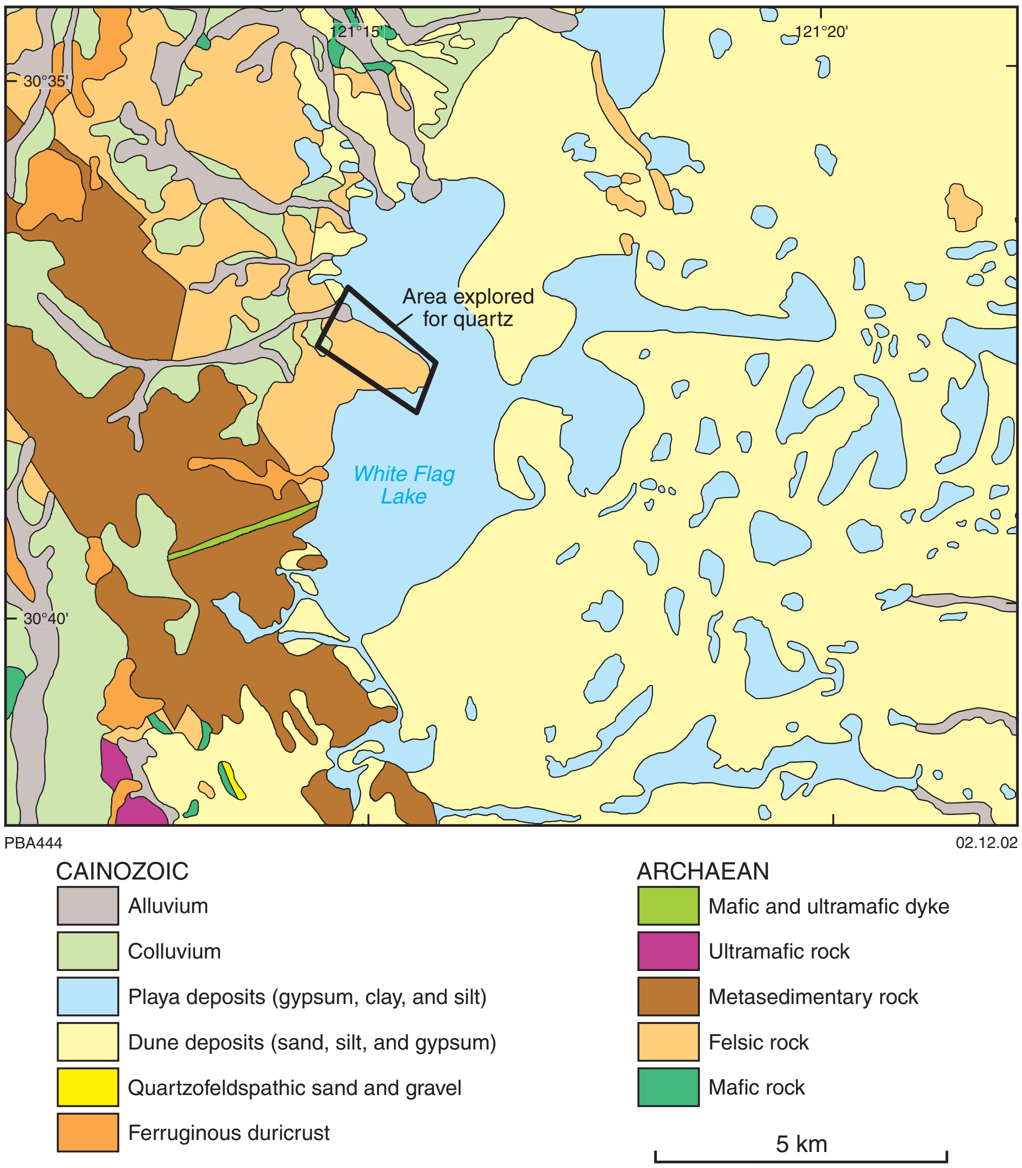

Figure 123. Geology around White Flag Lake (after Groenewald et al., 2000)

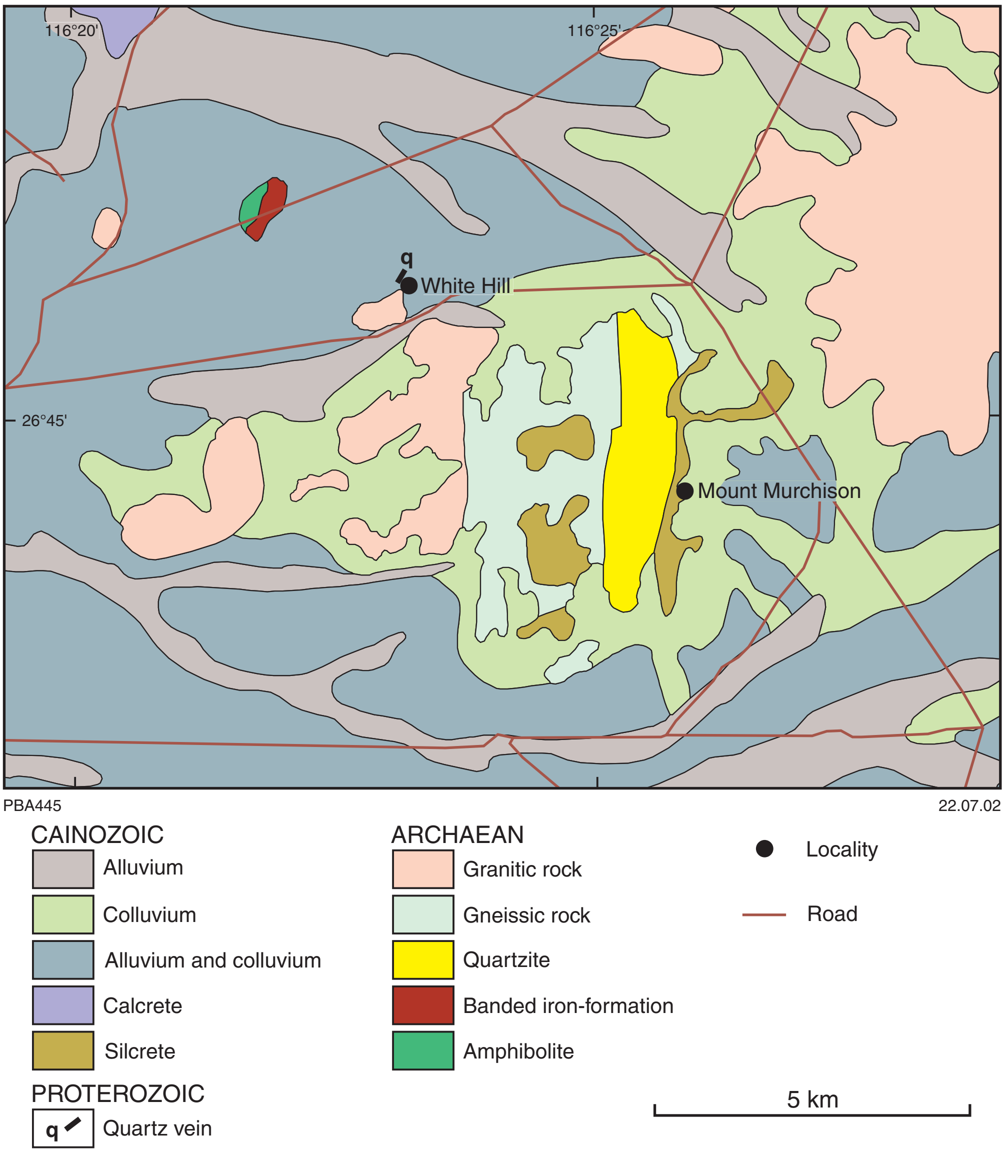

Figure 124. Geology around White Hill (after Myers et al., 1997)

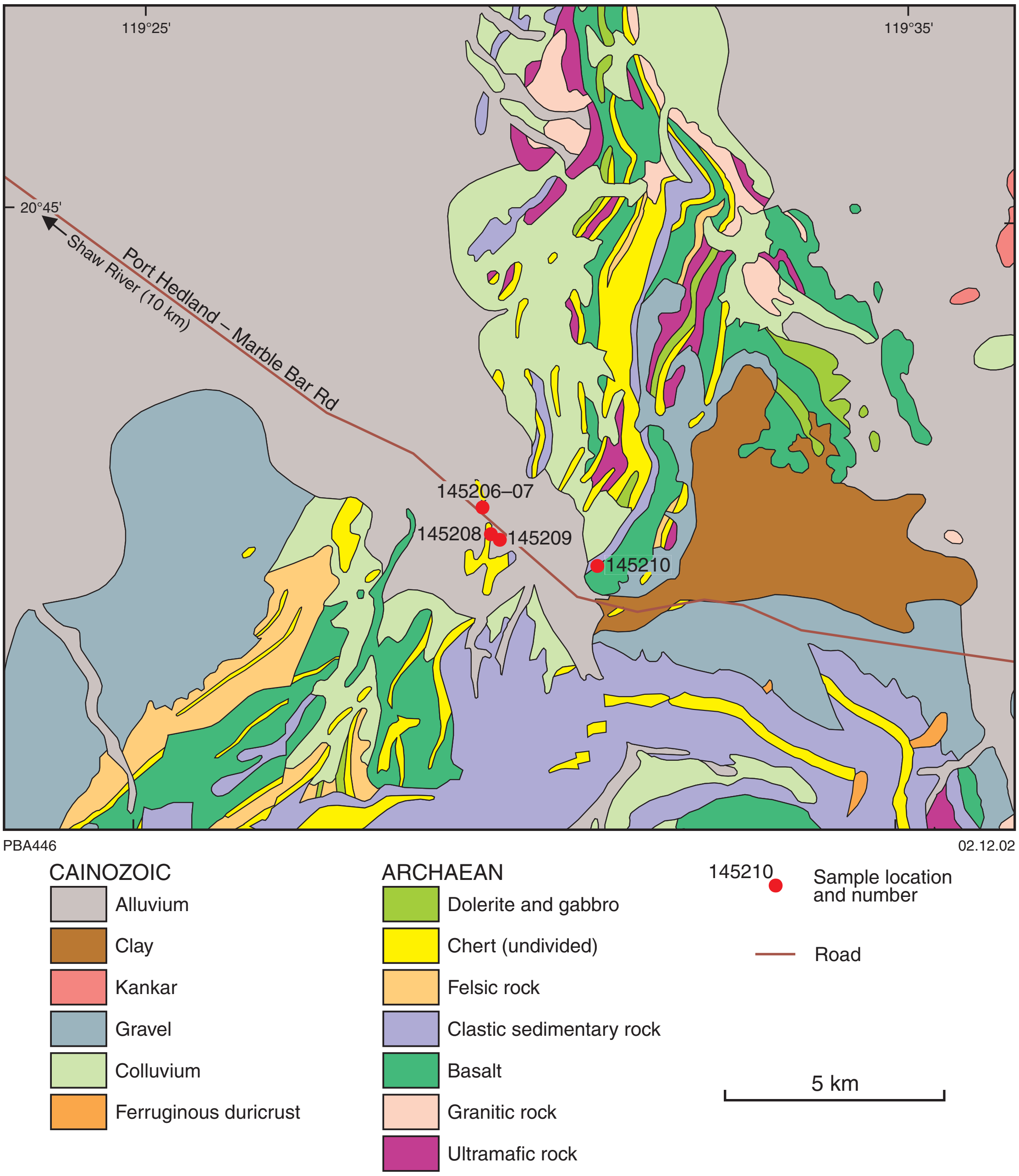

Figure 125. Geology of the area southeast of Shaw River (after Hickman and Gibson, 1981)

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Figure 126. Chert outcrop near Port Hedland – Marble Bar Road (approximately 23 km southeast of Shaw River)

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Figure 127. Photograph of chert showing grey and white bands with well-defined parallel layering — approximately 23 km southeast of Shaw River near Port Hedland – Marble Bar Road

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Figure 128. Chert ridge with well-developed steep joints (locations of samples GSWA145206–07: 23 km southeast of Shaw River)

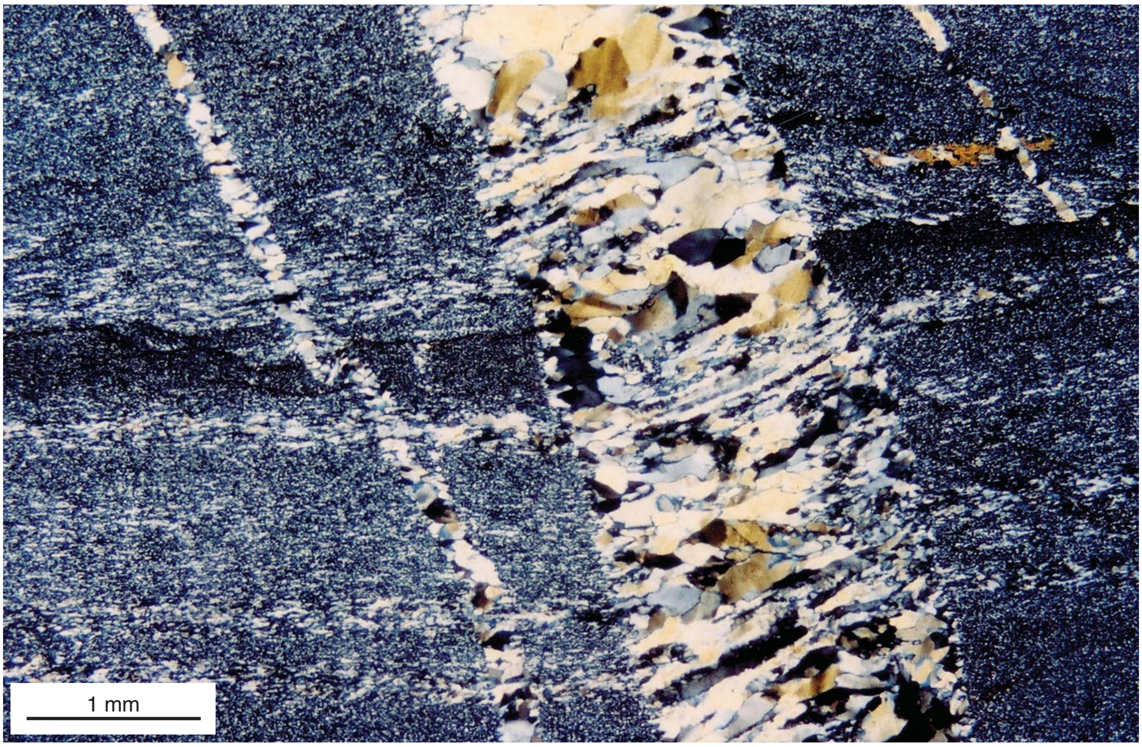


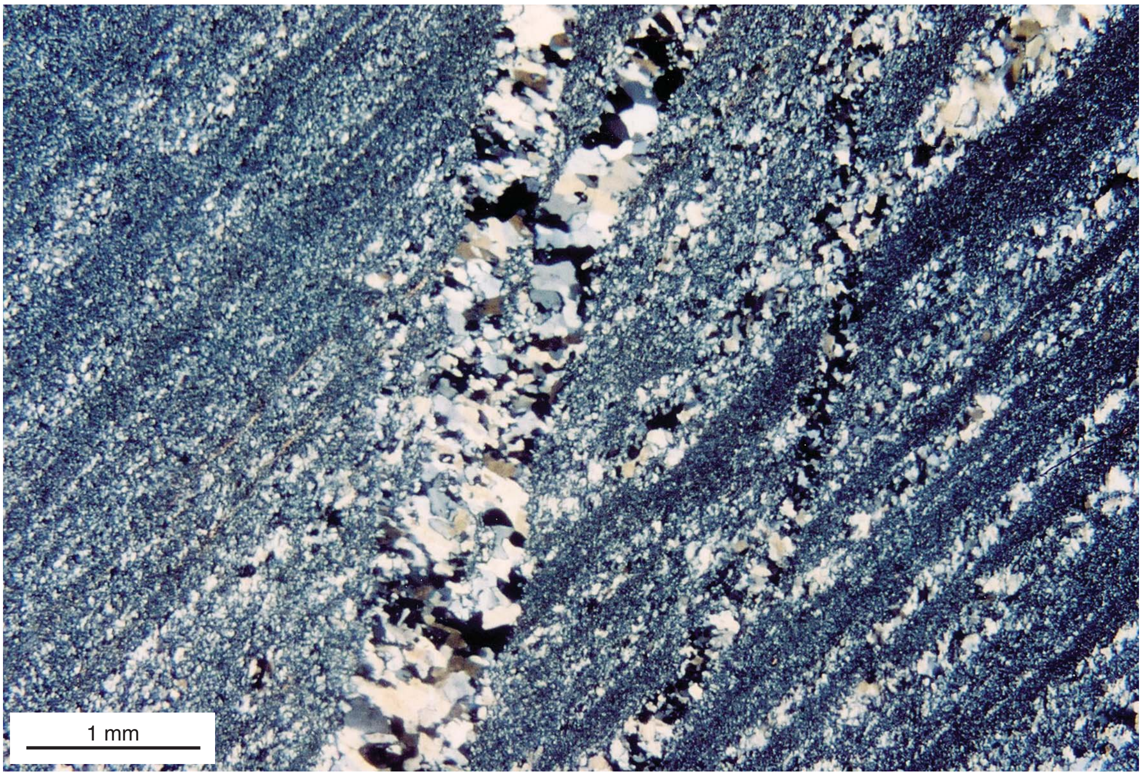
Figure 129. Photomicrograph (crossed nicols ×20) showing stringers and veins (width 0.5–1.5 mm) of quartz crosscutting chert layering at a fairly high angle (sample GSWA145206: 23 km southeast of Shaw River)

similar in appearance to that of the ridge at the northern side of the road. A thin section of white chert sample GSWA145208 indicates approximately 40% homogeneous ultrafine cryptocrystalline chert (Fig. 132a). About 20% consists of slightly coarser, elongate, cherty micromosaic, forming separate bands, but with a somewhat sporadic scattered distribution through the ultrafine-homogeneous chert. The remaining 40% of the section consists of coarser and texturally more heterogeneous microcrystalline/microgranular quartz stringers, veinlets, and associated reconstituted layers of chert (Fig. 132b,c). These seem to represent somewhat complex, multiple recrystallization/mobilization history. One well-defined relationship is late veinlets (with their diagnostic fabric) cutting through earlier and wider crosscutting veins (Fig. 132c). The thin section contains very sparse, weakly limonitic stylolites and limonitic dust.

Sample GSWA145209 from a ridge parallel to the one described above (Fig. 125), also on the south side of the road, essentially has three components. About 50% of a thin section of this sample consists of patchy, somewhat isolated zones of massive homogeneous ultrafine cryptocrystalline silica, which incorporate minor, but typical, scattered elongate-microcrystalline cherty quartz, locally forming incipient bands (Fig. 133). Approximately 30% of the thin section area consists of discontinuous veins, and irregular patches of 'vein' quartz, probably mobilized out of the host chert, but with more complex fine granular to coarse (and more heterogeneous) textures than seen in samples GSWA145206–08. The remaining 20% consists of a poorly defined internally ragged dark brown band of 'limonite' as an extensive matrix, incorporating minor voids that have formed due to leaching of former minerals and later pyrite (Fig. 133).

Sample GSWA145210 is from one of the three chert ridges approximately 3 km southeast of sample GSWA145206, north of the road and east of a creek (Fig. 125). In hand specimen, the chert here is similar to that from the ridges described above and is highly jointed with vertical as well as shallow easterly dipping joints (Fig. 134). In hand specimen, approximately 50% of sample GSWA145210 consists of milky-white and grey chert, which in thin section exhibits the ultrafine cryptocrystalline silica as reported in the four chert samples above. This chert, however, is rich in microcrystalline to microspherulitic quartz, some in poorly defined laminae (similar to those in 145207), but also as random stringers and poorly defined patches. These textures seem to represent a superimposed reconstitution/recrystallization of the original chert. The macroscopic grey streaking of ultrafine and dust-like material probably consists of oxidized carbonate, sericite, or opaque oxide. The other half of the hand specimen is distinctly milky white. In thin section, this portion consists of prominent quartz veining (12 mm wide within the area of thin section) with a layer of very coarse sparry crystals in 'cockade-layered' arrangement to 3 mm wide, each crystal with pyramidal terminations pointing inwards toward a central axial zone, also 3 mm wide (Fig. 135). The central core is occupied by colloform chalcedony as a late fill.

(a)



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(b)

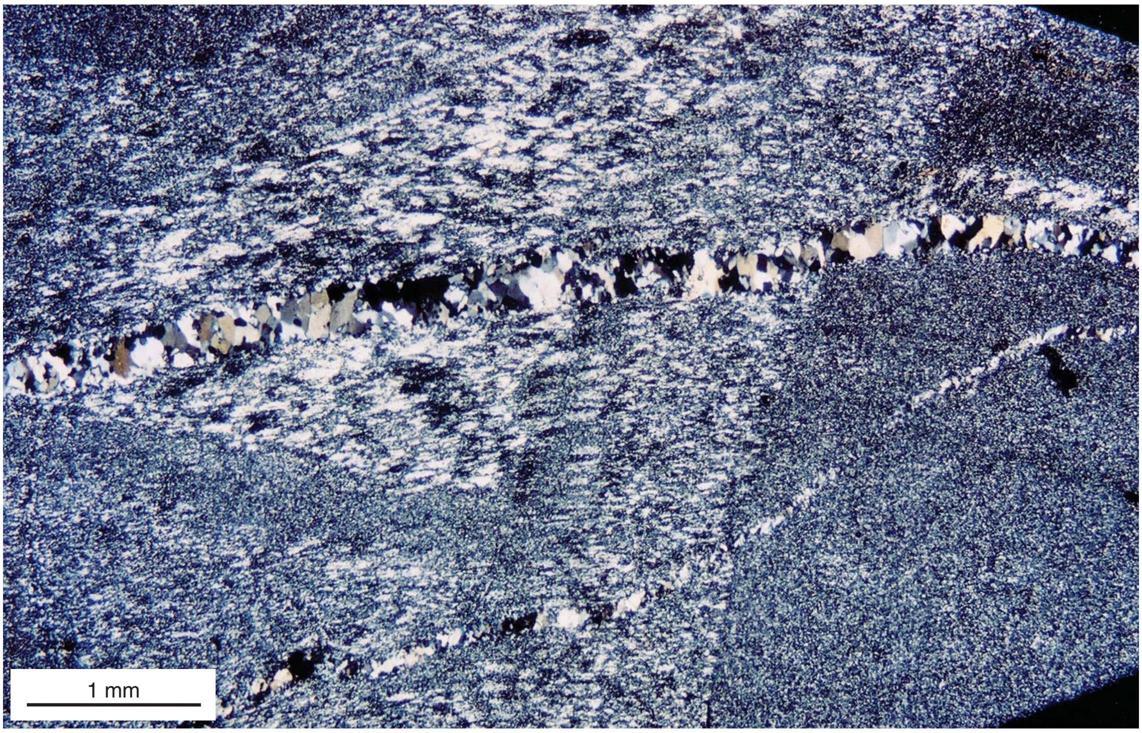

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Figure 130. a) Photomicrograph (crossed nicols ×20) showing regularly laminated chert crosscut by quartz veinlets (sample GSWA145207: 23 km southeast of Shaw River); b) Photomicrograph (crossed nicols ×20) of thin section of Figure 130a showing variation in microscopic textures of extremely fine quartz forming different bands and some disconformable domains in the chert (sample GSWA145207: 23 km southeast of Shaw River)

PBA517

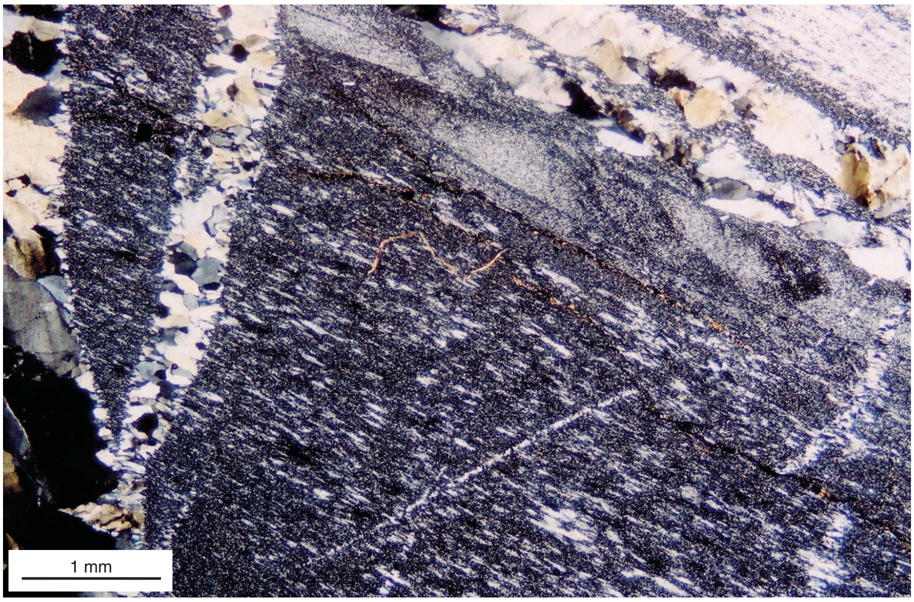
Figure 131. Chert ridge at the south side of the Port Hedland – Marble Bar Road (location of sample GSWA145208)

Quality

Sample GSWA145210 from the ridge 3 km southeast of GSWA145206 has 99.70% SiO_2, 0.08% Al_2O_3, 0.18% Fe_2O_3, <0.01% TiO_2 and 0.015% P_2O_5, indicating that the chert is of very high quality, and suitable for high-grade applications such as in the manufacture of metallurgical- and chemical-grade silicon metal. Two samples (GSWA145206–07) from the chert ridge (about 150 m long, 50 m wide, and at least 5 m high) immediately north of the Port Hedland – Marble Bar Road, averaged 98.75% SiO_2, 0.39% Al_2O_3, 0.37% Fe_2O_3, 0.015% TiO_2, and 0.011% P_2O_5. Samples GSWA145208–09 from the south side of the road averaged 97.50% SiO_2, 0.32% Al_2O_3, 1.75% Fe_2O_3, 0.025% TiO_2 and 0.019% P_2O_5, giving a relatively lower percentage of SiO_2 and higher proportion of Fe_2O_3 than those from the northern side of the road. The above five samples averaged 98.44% SiO_2, 0.30% Al_2O_3, 0.88% Fe_2O_3, 0.02% TiO_2, 0.002% CaO, 0.004% MgO and 0.015% P_2O_5, indicating the presence of quite high grade chert, possibly suitable for use in the manufacture of metallurgical- and chemical-grade silicon metal (Table 80).

Figure 132. a) Photomicrograph (crossed nicols) showing various textures in different bands forming the chert (sample GSWA145208: 23 km southeast of Shaw River); b) Photomicrograph (crossed nicols) showing complex textures and apparent pyramidal microstructures developed within chalcedonic silica (sample GSWA145208: 23 km southeast of Shaw River); c) Photomicrograph (crossed nicols ×1) showing central wide vein with later internal fabric and new layer-parallel veinlets at right angles to the host vein (sample GSWA145208: 23 km southeast of Shaw River)

(a)



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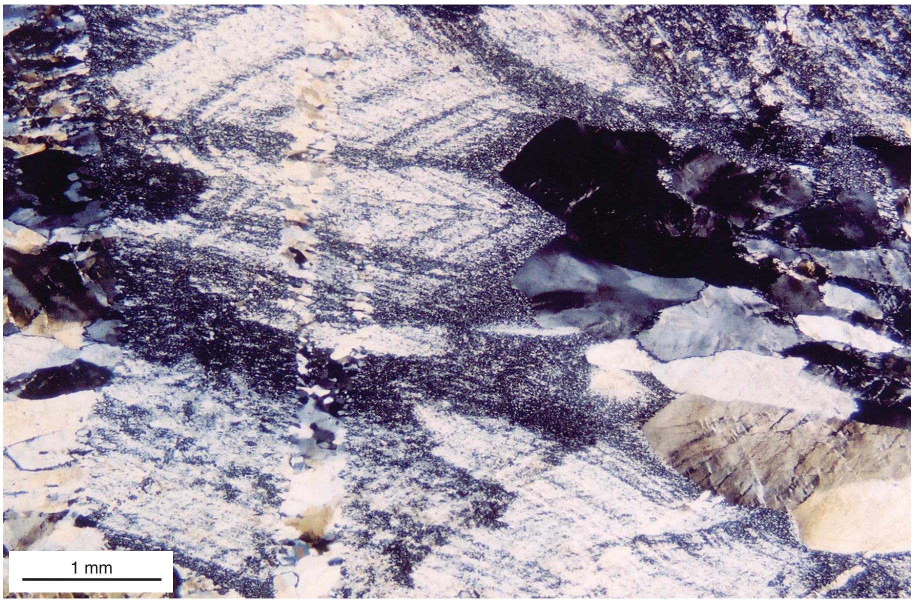
(b)



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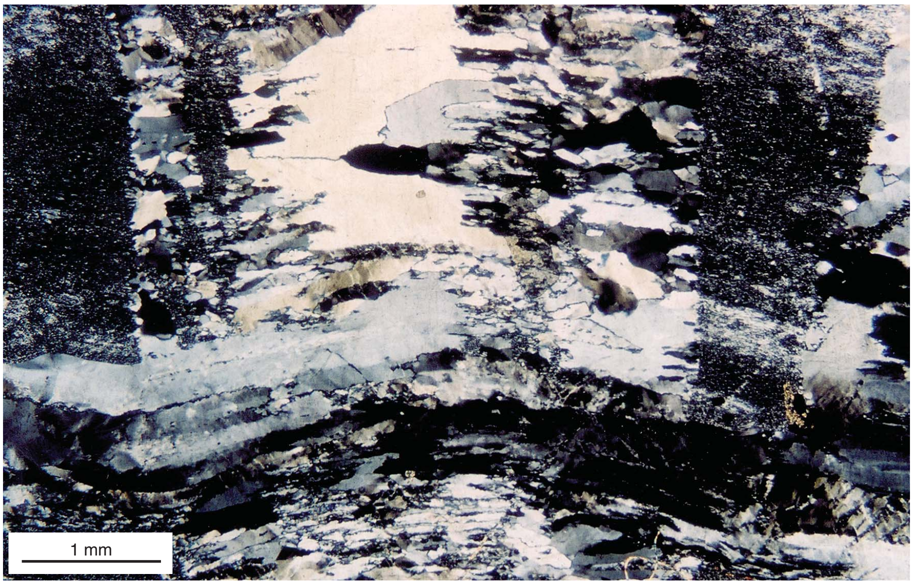
(c)



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The thermal strength of all five samples is excellent, with all exceeding 97.7% and averaging 98.5%; however, thermal stability averages only 84.1. Two samples (GSWA145207–08) have thermal stability above 95%, which is acceptable for high-grade applications (Tables 81 and 82). Overall, the area is likely to contain chert of sufficient quality for high-grade applications.

The chemical composition of some of the above samples is similar to that of Moora chert. In addition, thermal stability and thermal strength of the Shaw River chert are excellent and are equivalent to that at Moora.

Resource

Although the area of sampling is restricted to the outcrops close to the main road, the chert formations are widespread in the area (Fig. 125). On the basis of reconnaissance sampling and the distribution of chert, the potential for the region to have substantial resources of high-quality chert is very high.

Karratha (Mount Regal)

The Mount Regal area (Fig. 81), near Karratha, has been investigated for chert for use in landscaping purposes. Although there may be potential for high-grade chert in the area, neither chemical nor thermal properties of the chert in the area are available because the area has not been investigated for high-quality chert suitable for the production of silicon metal.

During 1989–90, MON-D-OR Resources investigated an area (within the expired Prospecting Licence P47/789) southeast of Mount Regal and north of Edna Well, approximately 15 km south of Karratha, for green chert suitable for landscaping. In this area, bright-green chert has been excavated as a semi-precious stone. The green colour of the chert is probably due to fuchsite (chromium-rich muscovite). The chert units outcrop as low-lying ridges trending approximately east–west. Overlying the green chert is dense black chert with an intermediate, separating zone of milky quartz. The resource of chert within the prospecting licence was estimated by Dey (1990) at 38 376 t. Other rocks distinguished in the area include mottled purple and brown siliceous tuffs, white, greenish and honey-coloured quartzites and green fuchsitic shales and cherts (Biggs, 1979).

Quartzite

As seen from geological maps of the Karratha, Roebourne, and Port Hedland regions, distribution of large formations of quartzite, within about 50 km of the main road, are restricted to the area south of Whim Creek (Kriewaldt, 1964; Biggs, 1979; Hickman and Gibson, 1981; Hickman and Smithies, 2000). Following is a description of sampling results of a quartzite ridge south of Whim Creek.

Whim Creek

A quartzite ridge is exposed approximately 10 km south of Whim Creek. The ridge, elongated in an east–west direction, cuts across the Croydon – Whim Creek Road (Figs 136–138), and is discontinuously exposed for a

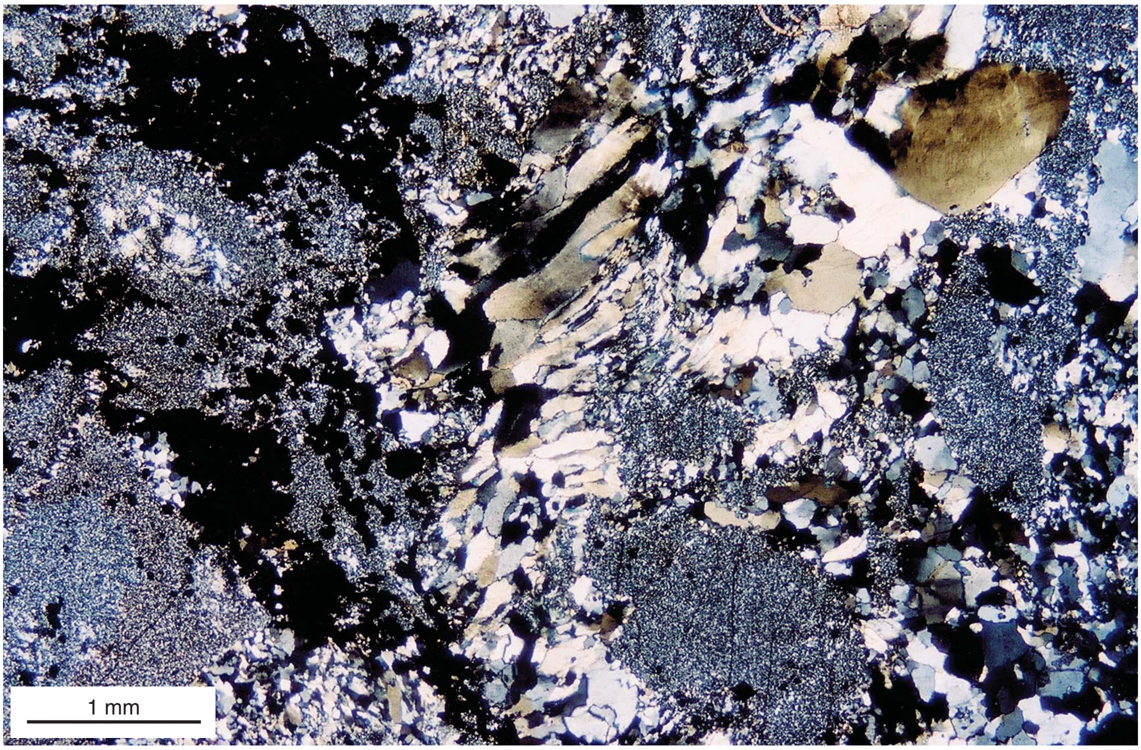

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Figure 133. Photomicrograph (crossed nicols) showing chaotic veining including black, limonitic voids, within host chert of massive ultrafine quartz (sample GSWA145209: 23 km southeast of Shaw River)

PBA522

Figure 134. Highly jointed chert with vertical and shallow easterly dipping joints at Shaw River sample location GSWA145209 (see Fig. 125)

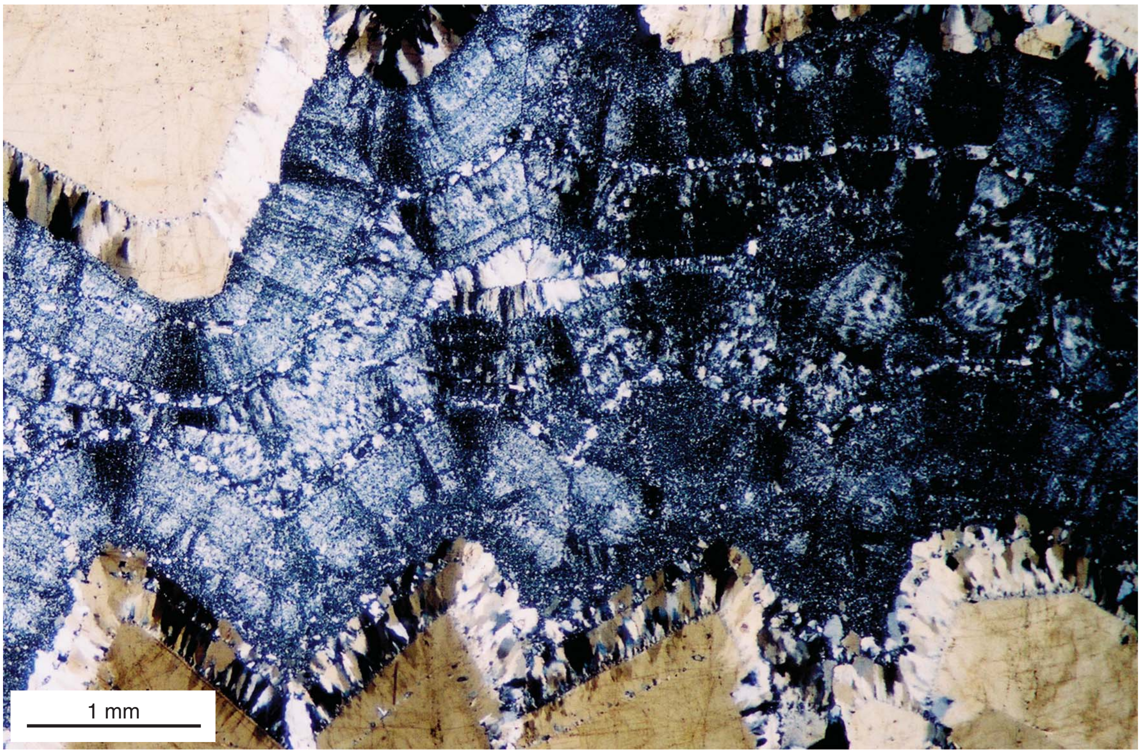

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Figure 135. Photomicrograph (crossed nicols) showing composite coarse band with coarse sparry/pyramidal quartz crystals lining the margins, with a central core of zoned chalcedonic silica (sample GSWA145210: 23 km southeast of Shaw River)

Table 80. Chemical analyses of chert, 23 km southeast of Shaw River

GSWA no.	*145206*	*145207*	*145208*	*145209*	*145210*
			Percentage		
SiO_2	98.80	98.70	98.60	96.40	99.70
Al_2O_3	0.38	0.39	0.62	0.02	0.08
Fe_2O_3	0.34	0.40	0.30	3.20	0.18
MgO	0.01	<0.01	0.01	<0.01	<0.01
CaO	<0.01	0.01	<0.01	<0.01	<0.01
Na_2O	<0.01	<0.01	<0.01	<0.01	<0.01
K_2O	0.10	0.08	0.13	<0.01	<0.01
TiO_2	0.02	0.01	0.05	<0.01	<0.01
MnO	0.01	0.01	0.01	0.02	0.01
P_2O_5	0.009	0.013	0.014	0.024	0.015
BaO	0.06	0.17	0.12	<0.01	0.02
SO_3	<0.01	0.11	<0.01	<0.01	<0.01
LOI	0.10	0.16	0.15	0.36	0.06
Total	**99.83**	**100.05**	**100.00**	**100.02**	**100.07**
H_2O	0.04	0.02	0.03	0.05	0.02

Table 81. Thermal strength of chert, 23 km southeast of Shaw River

GSWA no.	*Size fraction (mm)*					*Cumulative passing*				*Thermal*
	>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	*strength*
					Percentage					
145206	56.9	37.0	4.8	0.4	0.9	43.1	6.1	1.3	0.9	98.7
145207	58.9	33.8	5.1	1.2	1.1	41.1	7.4	2.3	1.1	97.7
145208	73.0	23.6	2.1	0.5	0.9	27.0	3.5	1.4	0.9	98.6
145209	71.8	25.2	1.4	0.6	1.0	28.2	3.0	1.6	1.0	98.4
145210	62.5	31.3	5.0	0.4	0.8	37.5	6.1	1.2	0.8	98.8

Table 82. Thermal stability of chert, 23 km southeast of Shaw River

GSWA no.	*Size fraction (mm)*					*Cumulative passing*				*Thermal*
	>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	*stability*
					Percentage					
145206	75.0	23.0	1.8	0.0	0.1	25.0	2.0	0.2	0.1	75.0
145207	95.2	3.7	0.8	0.2	0.1	4.8	1.1	0.3	0.1	95.2
145208	96.3	1.7	0.7	1.3	0.1	3.7	2.0	1.3	0.1	96.3
145209	84.3	14.6	0.9	0.2	0.1	15.7	1.1	0.3	0.1	84.3
145210	69.7	28.7	1.2	0.2	0.2	30.3	1.6	0.4	0.2	69.7

distance of about 7 km, rising in places to about 10 m above surrounding ground level.

Geology

The Archaean quartzite is of variable colour ranging from white to light grey to dark grey, and has brown to reddish-brown iron oxide staining, mostly along the abundant joint planes (Fig. 139). The quartzite exhibits closely spaced vertical joints and steep southerly dips (Fig. 140). Six samples (GSWA145211–16; Fig. 138) spaced about 70–100 m apart along the strike were collected for testing.

Petrography

The six samples from the quartzite ridge indicate the presence of detrital quartz grains, most of which probably derived from a source of massive hydrothermal vein quartz. The samples also contain minor cherty grains, quartz grit, and small pebbles. Original grain size of the quartz varies from medium to coarse to very coarse, with coarse material being predominant. These observations suggest that the quartzite was originally quartz-rich sandstone. The original sandstone appears to have undergone low-grade metamorphism to produce quartzite, with intergranular matrix mostly ranging from 20 to 35% by volume. Samples GSWA145211 and GSWA145216 are more quartzitic and contain less intergranular matrix (approximately 12%) than the others. Intergranular matrix is dominated by massive decussate sericite with or without lesser cryptocrystalline silica. Authigenic overgrowths on quartz grains are absent. Sericite also forms crosscutting veinlets in GSWA145212 (Fig. 141). This sericite (and the intergranular silica) in matrix and in veinlets appears to represent permeation and alteration of hydrothermal genesis, possibly filling original porosity, and possibly altering original pelitic material. Accessory to trace Fe–Ti opaque oxide grains and trace local zircon are found in most of these samples. There are minor local limonite-stained microstylolites. More detailed petrographic descriptions of the six samples are given in Table 83.

Quality and resource

Chemical analyses of the above samples (GSWA145211–16) yield averages of 94.45% SiO_2, 4.10% Al_2O_3, 0.17% Fe_2O_3, 0.09% TiO_2, and 0.028% P_2O_5 (Table 84). The percentage of SiO_2 is too low, and that of Al_2O_3 too high, for this material to be acceptable for high-grade applications such as in the manufacture of metallurgical- and chemical-grade silicon metal. However, samples have an average thermal stability of 92.5 and an average thermal strength of 98.1, which are within acceptable levels for use in the production of silicon metal (Tables 85 and 86).

The Department of Resources Development (1997) suggested the possibility of a resource exceeding 30 Mt of quartzite grading 97–99% silica in this ridge. However, the results from the six samples discussed above indicate that the chemical quality of the quartz is not as high as that suggested by DRD.

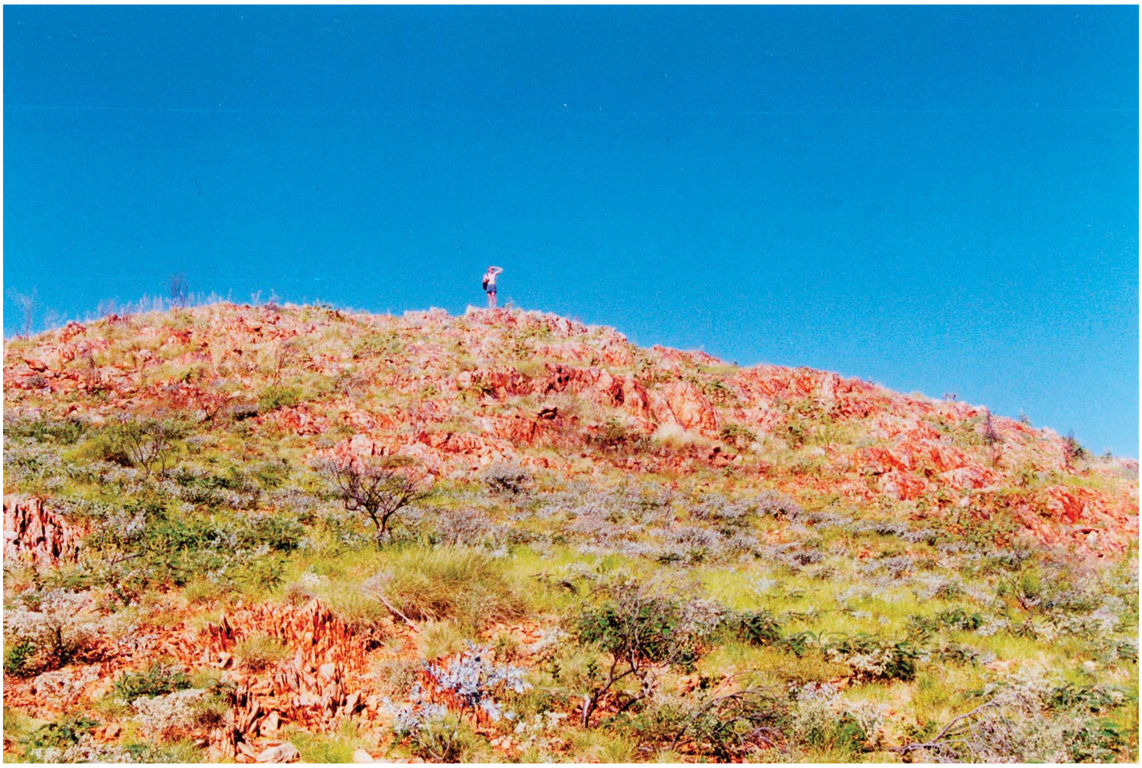

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Figure 136. Quartzite ridge (view from north) near Croydon – Whim Creek Road, 10 km south of Whim Creek

Figure 137. Quartzite ridge (view from west) near Croydon – Whim Creek Road, 10 km south of Whim Creek

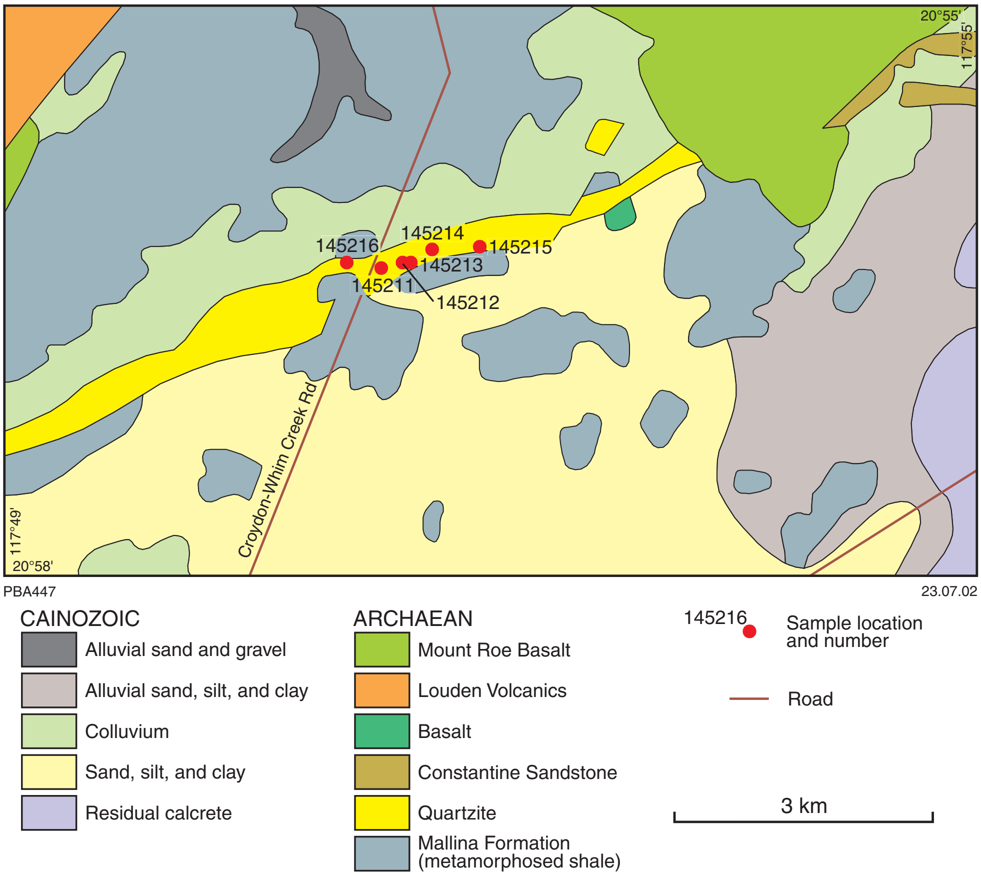

Figure 138. Geology around quartzite ridge near Croydon – Whim Creek Road, 10 km south of Whim Creek (after Hickman and Smithies, 2000)

PBA526

Figure 139. Quartzite showing brown to reddish-brown iron oxide staining, mostly along joint planes — Croydon – Whim Creek Road, 10 km south of Whim Creek

Quartz veins

A number of prominent quartz vein ridges are found along the North West Coastal highway in the Karratha–Roebourne area (Figs 81, 142–144). Most of these ridges are elongated in a north–south or north-northeast direction and are surrounded by Quaternary deposits of silty, red-brown, and eolian clayey sands (Figs 142 and 143).

Karratha–Roebourne

Samples from five of the quartz ridges between Karratha and Roebourne were collected for testing; these are marked as A, B, C, D, and E on Figures 142 and 143.

Location A

One of the most prominent of these quartz ridges is exposed on both sides of the highway, at Location A, about 0.5 km east of the turnoff to the Karratha township (Fig. 142). The portion of the ridge immediately south of the highway is about 50 m wide, rises to at least 10 m in height, and is continuously exposed for a distance of about 300 m in a southwesterly direction and discontinuously for a further 2 km. The portion of the ridge on the north side of the highway is continuously exposed for about 75 m, and discontinuously for at least a further 1 km. The quartz on both sides of the highway is massive, predominantly milky white with a cherty appearance, and has closely spaced vertical and horizontal joints. Four samples (GSWA145217–20), two each from the north and south sides of the highway, were collected for testing.

Thin sections of these samples indicate 35–60% of relatively early generation hydrothermal sparry vein quartz (typically milky-white quartz in hand specimen) clouded by fluid inclusions (Fig. 145). Normally, this early

PBA527

Figure 140. Closely spaced steep joints in quartzite — Croydon – Whim Creek Road, 10 km south of Whim Creek

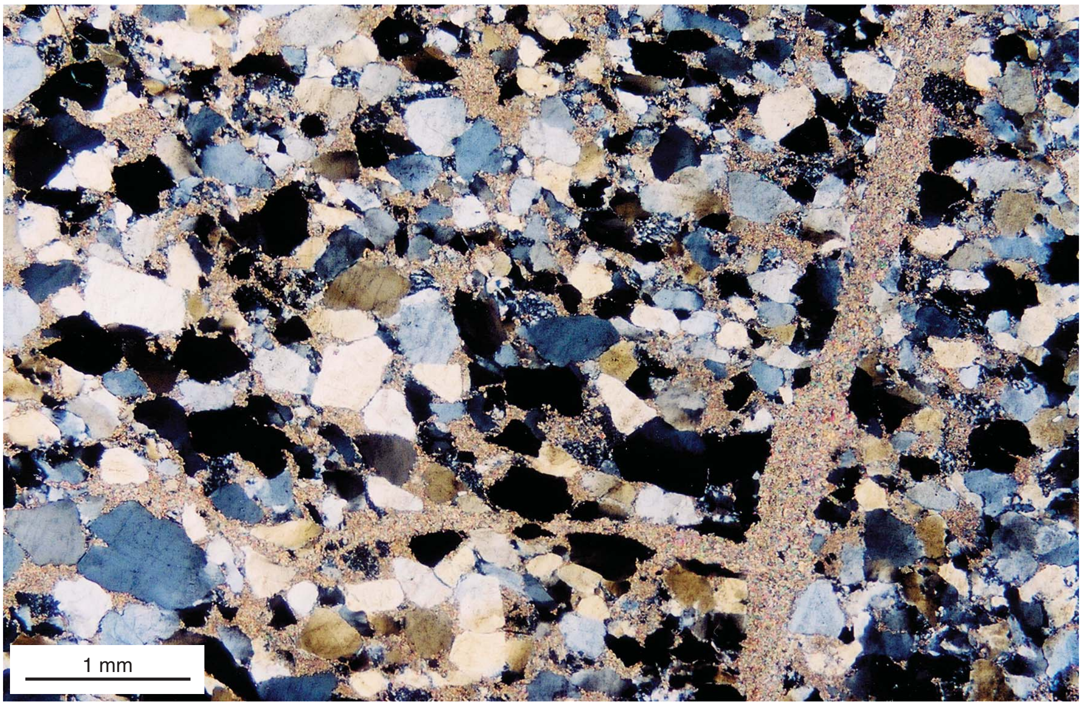

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Figure 141. Photomicrograph (crossed nicols ×20) showing sericite veinlets crosscutting quartzite (sample GSWA145212: Whim Creek)

Table 83. Petrographic descriptions of quartzite, 10 km south of Whim Creek

GSWA sample no.	*Petrographic description*
145211	Compact massive to weakly bedded aggregate of single crystal, subrounded well-sorted quartz grains (0.5 – 1.5 mm; av. ~1 mm). Grains distinctively crowded with abundant minute fluid inclusions ?inherited from hydrothermal quartz. Cherty/ 'lithic' fragments <2%. Negligible authigenic quartz overgrowths. ~75% of the intergranular matrix (≤15% of rock) is sericite and 25% is cryptocrystalline silica ± minor comminuted quartz, especially in breccia areas. Sericite locally weakly fine schistose, and forms very narrow rims around quartz grains, ?stylolitic between quartz grains. Some very fine silica fills small pressure shadows. Indistinct quartz veins grade into the host quartzite, apparently formed by in situ (authigenic) recrystallization
145212	~70% of loosely packed low-grade metamorphosed aggregates of subrounded to subangular quartz grains. Apparent bimodal distribution with 50% averaging ~0.3 mm, and the rest averaging ~0.7mm. Most grains occur as single crystals, but up to 7% occur in cherty quartz micromosaic. Intergranular matrix areas mostly occupied by massive, decussate very fine sericite, but with minor scattered, small irregular patches of diffuse quartz micromosaic (difficult to distinguish from detrital cherty grains). Sericite locally forms nearly continuous stringers, cutting across the bedding, and locally merging into matrix. This sericite is probably a result of hydrothermal alteration of an original pelitic matrix. Accessory amount of very fine Fe–Ti oxide oxide grains
145213	Very similar to GSWA145212 but contains slightly more cherty grains, less sericitic matrix, and rare sericite-rich stringers with schistose sericite. Two poorly defined (merging) beds, one with an average grain size ~0.3 mm and other ~0.7 mm, but with a mix of grains within this range. Up to ~12% of these grains are cherty. Intergranular matrix forms ~25% of the rock, mostly occupied by very fine decussate sericite, with minor, scattered, very small patches of quartz micromosaic. This probably represents hydrothermal sericitic alteration. Few crosscutting stringers consist of schistose sericite with sparse fine leucoxene. This fabric represents microshears, rather than alteration along partings (?incipient joints) as in 145212. Trace of discrete grains of Fe–Ti oxide
145214	~65% of loosely packed aggregate of subangular to subrounded quartz grains, ~two-thirds of grains range in size from 0.3 – 0.8 mm, with rest 2.5 – 3 mm. Both sizes probably derived from hydrothermal vein quartz. Coarser grains are similarly oriented and occur mostly in a single, very poorly defined bed. Minor cherty grains present. ~35% of the rock consists of intergranular matrix, reducing the incidence of contact between detrital grains. The intergranular matrix is (typically) dominated by decussate to weakly, very fine schistose sericite, probably a result of hydrothermal alteration. Weakly oriented/schistose sericite is locally present (especially between the very coarse quartz grains) associated with fine silica. Trace of scattered grains of very fine Fe–Ti oxide, some decorating sparse limonitic microstylolites
145215	More homogeneous and massive quartz-rich original sandstone with lesser sericitic matrix than the four quartzites described above. Clearer and more commonly polycrystalline (?metagranitoid or gneissic origin) individual quartz grains. One very small pebble (4 mm) of laminated microcrystalline chert. Aggregate of subrounded quartz grains (~85% of rock) seems to be largely bimodal, one population with an average size ~0.5 mm and another population ~2 mm. Intergranular matrix largely of patchy sericite, with local cryptocrystalline silica. Scattered accessory Fe–Ti opaque oxide grains (0.15 mm)
145216	Closely compares with GSWA145211. Patchy areas with reasonably compact aggregates of original detrital, angular to subrounded quartz grains (0.25 – 1 mm). Overall, intergranular matrix is less clearly defined than in the other quartzite samples, partly due to finer (and angular) grains, but seems to form 12–15% overall. This matrix consists partly of sericite, with more microcrystalline quartz, and is more siliceous than that of other quartzites. Several grains of zircon, up to 0.2 mm, and more of opaque iron oxides occur along a very poorly defined heavy mineral lamination

generation quartz is coarse, subhedral, partly prismatic to sparry, and stressed. Some coarse domains of quartz are disrupted with internal fractures or detached as breccia fragments. The characteristics of this coarser sparry quartz suggest a deep hypothermal, relatively high temperature source. A later generation of microgranular/microsparry quartz forms a matrix to the above early quartz (Fig. 145). Sparse sericite pervades the finer, later permeating quartz, and local banding, partly around enclosed residuals of the early quartz, is colloform in varying degrees. This younger, finer quartz has textures indicative of an epithermal to mesothermal genesis; it is shallower and formed at lower temperatures than the earlier, coarser crystalline quartz. More detailed petrographic descriptions of samples GSWA145217–20 are given in Table 87.

The quartz from this ridge appears to be of moderately high quality and the four samples from Location A average 98.75% SiO_2, 0.54% Al_2O_3, 0.20% Fe_2O_3, 0.01% TiO_2, 0.01% CaO, 0.04% MgO, and 0.07% P_2O_5 (Table 88). The samples have an average thermal stability of 92.2% (GSWA145217 is 98.1%) and an average thermal strength of 98.8%. Such values are within acceptable levels for use in the production of silicon metal (Tables 89 and 90).

Location B

At Location B (Fig. 142), another prominent, but smaller, vein quartz ridge (about 75 m long, 50 m wide, and up to 15 m high) known as Quartz Hill is exposed on the north side of the highway. The quartz vein trends east-northeasterly, and the quartz is massive, milky white, and exhibits closely spaced vertical and horizontal joints.

A thin section of a sample (GSWA145221) indicates that, compared with the four vein-quartz samples described from Location A, the quartz at Location B is

Table 84. Chemical analyses of quartzite, 10 km south of Whim Creek

GSWA no.	*145211*	*145212*	*145213*	*145214*	*145215*	*145216*
			Percentage			
SiO_2	94.2	92.9	94.4	94.3	95.7	95.2
Al_2O_3	4.04	5.56	4.2	4.18	3.13	3.48
Fe_2O_3	0.26	0.09	0.14	0.15	0.21	0.19
MgO	0.01	<0.01	<0.01	<0.01	<0.01	0.01
CaO	0.01	0.02	0.01	0.02	0.01	0.01
Na_2O	0.14	0.04	0.04	0.03	0.02	0.04
K_2O	0.33	0.04	0.04	0.07	0.06	0.05
TiO_2	0.05	0.09	0.08	0.16	0.10	0.06
MnO	<0.01	0.01	<0.01	0.01	0.01	0.01
P_2O_5	0.025	0.026	0.054	0.040	0.018	0.007
BaO	0.01	<0.01	0.01	0.01	<0.01	<0.01
SO_3	<0.01	<0.01	0.01	0.01	<0.01	<0.01
LOI	0.78	1.11	0.83	0.84	0.64	0.77
Total	**99.86**	**99.89**	**99.81**	**99.82**	**99.90**	**99.83**
H_2O	0.04	0.04	0.03	0.05	0.03	0.08

Table 85. Thermal stability of quartzite, 10 km south of Whim Creek

GSWA no.	*Size fraction (mm)*					*Cumulative passing*				*Thermal stability*
	>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	
					Percentage					
145211	92.0	6.9	0.8	0.1	0.2	8.0	1.2	0.4	0.2	92.0
145212	90.8	8.0	1.1	0.1	0.1	9.2	1.3	0.2	0.1	90.8
145213	86.9	12.3	0.6	0.2	0.1	13.1	0.9	0.3	0.1	86.9
145214	89.8	8.4	1.3	0.3	0.2	10.2	1.7	0.5	0.2	89.8
145215	97.7	0.9	1.1	0.1	0.3	2.3	1.4	0.3	0.3	97.7
145216	97.8	0.7	1.3	0.2	0.1	2.2	1.5	0.3	0.1	97.8

Table 86. Thermal strength of quartzite, 10 km south of Whim Creek

GSWA no.	*Size fraction (mm)*					*Cumulative passing*				*Thermal strength*
	>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	
					Percentage					
145211	92.8	3.4	1.8	0.5	1.5	7.2	3.8	2.0	1.5	98.0
145212	83.8	13.0	1.7	0.6	0.9	16.2	3.2	1.5	0.9	98.5
145213	95.0	3.0	0.8	0.4	0.8	5.0	2.0	1.2	0.8	98.8
145214	89.3	5.8	1.7	1.3	1.9	10.7	4.8	3.1	1.9	96.9
145215	89.0	7.9	1.1	0.4	1.6	11.0	3.1	2.0	1.6	98.0
145216	96.4	1.6	0.5	0.6	0.9	3.6	2.0	1.5	0.9	98.5

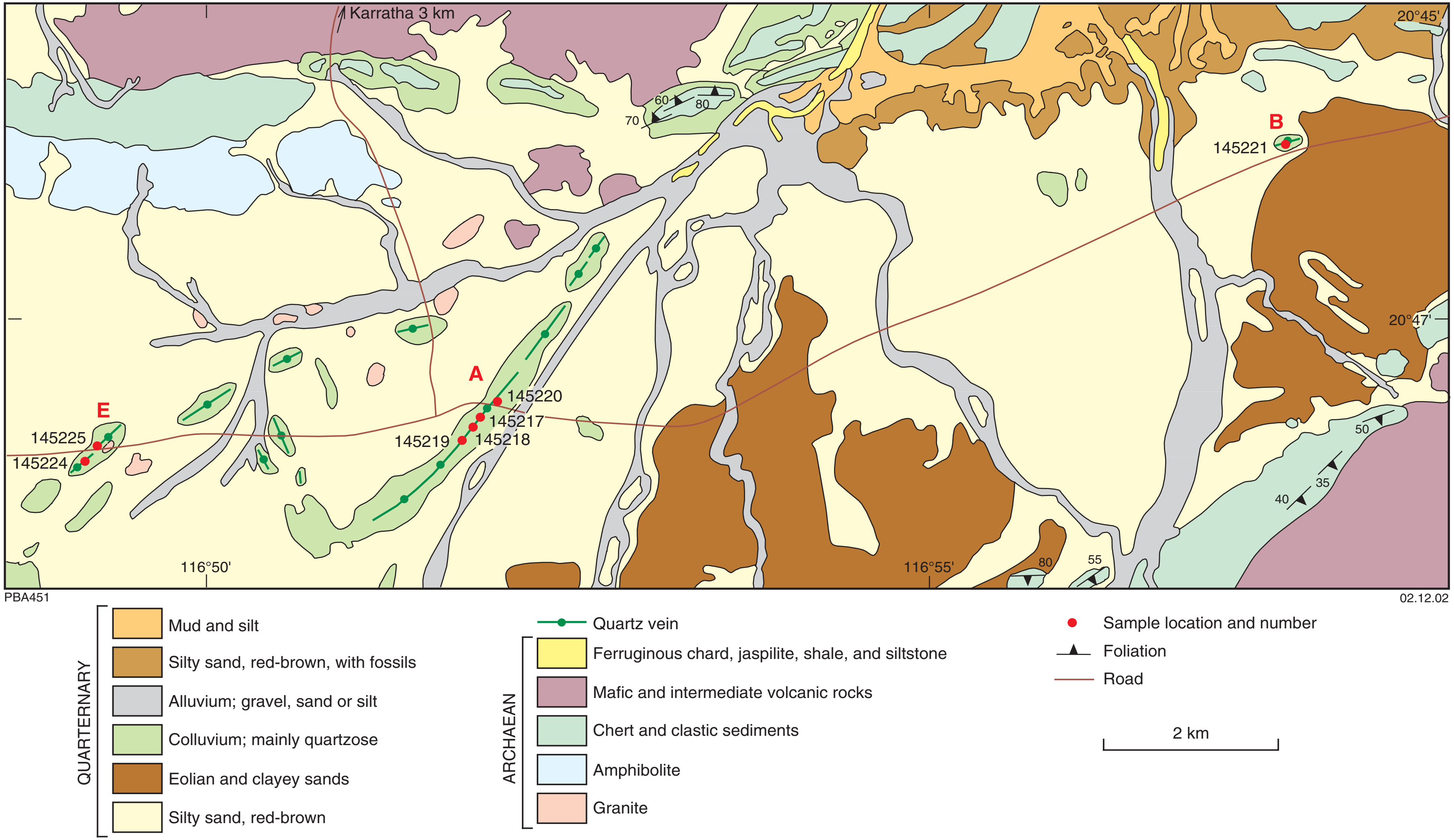

Figure 142. Geology south of Karratha (after Biggs, 1979)

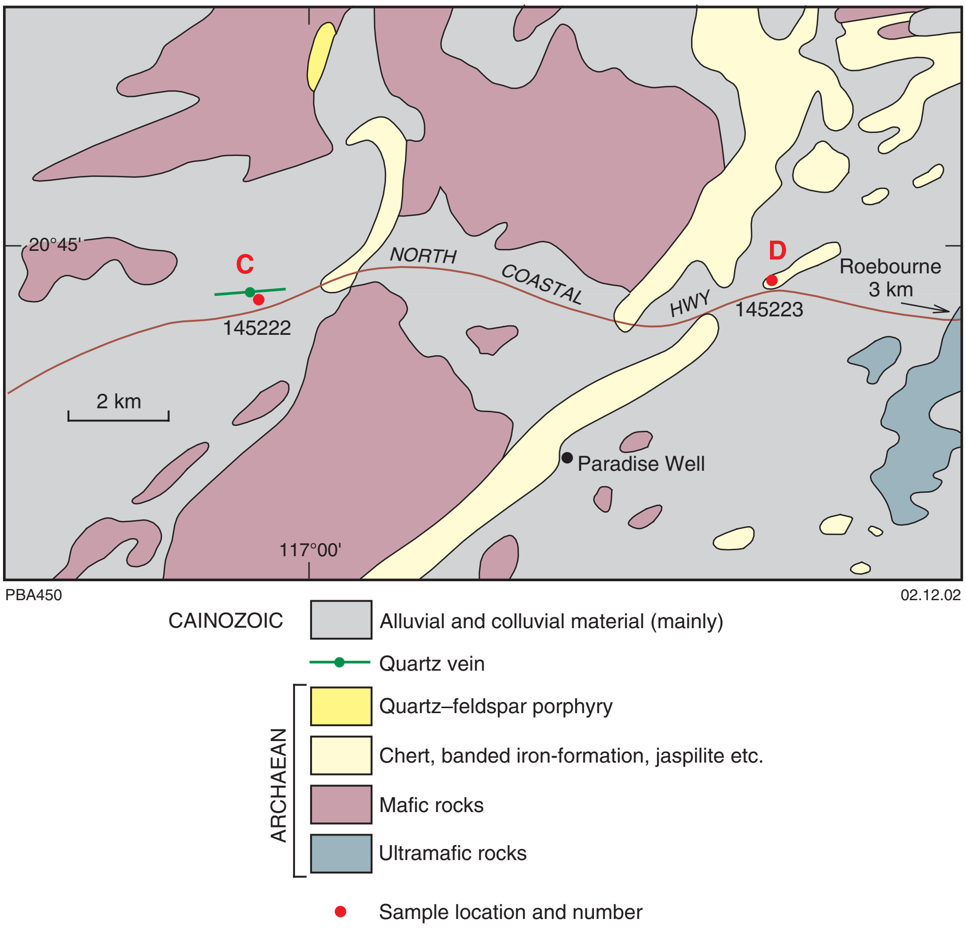

Figure 143. Simplified geology of the area west of Roebourne (after Kriewaldt et al., 1964; Hickman and Smithies, 2000)

Figure 144. Ridge of quartz vein at Location A, Fig. 142 (south of Karratha)

more homogeneous, microgranular (0.2 mm) to medium grained (1.5 mm), and has sutured intergranular contacts to form a massive mosaic. There are far fewer, and finer, fluid inclusions, and no clear distinction between the early and later ('epithermal') generations of quartz as reported in the samples from Location A. There are several short microstylolites with sparse sericite and limonite.

Chemical analysis of sample GSWA145221 from Location B indicates very high grade quartz with 99.8% SiO_2, 0.05% Al_2O_3, 0.05% Fe_2O_3, 0.02% CaO, 0.01% MgO, and 0.024% P_2O_5 (Table 88). The sample has a thermal stability of 99.7% and a thermal strength of 98.1%, indicating that the material is of excellent quality for use in the production of silicon metal (Tables 89 and 90).

Location C

A quartz vein smaller than those at Locations A and B is exposed on the south side of the highway at Location C (Fig. 143). The ridge formed by this milky-white quartz vein trends approximately north–south, and is about 75 m long, 30 m wide, and up to 3 m high. A thin section of a sample (GSWA145222) from this quartz vein indicates several irregular, poorly defined and merging domains 10–15 mm across, each dominated by its own rather distinctive texture, all combining to indicate a probable epithermal genesis (Fig. 146a,b). These textures include:

- massive mosaic of quartz, with randomly interlocking microsparry microprisms (approximately 2 mm), locally zoned and finely layered;
- patches of coarser (longer) sparry/prismatic crystals ($\leq$5 mm long) oriented with overall 'comb-like' structure, locally subradiating with 'cockade-like' structure (Fig. 146b);
- bands of fine 'comb-like' to 'feather-like' quartz with a common planar base of possible pre-existing platy crystals, such as gypsum plates. Minor sericite occurs in small patches and is irregularly interstitial within these textures.

Sample GSWA145222 has 98.5% SiO_2, 0.78% Al_2O_3, 0.15% Fe_2O_3, <0.01% TiO_2 and 0.012% P_2O_5, indicating the presence of moderately high quality quartz, probably suitable for high metallurgical- and chemical-grade silicon metal production (Table 88). The thermal stability and thermal strength of the sample are 88.9 and 97.7% respectively, and indicate moderate to good thermal properties (Tables 89 and 90).

Location D

At Location D (Fig. 143), on the north side of the highway, is another quartz vein ridge. This vein trends north-northeast and is about 150 m long, 50 m wide and 2.5 m high. A thin section of a sample (GSWA145223) from this quartz vein indicates that at least 50% of this rock consists of massive ultrafine cryptocrystalline silica (by definition, chert; Fig. 147), and is similar to material found in the Shaw River area, described earlier. Also much like the chert in the Shaw River area, this rock incorporates a network of numerous threads, stringers, and veins of

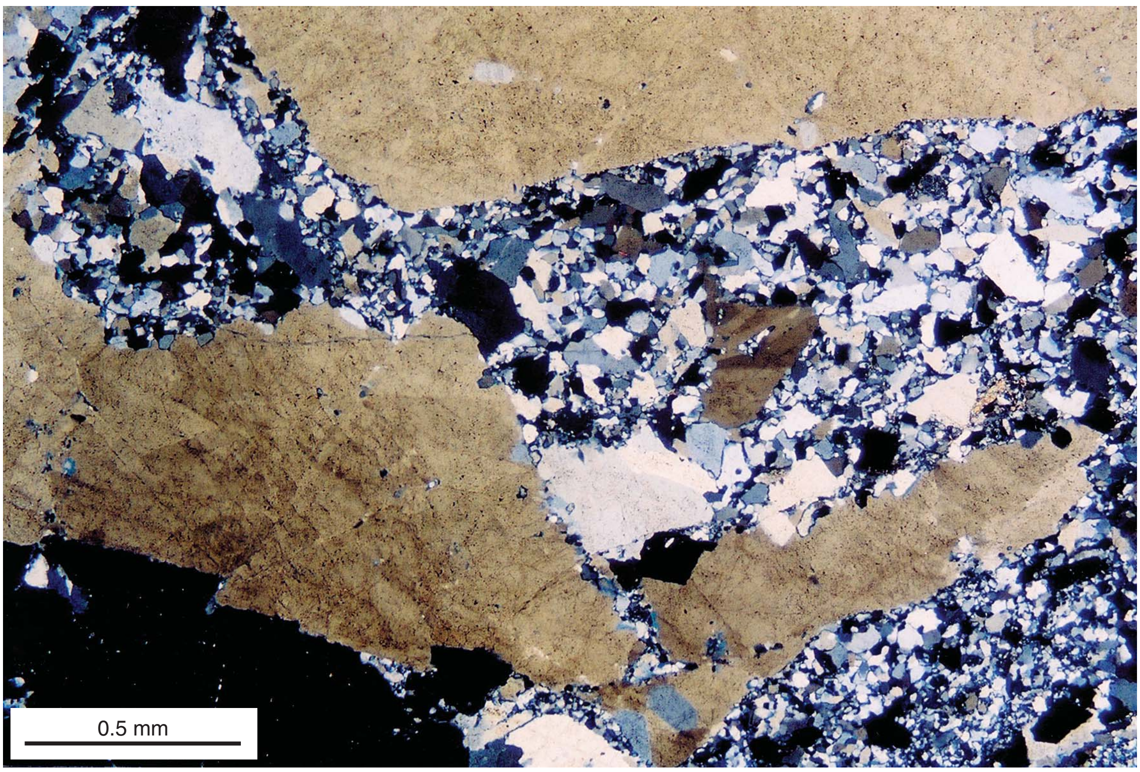

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Figure 145. Photomicrograph (crossed nicols ×50) showing coarse early quartz (dusted by fluid inclusions) and a later generation of microgranular/microsparry quartz in the matrix (sample GSWA145217, Location A, Fig. 142)

Table 87. Petrographic descriptions of quartz veins in the Karratha region (see Location A, Fig. 142)

GSWA sample no.	*Petrographic description*
145217	~60% of the thin section consists of angular blocky breccia fragments of polycrystalline and stressed vein quartz mosaic, commonly 3–7 mm across, and partly recrystallized in situ, as subhedral, partly prismatic crystals. These breccia fragments have a chaotic distribution through a matrix of finer vein quartz mosaic (40%) composed of randomly interlocking prismatic quartz crystals (0.2 – 0.5 mm). Quartz in matrix is a later generation related to hydrothermal activity. Sparse sericite occurs locally within fine vein quartz matrix. Sparse limonite-stained microstylolites present. Abundant fluid inclusions mostly crowding the early generation quartz fragments (producing the buck, milky-white character seen in hand specimen). Fewer fluid inclusions in later fine crystalline vein quartz. No accessory minerals
145218	~70% of the thin section consists of highly irregular domains (≤15 mm across) of mostly coarse randomly interlocking granular to subhedral grains of hydrothermal vein quartz, clouded with minute fluid inclusions. These quartz grains are fractured and commonly detached as breccia fragments, and more or less incorporated in equally irregular domains of massive microcrystalline to cryptocrystalline vein quartz (which also permeates and heals the internal fractures). Sparse sericite (2–3%) is dispersed and occurs in very small patches
145219	The thin section has the same two generations of quartz as above samples, but somewhat different proportions and distribution. ~80% of the section consists of the early relatively coarse crystalline granular to subhedral mosaic, in areas to 20 mm across. This quartz is clouded with fluid inclusions, stressed and fractured, but not always dislocated or detached as discrete breccia fragments. Later microcrystalline, microsparry and microgranular vein quartz permeates between these domains and typical heals fractures within them. There are rare short limonitic stylolites, but (typically) no accessory minerals
145220	~40% of this sample consists of medium to coarse, more or less sparry quartz comparable to the coarse early generation quartz in the three vein quartz samples described above. This quartz is randomly disposed as apparent small (1–2 mm) breccia fragments, also as less well defined ‘patches’, all within irregular patchy domains of microcrystalline to cryptocrystalline quartz (60% of sample). The scattered “patches” may be partly resorbed breccia fragments of the early quartz. Incipient fine colloform banding within the finer massive later quartz suggests an epithermal genesis

Table 88. Chemical analyses of quartz veins in the Karratha region (see Figs 142–143)

GSWA no.	*145217*	*145218*	*145219*	*145220*	*145221*	*145222*	*145223*	*145224*	*145225*
					Percentage				
SiO_2	98.9	98.1	98.4	99.6	99.8	98.5	99.2	99.5	97.4
Al_2O_3	0.37	1.00	0.73	0.04	0.05	0.78	0.30	0.18	1.55
Fe_2O_3	0.24	0.27	0.23	0.06	0.05	0.15	0.11	0.11	0.18
MgO	0.01	0.07	0.03	0.04	0.01	0.02	0.02	0.01	0.04
CaO	0.01	0.01	0.01	0.02	0.02	0.03	0.02	0.01	0.01
Na_2O	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.01	<0.01	0.01
K_2O	0.08	0.34	0.26	0.02	0.02	0.16	0.06	0.06	0.49
TiO_2	0.01	0.02	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	0.01
nO	0.01	0.02	0.02	0.01	<0.01	0.01	0.01	0.01	0.01
P_2O_5	0.230	0.010	0.007	0.025	0.024	0.012	0.055	0.008	0.004
BaO	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	0.01
SO_3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	0.14	0.17	0.16	0.14	0.06	0.23	0.24	0.06	0.28
Total	**100.00**	**100.01**	**99.85**	**99.96**	**100.03**	**99.92**	**100.05**	**99.95**	**99.99**
H_2O	0.03	0.02	0.01	0.03	0.04	0.04	0.07	0.04	0.04

Table 89. Thermal stability of quartz veins in the Karratha region (see Figs 142–143)

GSWA no.	*Size fraction (mm)*					*Cumulative passing*				*Thermal*
	>19	*9.5 – 19.0*	*4.8 – 9.5*	*2.0 – 4.8*	*<2*	*19 mm*	*9.5 mm*	*4.8 mm*	*2 mm*	*stability*
					Percentage					
145217	98.1	1.1	0.5	0.2	0.1	1.9	0.8	0.3	0.1	98.1
145218	88.2	10.8	0.5	0.3	0.2	11.8	1.0	0.5	0.2	88.2
145219	89.1	10.7	0.0	0.0	0.1	10.9	0.1	0.1	0.1	89.1
145220	93.5	6.3	0.0	0.1	0.0	6.5	0.1	0.1	0.0	93.5
145221	99.7	0.0	0.0	0.1	0.2	0.3	0.3	0.3	0.2	99.7
145222	88.9	9.9	0.9	0.2	0.2	11.1	1.2	0.4	0.2	88.9
145223	95.5	3.7	0.6	0.1	0.1	4.5	0.8	0.2	0.1	95.5
145224	95.2	3.4	1.1	0.2	0.1	4.8	1.4	0.3	0.1	95.2
145225	97.8	0.0	1.8	0.3	0.2	2.2	2.2	0.5	0.2	97.8

Table 90. Thermal strength of quartz veins in the Karratha region (see Figs 142–143)

GSWA no.	Size fraction (mm)					Cumulative passing				Thermal strength
	>19	9.5 – 19.0	4.8 – 9.5	2.0 – 4.8	<2	19 mm	9.5 mm	4.8 mm	2 mm	
					Percentage					
145217	75.7	20.7	2.2	0.6	0.9	24.3	3.6	1.4	0.9	98.6
145218	92.4	5.3	0.9	0.8	0.6	7.6	2.3	1.4	0.6	98.6
145219	83.8	14.2	0.8	0.6	0.7	16.2	2.1	1.2	0.7	98.8
145220	96.8	1.8	0.7	0.4	0.4	3.2	1.4	0.7	0.4	99.3
145221	88.5	8.8	0.8	0.6	1.3	11.5	2.7	1.9	1.3	98.1
145222	61.2	33.0	3.4	1.2	1.1	38.8	5.8	2.3	1.1	97.7
145223	85.1	12.5	1.2	0.4	0.8	14.9	2.4	1.2	0.8	98.8
145224	53.2	40.8	3.8	1.2	1.1	46.8	6.0	2.3	1.1	97.7
145225	72.3	23.3	2.1	1.0	1.4	27.7	4.5	2.4	1.4	97.6

microcrystalline quartz (to microsparry in the coarser veins), partly along a primary layering, but mostly at random across the layering. There are also minor scattered individual quartz crystals. The sample is interpreted as a probable host rock of chert (with the ultrafine 'cherty' silica as an integral part) that has been fractured and invaded by an extensive network of epithermal quartz veins.

Sample GSWA145223 assayed 99.2% SiO_2, 0.3% Al_2O_3, 0.11% Fe_2O_3, 0.02% TiO_2 and 0.055% P_2O_5, indicating the presence of moderately high quality quartz, probably suitable for metallurgical- and chemical-grade production of silicon metal (Table 88). The thermal stability and thermal strength of the sample (95.5 and 98.8% respectively) also indicate that the material is suitable for use in the production of silicon metal (Tables 89 and 90).

Location E

At Location E, approximately 5 km west of Location A (Fig. 142), and about 4.5 km west of the turnoff to the Karratha township, a ridge of vein quartz crosses the highway. The ridge trends northeasterly and appears to extend, with discontinuous outcrops, for a distance of some 2 km. The quartz is white and the vein is vertically jointed.

A sample (GSWA145224) of this vein from the south side of the highway shows the quartz to be massive, microcrystalline and milky, incorporating an apparent random breccia texture. In thin section, this sample consists essentially of a microcrystalline quartz mosaic, although ubiquitous microtextures related to brecciation are different from those in any sample so far described. Individual grain size is less than 0.05 mm. The rock displays large-scale breccia domains (2–20 mm across) with angular, sharp-blocky outlines, including straight fracture traces dividing optical continuity within patchy micromosaic in adjacent domains (Fig. 148). Minor quartz veinlets cut across the blocky breccia domains and the micromosaic. Also, minor sericite is present in some of the breccia blocks. A thin section from another sample (GSWA14525) taken from the north side of the highway shows that at least 60% of the sample consists of a very irregular network of veins that coalesce into patches of coarse granular to interlocking sparry, subhedral-prismatic quartz crystals. Average individual size of these patches is about 1 mm, but some reach 3 mm. Irregular domains up to 7 mm across, consisting of much finer microgranular and microsparry quartz micromosaic, exist mostly between and partly within this vein network. These microgranular domains consist of 10–35% sericite, and total sericite in the whole rock is estimated to be 7–10%. The finer quartz(–sericite) seems mostly to have been introduced into a brecciated mass of the coarser sparry quartz, although locally, the textural relationship suggests the reverse of this. The presence of coarser sparry vein quartz, and sporadic domains (apparently matrix) of much finer quartz, is reminiscent of samples from Location A, except that in the Location E samples the finer quartz (with or without only sparse sericite) normally seems to have been introduced later into the vein quartz.

Samples GSWA145224–225 assayed 97.4–99.5% SiO_2, 0.18–1.55% Al_2O_3, 0.11–0.18% Fe_2O_3, <0.01–0.01% TiO_2, 0.01% CaO, 0.01–0.04% MgO and 0.004–0.008% P_2O_5, indicating possible high-quality quartz suitable for metallurgical- and chemical-grade silicon metal production (Table 88). The thermal stability and thermal strength of the samples average 96.5 and 97.7% respectively, which supports the suitability of this material for use in the production of silicon metal (Tables 89 and 90).

Gascoyne Complex

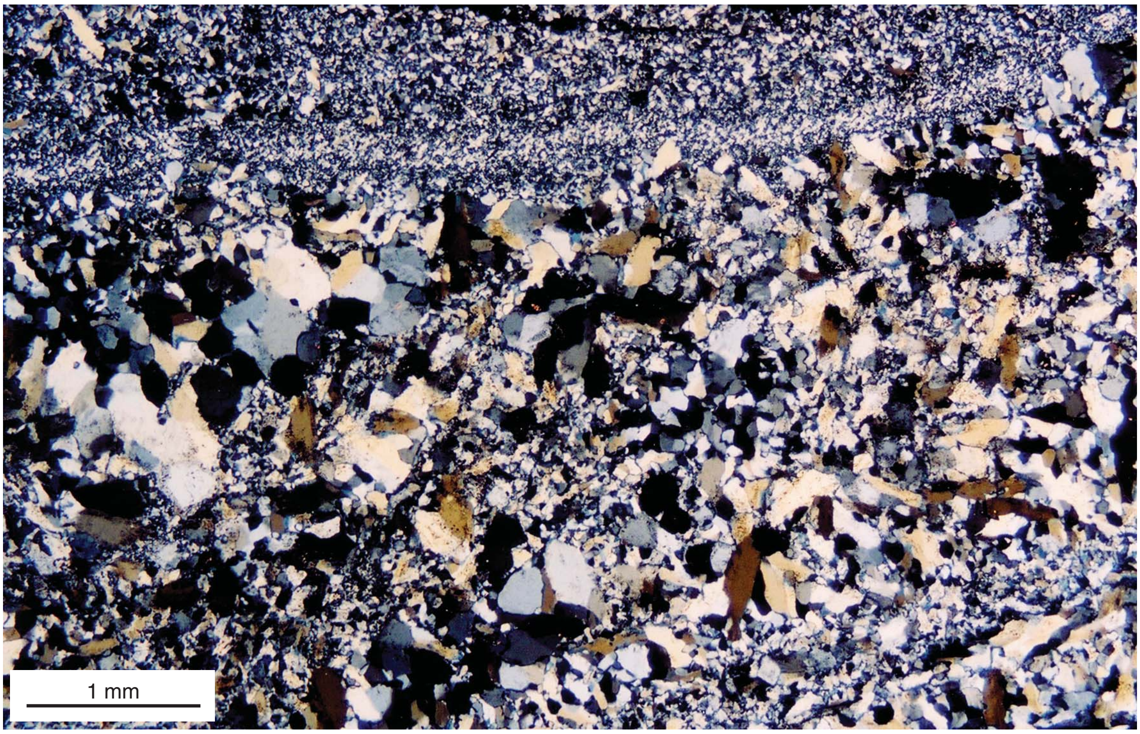
The main known silica rock occurrences in the Gascoyne Complex are a quartz vein at Nanutarra and a pegmatite at Andrew Bore (Fig. 81). The description of the Nanutarra occurrence is based on reconnaissance sampling carried out by the author. The silica rock occurrence at Andrew Bore is held under various mining leases for its silica rock potential, and the results of investigations remain confidential. Following are brief descriptions of these occurrences.

Quartz veins

Nanutarra

Approximately 325 km northeast of Carnarvon and 9 km southwest of Nanutarra there is a prominent ridge of vein quartz nearly parallel to, and on the eastern side of, the

(a)



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(b)

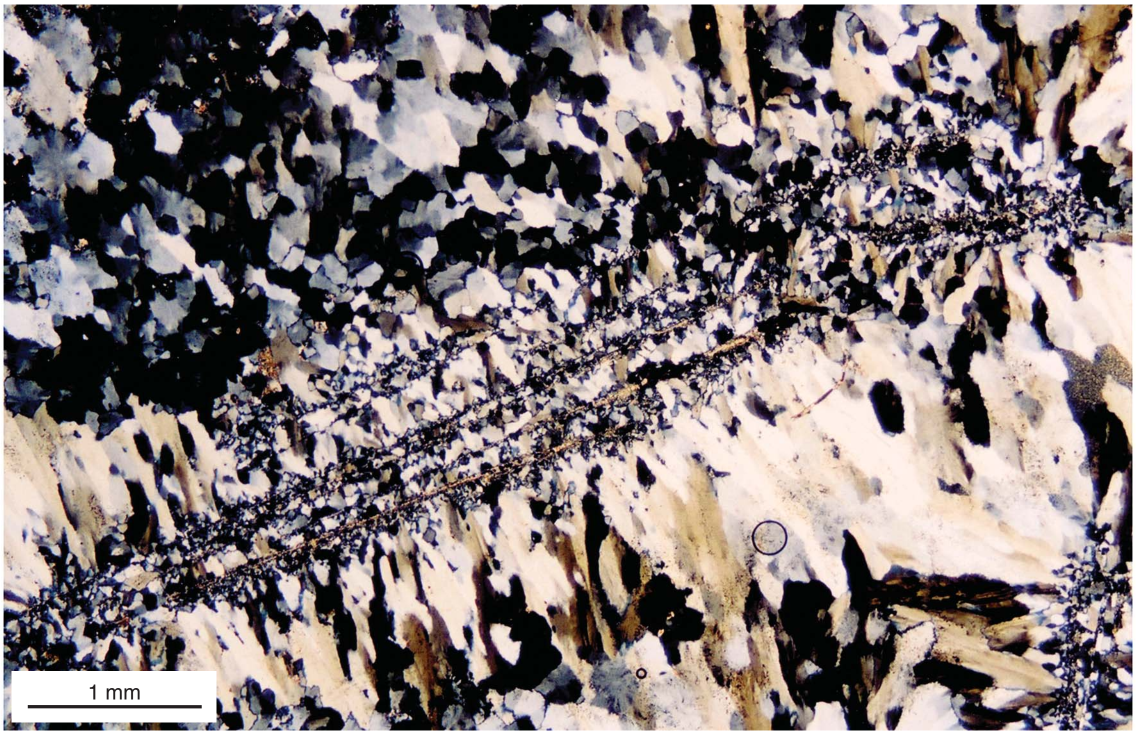

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Figure 146. a) Photomicrograph (crossed nicols ×20) showing several irregular, poorly defined and merging domains of quartz (sample GSWA145222, Location C, Fig. 143); b) Photomicrograph (crossed nicols ×20) showing subradiating textures interpreted as epithermal vein quartz (sample GSWA145222, Location C, Fig. 143)

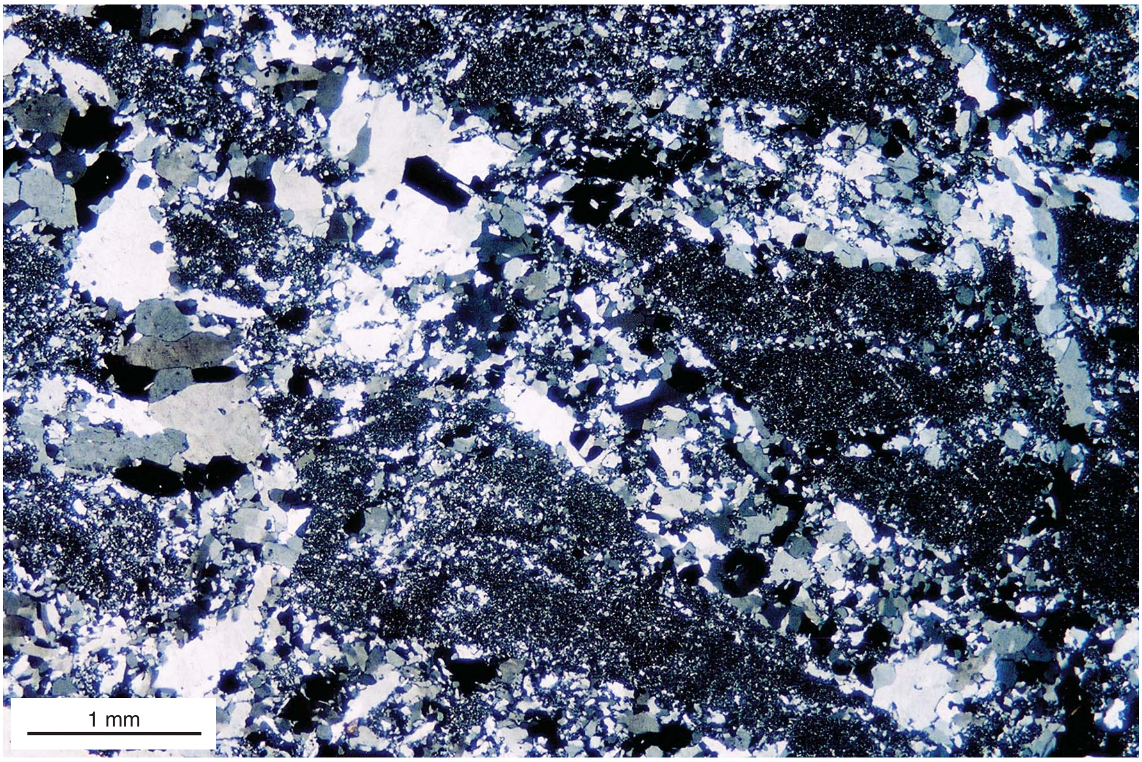

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Figure 147. Photomicrograph (crossed nicols ×20) showing massive ultrafine cryptocrystalline chert (GSWA145223, Location D, Fig. 143)

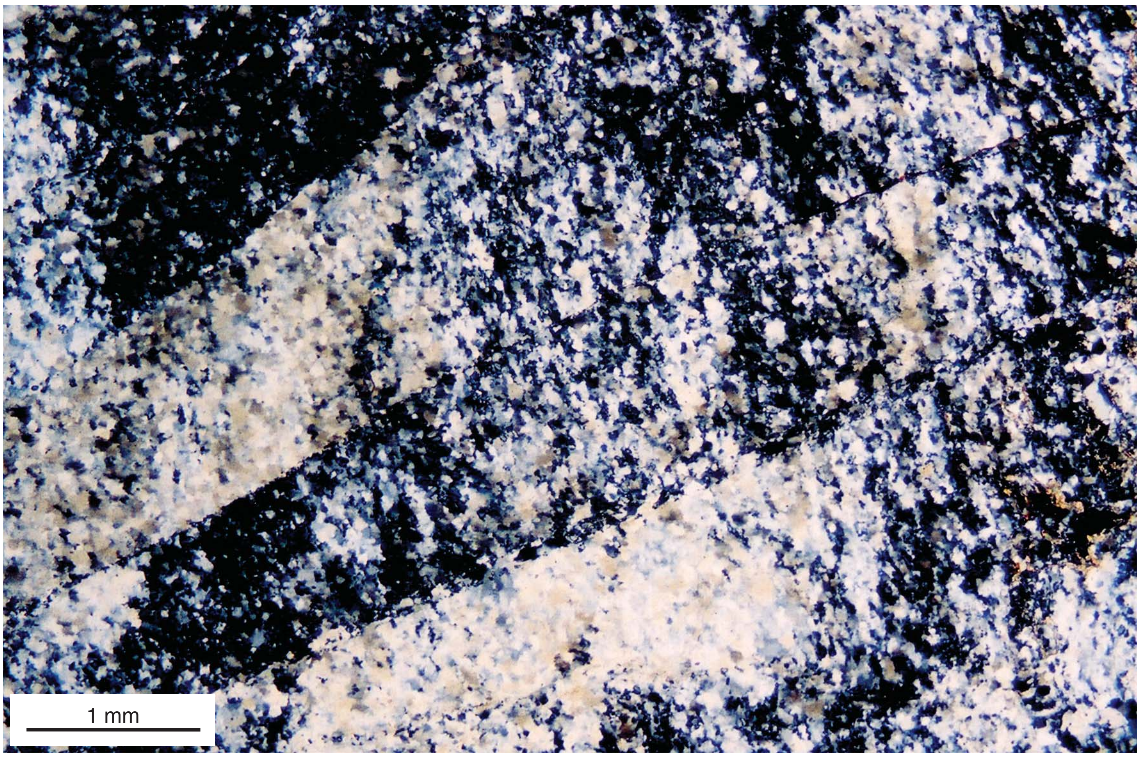

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Figure 148. Photomicrograph (crossed nicols ×20) showing large-scale breccia domains, with angular, sharp-blocky outlines, and straight fracture traces (sample GSWA145224, Location E, Fig. 142)

Table 91. Chemical analysis of quartz vein, south of Nanutarra (see Fig. 149)

GSWA no.	*145226*
	Percentage
SiO_2	99.70
Al_2O_3	0.04
Fe_2O_3	0.04
MgO	<0.01
CaO	0.01
Na_2O	0.01
K_2O	0.01
TiO_2	<0.01
MnO	<0.01
P_2O_5	0.007
BaO	<0.01
SO_3	<0.01
LOI	0.05
Total	**99.87**
H_2O	0.02

North West Coastal Highway (Figs 81 and 149). The quartz ridge extends for a distance of about 2–2.5 km in a northwesterly direction, and the vein is some 30 m wide, and 3.5–4 m high. The quartz is massive and white, and a thin section of a sample (GSWA145226) indicates that this quartz closely resembles that of sample GSWA145221 from Location B in the Karratha region. The rock consists of a massive, inequigranular (0.2–2.5 mm) mosaic of quartz, with most intergranular contacts sutured/interlocking on a micro to broader (1 mm) scale. Fluid inclusions are common, including numerous subparallel microscopic trains cutting across the overall mosaic texture. There are no other minerals or distinctive fabrics and there is no diagnostic criterion to identify any unique or specific genesis except for ‘massive vein quartz’, conceivably recrystallized.

The above sample (GSWA145226) has 99.7% SiO_2, 0.04% Al_2O_3, 0.04% Fe_2O_3, <0.01% TiO_2, 0.01% CaO, <0.01% MgO and 0.007% P_2O_5 (Table 91), indicating very high grade quartz suitable for metallurgical- and chemical-

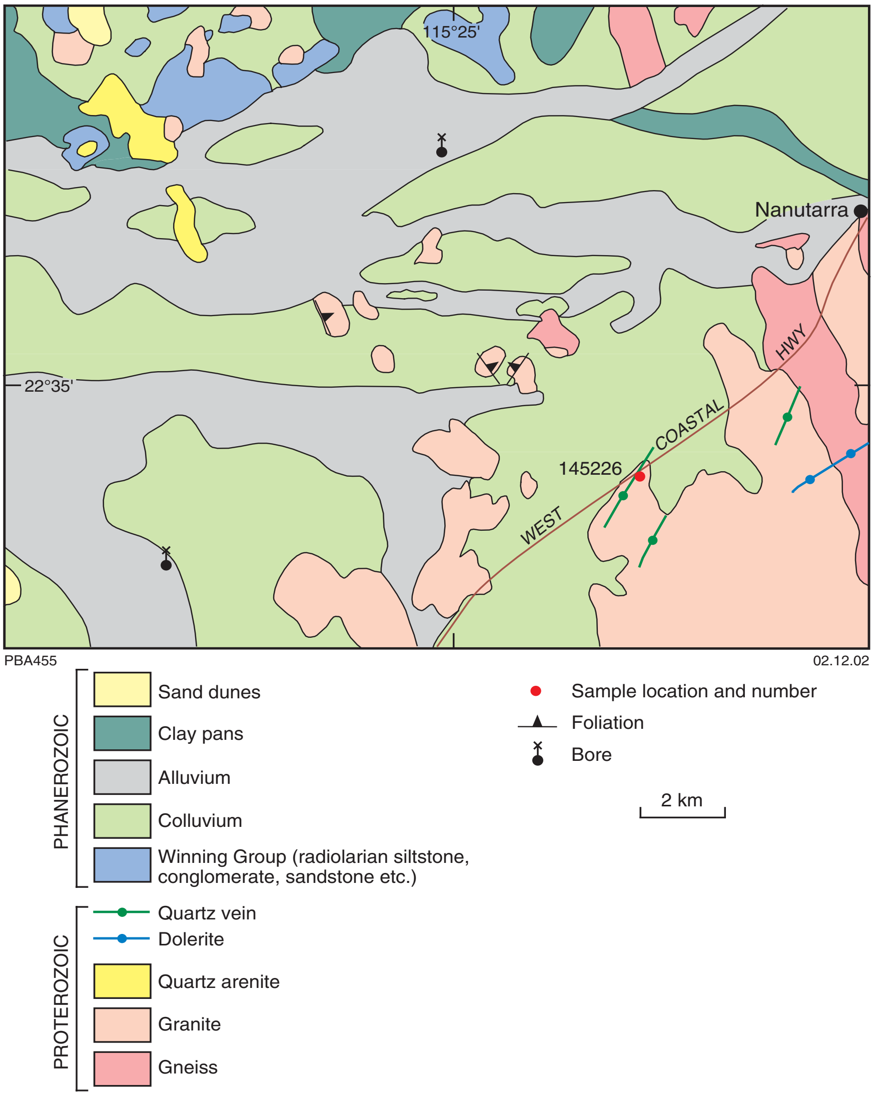

Figure 149. Geology west of Nanutarra (after van de Graaff et al., 1980)

Table 92. Thermal stability of quartz vein, south of Nanutarra (see Fig. 149)

GSWA no.	Size fraction (mm)					Cumulative passing				Thermal stability
	>19	9.5 – 19.0	4.8 – 9.5	2.0 – 4.8	<2	19 mm	9.5 mm	4.8 mm	2 mm	
	Percentage									
145226	97.6	1.6	0.4	0.1	0.2	2.4	0.7	0.3	0.2	97.6

Table 93. Thermal strength of quartz vein, south of Nanutarra (see Fig. 149)

GSWA no.	Size fraction (mm)					Cumulative passing				Thermal strength
	>19	9.5 – 19.0	4.8 – 9.5	2.0 – 4.8	<2	19 mm	9.5 mm	4.8 mm	2 mm	
	Percentage									
145226	82.2	13.6	2.2	0.7	1.3	17.8	4.2	2.0	1.3	98.0

grade production of silicon metal. The thermal stability and thermal strength of the sample are 97.6 and 98.0% respectively, which are excellent thermal properties for use in the production of silicon metal (Tables 92 and 93). The available resource is potentially large, and the location of this deposit close to the North West Coastal Highway favours economic development.

Pegmatite

Andrew Bore

An area 25 km east-southeast of Yinnetharra Homestead and 4 km south of Andrew Bore (Fig. 81) (within Mining Lease M9/58) is being investigated by Mr R. M. Walker for mineralized pegmatites. The main aim is to identify any pegmatites with possible commercial concentrations of tantalum, niobium, rare earths, beryllium, and high-quality quartz. Pegmatites in the area intrude migmatite and schist of the Early Proterozoic Morrissey Metamorphic Suite. The area is already known to contain tantalum, beryl, and other semi-precious mineral-bearing pegmatites (Williams et al., 1983b). Mr Walker has mapped and demarcated quartz outcrops within Mining Lease M9/58, and bulk samples of this quartz have been sent to Taiwan for testing.

Carnarvon Basin

The main known silica rock in the Carnarvon Basin is Windalia Radiolarite, which is a unit in the Cretaceous Winning Group and consists of radiolarite, sandy radiolarite, and chert. This unit rests conformably on the Muderong Shale or the Birdrong Sandstone, and is unconformably overlain by the Gearle Siltstone. The Windalia Radiolarite commonly has a porcellanized, cherty appearance due to secondary silicification during silcretization, and exhibits liesegang banding and blotchy iron staining. The rock is dominantly white, but the colour locally varies from yellow to red, purple, and brown (Hocking et al., 1987).

Windalia Radiolarite

Winning

Lyndon Mining Pty Ltd currently holds an area approximately 3 km north of Winning Homestead (Fig. 81) and about 190 km northeast of Carnarvon. The major phase of the Windalia Radiolarite here is cristobalite, which has silica rock potential. The area lies within their Mining Lease M8/135, and the results of exploration work remain confidential.

Chapter 6

Summary

Silica is obtained from many sources including silica sand, quartzite, pegmatite, vein quartz, sandstone, novaculite, flint, chert, and quartz crystal. Although these rock types are very common in nature, high-grade silica deposits suitable for many specialty applications are not easily found.

The current world production of silica and quartz is estimated at 120–150 Mt. The United States is the leading producer of silica, with about 24% (29 Mtpa) of global production, followed by the Netherlands with about 20% (24 Mtpa). France, Austria, Germany, Belgium, and Paraguay each produce in excess of 5 Mtpa. Australia produces about 3.9 Mtpa, which is about 3% of the global output. Western Australia's contribution approaches 0.9 Mtpa.

World prices of silica raw materials range between $10 and 45/t. However, the prices of value-added products can be very high (e.g. silicon metal $2130–3180/t, colloidal silica $11–14/kg). The positive trends in global prices during the last six years for some grades of silica sand suggest a steady growth in the silica sand industry. The specialty silica industry, which involves products such as precipitated, fumed, and colloidal silica used in diverse applications, is currently estimated to be worth about $3800 million globally, and is expanding at a steady rate.

Silica sand

High-grade silica sand is used in a variety of industrial applications, which include the glass industry, foundry-casting industry, filtration sand, blasting sand, chemicals manufacture, proppant sand, filler and pigment extender, and also in the environmental applications to remove hazardous and industrial particles from waste water. Many of these applications require silica sand of very high purity, often in excess of 99% SiO_2 with very few impurities. Particle size is another important aspect in many applications.

Of the Australian production of 3.9 Mt of silica during 1998–99, 3.7 Mt is silica sand. Of this, about 54% (2.1 Mt) was from Queensland. Western Australia is the next biggest producer of silica sand with a reported production of 848 887 t in 1998–99 (898 994 t in 2000).

In Western Australia, economically significant silica sand deposits are mostly found in the Pleistocene Bassendean Sand in the coastal regions of the Perth Basin. There is large-scale mining at Gnangara and Jandakot (suburbs of the Perth Metropolitan Area) and at Kemerton (25 km north-northeast of Bunbury). Resources of silica sand in Bassendean Sand are estimated to total 292 Mt, but this does not include the Jandakot deposit, which has no published resource.

The Albany region is the next most important area for high-grade silica sand in Western Australia. In this region, commercially significant silica sand deposits overlie the Proterozoic Albany–Fraser Orogen, and Eocene Bremer Basin sedimentary rocks located north and northeast of Albany and along the coastal regions from Walpole to east of Esperance. Currently, a high-grade silica sand deposit is mined at Mindijup, 35 km northeast of Albany, where resources are estimated at 20 Mt of high-grade silica sand. In addition, other high-grade silica sand deposits are found in regions north of Albany, such as at Lake Don, and variously distributed along the southern coast in the Albany–Esperance region. The total published resources of silica sand in Western Australia are 324 Mt (Table 59), with significant exploration potential remaining.

The chemical quality of the sand produced from the Gnangara, Jandakot, and Mindijup deposits is very high, with >99.5% SiO_2 and low levels of impurities. Sand processed at Kemerton mine typically contains 95% SiO_2 and 2.4% Al_2O_3 and is produced for specific customer requirements. The main difference in the quality of sand from deposits at Gnangara and Jandakot in the Perth Basin and that from Kemerton and Mindijup, lies in the latter deposits containing finer sand.

Most of the sand produced in the State is exported, without much downstream processing, to the Asian region. Sand from many localities within the Bassendean Sand is suitable for high-grade applications such as in the glass, chemical, and foundry industries, and also for use as filtration sand. Apart from the Bassendean Sand of the Perth Basin and coastal dunes in the Albany region, the main prospective areas for high-grade silica sand in the State are likely to be in the Condingup and Merivale regions east of Esperance. Sand from Mount Burges, in the Coolgardie area, is used for nickel smelting at Kalgoorlie. Chemical analyses of sand samples taken within 100 km of Kalgoorlie indicate a quality which is inferior to that of sand from the Perth Basin and the Albany region.

Unimin (formerly ACI) is the only company involved in value adding locally, with the manufacture of clear and coloured container glass.

Silica rock

Sandstone, quartz, quartzite, chert, quartz pebbles, silica gravel and lump, novaculite, and quartz crystals may be used in a variety of industrial applications depending on chemical and physical properties. The applications include the production of silicon metal, ferrosilicon and other silicon alloys, chemical-grade silicon, as a flux (in the smelting of elemental phosphorus, iron, nickel, zinc, copper, and lead), refractories, abrasives, electronics and optics, and in lining acid tanks, towers, and trays.

In the production of silicon metal, from using quartz and quartzite lumps, the most commonly used sizes are either 3.81–10.16 cm diameter or 2.54–7.62 cm. The raw material should typically contain 99.3–99.8% SiO_2, and less than each of 0.1% Fe_2O_3, 0.15% Al_2O_3, 0.2% CaO, 0.2% MgO and 0.2% loss on ignition, with thermal stability and strength each preferably above 95%. Products such as precipitated, fumed, and colloidal silica are specialized products often tailored to customer specifications.

During 1998–99, Australia produced 269 147 t of silica rock, of which Western Australia produced 90 069 t. In 2000, Western Australia produced 92 149 t of chert valued at $921 493.

At present, the only production of quartz rock in Western Australia is chert from a mine 14 km north of Moora. Production from the Moora deposit commenced in 1989. The deposit is currently owned by Simcoa Operations Pty Ltd, which has a silicon production plant at Kemerton, about 15 km north-northeast of Bunbury. The high-quality chert at Moora is developed predominantly within the Noondine Chert (Coomberdale Subgroup), which is a silicified, bedded carbonate (siliceous limestone/dolomite) unit. The chert in the deposit has variable chemical grades, but the average quality is acceptable for many metallurgical and chemical end-uses in the silicon industry. A typical high-quality Moora chert contains around 0.082% Fe_2O_3, 0.220% Al_2O_3, 0.033% TiO_2, 0.012% P_2O_5, and 99.7% SiO_2. The measured resource in the deposit is estimated at 2 Mt of chert at 99.3% silica. A second openpit is planned at the western side of the current openpit and this will lead to further expansion of chert production.

The chert in the Moora deposit is mined from an openpit, with about nine different grades of chert separately stockpiled at the mine. This chert is then transported to Kemerton for the production of silicon metal. The manufacture of silicon metal is carried out in a submerged-arc electric smelting furnace by the reduction of chert with carbonaceous reducing agents. Raw materials are selected on the basis of chemical purity, size consistency, thermal stability, thermal strength, and smelting characteristics.

The Kemerton plant is considered to be one of the most efficient in the world, and produces different grades depending on customer requirements. The plant has a capacity to produce around 31 000 tpa of silicon metal, which is about 4% of world production. In addition to the standard products of silicon smelting, the byproduct silica fume has a strong market in the concrete industry. Some 10 000 tpa of silica fume is extracted from furnace off-gases for use in the manufacture of high-strength or corrosion-resistant concrete and industrial refractories. At present, approximately 15% of production is sold to the domestic market, with the remainder exported to the United States, Japan, India, and some countries in Europe.

Reconnaissance sampling by the author from various localities in the State has identified a number of areas of silica rocks with suitable chemical composition and thermal stability and strength as potential raw material for silicon metal production. The main rock types and localities are quartz–feldspar pegmatites at Karloning and Mukinbudin, quartz veins near the Karratha and Nanutarra regions, and chert at Shaw River. Information obtained from other localities suggests that quartz veins at Bonnie Rock and White Flag Lake, and a pegmatite body at Snake Rock may also be prospective areas for high-grade silica rock.

References

ABARE, 1999, Summary of Australian statistics for silica; Commodity Statistical Bulletin, Australian Bureau of Agricultural and Resource Economics, Canberra, p. 327–329.

ABEYSINGHE, P. B., 1998, Limestone and limesand resources of Western Australia: Western Australia Geological Survey, Mineral Resources Bulletin 18, 140p.

ABEYSINGHE, P. B., and FETHERSTON, J. M., 1999, Kaolin in Western Australia: Western Australia Geological Survey, Mineral Resources Bulletin 19, 142p.

ALSOBROOK, A. F., 1994, Silica, specialty materials, *in* Industrial Minerals and Rocks (6th edition), *edited by* D. D. CARR (Senior Editor): Littleton, Colorado, Society for Mining, Metallurgy, and Exploration, Inc., p. 893–911.

AUSTIN, G. T., 1991, Abrasive materials 1990 Annual Report, US Bureau of Mines, 20p.

AUSTRALIAN JOURNAL OF MINING, 2001, Portman drops silicon, targets iron ore: Australian Journal of Mining, News, February 2001, p. 9.

BAXTER, J. L., and LIPPLE, S. L., 1985, Perenjori, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 32p.

BENBOW, J., 1989, Industrial silica sand, and operational view: Industrial Minerals, no. 262, p. 19–36.

BETTENAY, E., and HINGSTON, F. J., 1964, Development and distribution of soils in the Merredin area, Western Australia: Australian Journal of Soil Research, v. 2, p. 173–186.

BIGGS, E. R., 1979, Karratha, W.A., Sheet 2256 II: Western Australia Geological Survey, 1:50 000 Urban Geology Series.

BLIGHT, D. F., CHIN, R. J., SMITH, R. A., BUNTING, J. A., and ELIAS, M., 1983, Bencubbin, W.A. Sheet SH 50-11: Western Australia Geological Survey, 1:250 000 Geological Series.

BOLGER, R., 1996, Foundry minerals; Recycling, the new name of the game: Industrial Minerals, no. 351, p. 29–39.

BRAKEL, A. T., MONCRIEFF, J. S., MUHLING, P. C., and CHIN, R. J., 1985, Dumbleyung, W.A. Sheet SI 50-7: Western Australia Geological Survey, 1:250 000 Geological Series.

BREWER, R., and BETTENAY, E., 1973, Further evidence concerning the origin of the Western Australian sandplains: Journal of the Geological Society of Australia, v. 19, p. 533–541.

BROWN, M., 1986, Silica sand and gypsum, Australian export commodities of growing significance: Industrial Minerals, no. 229, p. 40–57.

BRUVEL, F., 1999, Silica sand: Department of Mines and Energy, Brisbane, Queensland, Mineral Information Leaflet, no. 3, 3p.

CARROLL, D., 1939, Appendix — Sandplain soils from the Yilgarn Goldfield *in* The geology of the Yilgarn Goldfield south of the Great Eastern Railway *by* H. A. ELLIS: Western Australia Geological Survey, Bulletin 97, p. 161–179.

CARTER, J. D., and LIPPLE, S. L., 1982, Moora, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 25p.

CAWOOD, P. A., and NEMCHIN, A. A., 2000, Provenance record of a rift basin: U/Pb ages of detrital zircons from the Perth Basin, Western Australia: Sedimentary Geology, v. 134 (3–4), p. 209–234.

CHIN, R. J., SMITH, R. A., and BUNTING, J. A., 1983, Jackson, W.A. Sheet SH 50-12: Western Australia Geological Survey, 1:250 000 Geological Series.

CHRISTIE, A. B., DOUCH, C. J., and WINFIELD, B. J., 2000, New Zealand's industrial mineral potential: Industrial Minerals, no. 394, p. 66–77.

CHURCHWARD, H. M., 1970, Erosional modification of a lateritized landscape over sedimentary rocks; its effect on distribution: Australian Journal of Soil Research, v. 8, p. 1–19.

CLAYTON, W., 1984, Geological report on Prospecting Licence PL 70/19, Narrikup; Westralian Sands Limited: Western Australia Geological Survey, Statutory mineral exploration report, Item 3559 A14245 (unpublished).

COCKBAIN, A. E., 1990, Perth Basin, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 495–524.

COLES, R., 1975a, Report on geological investigations, Mukinbudin quartz deposit: Snowstone Pty Ltd (unpublished).

COLES, R., 1975b, Report on geological mapping and correlation of results; Karloning feldspar deposit; Snowstone Pty Ltd: Western Australia Geological Survey, Statutory mineral exploration report, Item 6024 A6141 (unpublished).

COMMANDER, D. P., KERN, A. M., and SMITH, R. A., 1992, Hydrogeology of the Tertiary Palaeochannels in the Kalgoorlie Region (Roe Palaeodrainage): Western Australia Geological Survey, Record 1991/10, 56p.

COOPE, B. M., 1989, Synthetic silicas & silicon chemicals; Natural silica consumers & rivals: Industrial Minerals, no. 258, p. 43–55.

COOPER, W., 1993, Queensland mineral commodity report: Queensland Government Mining Journal, no. 3, p. 7–15.

COOPER, W., and SAWERS, J. D., 1990, Cape Flattery and Shelburne Bay silica sand deposits, *in* Geology of the mineral deposits of Australia and Papua New Guinea *edited by* C. L. KNIGHT: Australasian Institute of Mining and Metallurgy, p. 1665–1667.

DANIELS, J. L., 1969, Sand ridge distribution in the Gibson and Great Victoria deserts of Western Australia: Western Australia Geological Survey, Annual Report for 1968, p. 38–39.

DENMAN, P. D., HOCKING, R. M., MOORE, P. S., WILLIAMS, I. R., and van de GRAAFF, W. J. E., 1985, Wooramel, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 21p.

DEPARTMENT OF RESOURCES DEVELOPMENT, 1997, The potential for ferro-alloy manufacture in Western Australia; a prefeasibility study: Department of Resources Development of Western Australia.

DEPARTMENT OF RESOURCES DEVELOPMENT, 1999, Silicon/silica sand/silica fume/quartz: Western Australian Industrial Minerals Review 1999; Department of Resources Development of Western Australia, p. 49–52.

DEY, R., 1990, MON-D-OR resources, Report on Mining Tenement PL 47/789: Western Australia Geological Survey, Statutory mineral exploration report, Item 6864 A34030 (unpublished).

DUNDON, P. J., PRESTON M. J. R., and HAYDON, D., 1984, Sand mining project; report on geological investigations grade results and probable reserves volume 1: Silica Sales Pty Ltd.

ELLIOTT, A., and BENSON, S., 2001, Staurolite product development: Australasian Institute of Mining and Metallurgy, International Heavy Minerals Conference 2001, June 2001, Fremantle, Western Australia.

FETHERSTON, J. M., 1990, High-grade silica resources of Western Australia — commodities of international significance *in* Papers for the 9th Industrial Minerals International Congress *edited by* J. B. GRIFFITHS: Metal Bulletin PLC London, March 1990, p. 138–139.

FLINT, D. J., FLINT, R. B., and FLINTOFT, M. W., 1992, Flint deposits in the South-East: South Australia Department of Mines and Energy, Mines and Energy Review, no. 158, p. 70–74.

FLINT, D. J., and ABEYSINGHE, P. B., 2001, Western Australia mineral exploration and development for 1999 and 2000: Western Australia Geological Survey, 35p.

GEE, R. D., 1981, Southern Cross, W.A. Sheet SH 50-16: Western Australia Geological Survey, 1:250 000 Geological Series.

GEOLOGICAL SURVEY and MINES BUREAU, SRI LANKA, 1999, Sri Lanka Minerals Year Book 1999, p. 8–9.

GLASSFORD, D. K., and SEMENIUK, V., 1995, Desert–aeolian origin of Late Cenozoic regolith in arid and semi-arid south-western Australia: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 114, p. 131–166.

GONZÁLEZ-BARROS, M. R., and SANZ, C. M., 2000, Industrial minerals of Spain; Europe's mining stronghold: Industrial Minerals, no. 394, p. 53–65.

GOZZARD, J. R., 1983, Fremantle, W.A. part Sheets 2033 I and 2033 IV: Western Australia Geological Survey, Perth Metropolitan Region, 1:50 000 Environmental Geology Series.

GOZZARD, J. R., 1986, Perth, W.A. Sheet 2034 II and part Sheets 2034 III and 2134 III: Western Australia Geological Survey, Perth Metropolitan Region 1:50 000 Environmental Geology Series.

GOZZARD, J. R., 1987a, Information on industrial minerals — coastal plain between Lancelin and Fremantle: Western Australia Geological Survey, Record 1987/11, 180p.

GOZZARD, J. R., 1987b, Information on industrial minerals — coastal plain between Fremantle and Bunbury: Western Australia Geological Survey, Record 1987/9, 213p.

GOZZARD, J. R., 1987c, Information on industrial minerals — Collie area: Western Australia Geological Survey, Record 1987/8, 28p.

GRIFFIN, T. J. 1990, Eastern Goldfields Province, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 77–79.

GROENEWALD, P. B., PAINTER, M. G. M., ROBERTS, F. I., McCABE, M., and FOX, A., 2000, East Yilgarn geoscience database 1:100 000 geology Menzies to Norseman — an explanatory note: Western Australia Geological Survey, Report 78, 53p.

GUY, J. W., 1988, Matlock Mining NL, Mukinbudin Project, South West Mineral Field, Western Australia, Annual Report — August 1988: Matlock Mining NL.

HARBEN, P. W., 1999, Distribution of world industrial mineral production, *in* The industrial minerals handybook (3rd edition): United Kingdom, Metal Bulletin PLC, Industrial Minerals Division, 295p.

HARBEN, P. W., and KUZVART, M., 1996, Silica, *in* A global geology; Industrial Minerals: United Kingdom, Metal Bulletin PLC, Industrial Minerals Division, p. 352–364.

HARRINGTON, D., 1993, Pit plan and environmental management report P70/229 Hope Valley Rd, Wandi: Silicon Quarries Pty Ltd.

HARRISON, B. R., ARCHER, R. H., and SILICA, M. K., 1988, Tasmanian silica flour — a new silica source for high grade glass, *in* Proceedings of 8th Industrial Minerals Congress *edited by* G. M. CLARKE: Metal Bulletin PLC, Industrial Minerals Division, p. 278–286.

HARRISON, P. H., 1990, Mineral sands, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 694–701.

HICKMAN, A. H., and GIBSON, D. L., 1981, Port Hedland – Bedout Island (2nd Edition), W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes.

HICKMAN, A. H., and SMITHIES, R. H., 2000, Roebourne, W.A. Sheet SH 50-3, 2nd edition: Western Australia Geological Survey, 1:250 000 Geological Series.

HOCHWIMMER, B., 1982, Geological report on Albany silica sand project; report prepared for Westralian Sands Limited: Western Australia Geological Survey, Statutory mineral exploration report, Item 5867 A23593 (unpublished).

HOCKING, R. M., 1994, Subdivisions of Western Australian Neoproterozoic and Phanerozoic sedimentary basins: Western Australia Geological Survey, Record 1994/4, 84p.

HOCKING, R. M., van de GRAAFF, W. J. E., BLOCKLEY, J. G., and BUTCHER, B. P., 1982, Ajana, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 27p.

HOCKING, R. M., WILLIAMS, S. J., LAVERING, I. H., and MOORE, P. S., 1985a, Winning Pool – Minilya, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 36p.

HOCKING, R. M., WILLIAMS, S. J., MOORE, P. S., DENMAN, P. D., LAVERING, I. H., and van de GRAAFF, W. J. E., 1985b, Kennedy Range, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 31p.

HOCKING, R. M., WILLIAMS, S. J., MOORS, H. T., and van de GRAAFF, W. J. E., 1987, Geology of the Carnarvon Basin, Western Australia: Western Australia Geological Survey, Bulletin 133, 289p.

HUNTER, W. M., 1988, Boorabbin, W.A. Sheet SH 51-13: Western Australia Geological Survey, 1:250 000 Geological Series.

INDUSTRIAL MINERALS, 1989, World of minerals, Australia, Gnangara speciality silica project for sale: Industrial Minerals, no. 264, p. 13.

INDUSTRIAL MINERALS, 1994 to 2000, Prices: Industrial Minerals, nos 316 to 405, (various).

INDUSTRIAL MINERALS, 2000, World of minerals, Australia, Unimin acquires ACI Industrial Minerals: Industrial Minerals, no. 403, p. 10.

JACKSON, J. A., 1997, Glossary of geology (4th edition) *edited by* J. A. JACKSON: Virginia, USA, American Geological Institute, 769p.

JOINT ORE RESERVES COMMITTEE OF THE AUSTRALASIAN INSTITUTE OF MINING AND METALLURGY, AUSTRALIAN INSTITUTE OF GEOSCIENTISTS, and MINERALS COUNCIL OF AUSTRALIA (JORC), 1999, Australasian code for reporting of mineral resources and ore reserves: Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists, and Minerals Council of Australia, 16p.

JORDAN, J. E., 1986, Armadale, W.A. part Sheet 2033 I and Sheet 2133 IV: Western Australia Geological Survey, Perth Metropolitan Region 1:50 000 Environmental Geology Series.

KEELING, J. L., PAIN, A. M., and VALENTINE, J. T., 1990, Industrial minerals in South Australia — current operations and future trends *in* Papers for the 9th Industrial Minerals International Congress *edited by* J. B. GRIFFITHS: Metal Bulletin PLC, p. 30–46.

KELLER, W. D., VIELE, G. W., and JOHNSON, C. H., 1977, Texture of Arkansas novaculite indicates thermally induced metamorphism: Journal of Sedimentary Petrology, v. 47, p. 834–843.

KENDALL, T., 1996, Brazil, dancing to new tune: Industrial Minerals, no. 350, p. 21–51.

KENDALL, T., 2000, Written in sand, the world of speciality silicas: Industrial Minerals, no. 390, p. 40–53.

KENDRICK, G. W., WYRWOLL, K. H., and SZABO, B., 1991, Pliocene–Pleistocene coastal events and history along the western margin of Australia: Quaternary Science Reviews, no. 10, p. 419–439.

KRIEWALDT, M., HORWITZ, R. C., RYAN, G. R., BOCK. W. M., 1964, Dampier and Barrow Island, W.A. Sheet SF 50-2 and part Sheet SF 50-1: Western Australia Geological Survey, 1:250 000 Geological Series.

LANDVISION, 1996, Managing the basic raw materials of Perth and outer Metropolitan region — a report prepared for the Extractive Industries Committee of the Chamber of Commerce and Industry of Western Australia: Chamber of Commerce and Industry of Western Australia, 166p.

LINDEN, J., 1971, Wabling Hills silica sand prospect: Western Australia Geological Survey, Statutory mineral exploration report, Item 2182 A3610 (unpublished).

LISHMUND, S., PATERSON, I., and RAY, H., 1999, Opportunities in New South Wales, minerals of Australia's oldest state reviewed: Industrial Minerals, no. 380, p. 57–68.

LOGAN, B. W., and CHASE, L. R., 1961, The stratigraphy of the Moora Group, Western Australia: Royal Society of Western Australia, Journal, v. 44, p. 14–26.

LOW, G. H., LAKE, R. W., and WILDE, S. A., 1978, Perth, W.A. Sheet SH 50-14 and part Sheet SH 50-13: Western Australia Geological Survey, 1:250 000 Geological Series.

LOW, G. H., LOWRY, D. C., CARTER, J. D., and LIPPLE, S. L., 1982, Moora, W.A. Sheet SH 50-10: Western Australia Geological Survey, 1:250 000 Geological Series.

LOW, G. H., LOWRY, D. C., LAKE R. W., WILDE, S. A., and HIRSCHBERG, K-J. B., 1980, Pinjarra, W.A. Sheet SI 50-2 and part Sheet SI 50-1: Western Australia Geological Survey, 1:250 000 Geological Series.

LOWRY, D. C., 1967, Busselton and Augusta, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes.

LOWRY, D. C., 1974, Dongara – Hill River, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes.

LOWRY, D. C., 1977, Perth Basin yellow sand: Search, v. 8, no. 3, p. 54–55.

LOWRY, D. C., HORWITZ, R. C., and GEMUTS, I., 1967, Busselton and Augusta, W.A. part Sheets SI 50-5 and SI 50-9: Western Australia Geological Survey, 1:250 000 Geological Series.

LOWRY, D. C., WILDE, S. A., and WALKER, I. W., 1983, Collie, W.A. Sheet SI 50-6: Western Australia Geological Survey, 1:250 000 Geological Series.

McCULLOCH, M. T., COMPSTON, W., and FROUDE, D., 1983, Sm–Nd and Rb–Sr dating of Archaean gneisses, eastern Yilgarn Block, Western Australia: Geological Society of Australia, Journal, v. 30, p. 149–153.

McHAFFIE, I. W., and BUCKLEY, R. W., 1995, Industrial minerals and rocks of Victoria: Geological Survey of Victoria, Report 102, 209p.

McNAB, B., 1991, Annual report for PL 20/1349 from 25th September 1990 to 25th September 1991: Western Australia Geological Survey, Statutory mineral exploration report, Item 7780 A37248 (unpublished).

MARTIN, R., 1997, Annual report for period 8 July 1996 to 7 July 1997 Mining Licence 70/118; Mukinbudin Feldspar Project, Western Australia, Bencubbin SH 50-11, 1:250 000 Sheet: Commercial Minerals Ltd.

MARTIN, R., 1999, Annual report for period 8 July 1998 to 7 July 1999 ML 70/118; Mukinbudin Feldspar Project, Western Australia, Bencubbin SH 50-11, 1:250 000 Sheet: Commercial Minerals Ltd.

MENZEL, B. W., 1993, EL 63/302 annual report for period 7th August 1992 to 6th August 1993; report prepared for Kriston Pty Ltd: Western Australia Geological Survey, Statutory mineral exploration report, Item 7287 A39856 (unpublished).

MONKS, T. F., 1993, Narrikup silica sand, annual report for the period 24/4/92 to 23/4/93: Western Australia Geological Survey, Statutory mineral exploration report, Item 8186 A38254 (unpublished).

MOORE, P., 2001, European container glass; It's got a lot of bottle: Industrial Minerals, no. 402, p. 35–47.

MORGAN, K. H., 1972, Esperance — Mondrain Island, W.A.: Sheet SI 51-6 and part Sheet SI 51-10: Western Australia Geological Survey, 1:250 000 Geological Series.

MORGAN, K. H., and PEERS, R., 1973, Esperance – Mondrain Island, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes.

MORTON, J. L., 1972, Report on work carried out on Mineral Claims 219, 220, 221 and 223 to 229 inclusive, Yilgarn Goldfield, for 12 months ending 31 December 1971; Barrier Exploration NL: Western Australia Geological Survey, Statutory mineral exploration report, Item 2477 A6224 (unpublished).

MORY, A. J., and IASKY, R. P., 1996, Stratigraphy and structure of the onshore northern Perth Basin, Western Australia: Western Australia Geological Survey, Report 46, 102p.

MORY, A. J., NICOLL, R. S., and GORTER, J. D., 1998, Lower Palaeozoic correlations and maturity, Carnarvon Basin, WA, *in* The sedimentary basins of Western Australia 2 *edited by* P. G. PURCELL and R. R. PURCELL: Petroleum Exploration Society of Australia; The Sedimentary Basins of Western Australia Symposium, Perth, W.A., 1998, Proceedings, p. 599–611.

MUHLING, P. C., BRAKEL, A. T., and MONCRIEFF, J. S., 1984, W.A. Sheet SI 50-11 and part Sheet SI 59-15: Western Australia Geological Survey, 1:250 000 Geological Series.

MUHLING, P. C., and THOM, R., 1985a, Kellerberrin, W.A. Sheet SH 50-15: Western Australia Geological Survey, 1:250 000 Geological Series.

MUHLING, P. C., and THOM, R., 1985b, Corrigin, W.A. Sheet SI 50-3: Western Australia Geological Survey, 1:250 000 Geological Series.

MULCAHY, M. J., 1959, Topographic relationships of laterite near York, Western Australia: Royal Society of Western Australia, Journal v. 42, p. 44–48.

MULCAHY, M. J., 1960, Laterites and lateritic soils in southwestern Australia: Journal of Soil Science, v. 11, p. 206–225.

MULACAHY, M. J., and HINGSTON, F. J., 1961, The development and distribution of the soils of the York–Quairading area Western

Australia in relation to landscape evolution: CSIRO, Soils Publication 17.

MYERS, J. S., 1990, Pinjarra Orogen *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 265–273.

MYERS, J. S., WILLIAMS, I. R., WALKER, I. W., WILLIAMS, S. J., HOCKING, R. M., and van de GRAAFF, W. J. E., 1997, Byro, W.A. Sheet SG 50-10: Western Australia Geological Survey, 1:250 000 Geological Series.

NEWSOME, D., 2000, Origin of sandplains in Western Australia; a review of the debate and some recent findings: Australian Journal of Earth Sciences, v. 47, p. 695–706.

O'DRISCOLL, M., 1996, Minerals of Vietnam, sands' future black and white: Industrial Minerals, no. 350, p. 72–93.

O'DRISCOLL, M., 1997, Fused silica, switched on by electronics: Industrial Minerals, no. 355, p. 49–59.

OMEN PTY LTD, 1988, Avon Valley silica project; Status report for Tangram Pty Ltd: Western Australia Geological Survey, Statutory mineral exploration report, Item 4730 A25969 (unpublished).

PARKER, T., 1992, Moora quartzite mine, M70/191, diamond drilling programme, December 1991: Simcoa Operations Pty Ltd (unpublished).

PARKER, T., 1999, Alternative quartz exploration southwest of Western Australia, results of reconnaissance phase: Simcoa Operations Pty Ltd (unpublished).

PELL, S. D., CHIVAS, A. R., and WILLIAMS, I. S., 1999, Great Victoria Desert; development and sand provenance: Australian Journal of Earth Sciences, no. 46, p. 289–299.

PLAYFORD, P. E., COCKBAIN, A. E., and LOW, G. H., 1976, Geology of the Perth Basin: Western Australia Geological Survey, Bulletin 124, 310p.

PLAYFORD, P. E., and LOW, G. H., 1972, Definitions of some new and revised rock units in the Perth Basin: Western Australia Geological Survey, Annual Report for 1971, p. 44–46.

PRIDER, R. T., 1966, The lateritized surface of Western Australia: Australian Journal of Science, v. 28, p. 443–451.

ROCLA QUARRY PRODUCTS, 1994, Prospecting results and conclusions, Prospecting Licence No. 70/1145, report prepared for Rocla Quarry Products: Western Australia Geological Survey, Statutory mineral exploration report, Item 8612 A40824 (unpublished).

RONK, A., 1986, Quartz resource P70/525, South West Mineral Field, Western Australia: Western Australia Geological Survey, Statutory mineral exploration report, Item 7438 A41605 (unpublished).

SALLER, M., 1999, Tales from the sandmen; A review of Europe's glass sand supply: Industrial Minerals, no. 381, p. 25–33.

SANDERS, A. J., FAULKNER, J. A., COKER, J., and MORRIS, P. A., 1998, Geochemical mapping of the Glenburgh 1:250 000 sheet: Western Australia Geological Survey, 1:250 000 Regolith Geochemistry Series Explanatory Notes, 33p.

SANDERS, A. J., and McGUINNESS, S. A., 2000, Geochemical mapping of the Ajana 1:250 000 map sheet: Western Australia Geological Survey, 1:250 000 Regolith Geochemistry Series Explanatory Notes, 55p.

SHACKLETON, I., 1993, Bi-Annual report for period 8 July 1991 to July 1993, Mining Licence 70/118; Mukinbudin feldspar project, Western Australia, Bencubbin SH 50-11, 1:250 000 Sheet: Commercial Minerals Ltd.

SIRCOMBE, K. N., and FREEMAN, M. J., 1999, Provenance of detrital zircons on the Western Australia coastline — implications for the geologic history of the Perth basin and denudation of the Yilgarn Craton: Geology, v. 27, no. 10, p. 879–882.

SORENSEN, E., and BUONAIUTO, F., 1991, Surrender Report, Stage two exploration, Exploration Licence 70/479, Gnangara Pine Plantation for silica sand: Western Australia Geological Survey, Statutory mineral exploration report, Item 6912 A39001 (unpublished).

SPRATT, D. M., LEUPEN, R. A., and BIBBY, P. A., 1989, Silicon manufacture in Western Australia using local raw materials: The AusIMM Annual Conference, Perth–Kalgoorlie, Western Australia, May 1989.

THOM, R., and CHIN, R. J., 1984, Bremer Bay, W.A. Sheet SI 50-12: Western Australia Geological Survey, 1:250 000 Geological Series.

THOM, R., and LIPPLE, S. L., 1974, Ravensthorpe, W.A. Sheet SI 51-5: Western Australia Geological Survey, 1:250 000 Geological Series.

THYNNE, D. S., 1991, Bi-Annual report for M70/118 Mukinbudin for period 8/7/89 to 7/7/91: Commercial Minerals Ltd.

TT SAND PTY LTD, 1994, Mining Lease 70/793, report on operations, July 1993 to June 1994, Mindijup silica sand project: TT Sand Pty Ltd.

van de GRAAFF, W. J. E., DENMAN, P. D., HOCKING, R. M., and BAXTER, J. L., 1980, Yanrey–Ningaloo, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 24p.

van de GRAAFF, W. J. E., HOCKING, R. M., and BUTCHER, B. P., 1983, Yaringa, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 23p.

WESTERN MINING CORPORATION, 1973, Mount Hunt Mineral Claim, annual tenement report, 1971–1973: Western Australia Geological Survey, Statutory mineral exploration report, Item 2187 A3083 (unpublished).

WESTERN MINING CORPORATION LIMITED, 1986, Progress report on White Flag Lake Quartz deposit; Mining Lease 16/12: Western Australia Geological Survey, Statutory mineral exploration report, Item 6480 A37135 (unpublished).

WESTERN MINING CORPORATION LIMITED, 1988, Annual technical report; Quartz Flux Lease M 16/12: Western Australia Geological Survey, Statutory mineral exploration report, Item 5590 A24519 (unpublished).

WESTERN MINING CORPORATION LIMITED, 1989, Final technical report; Project 7687; Quartz Flux Lease M 16/12: Western Australia Geological Survey, Statutory mineral exploration report, Item 5590 A24519 (unpublished).

WESTERN MINING CORPORATION, 1997, Annual report, 1/9/96 to 6/9/97, Mt Burgess, Mining Lease 15/125: Western Mining Corporation Ltd.

WESTERN SILICATES PTY LTD, 1992, Report on operations on Prospecting Licences 70/648–651: Western Australia Geological Survey, Statutory mineral exploration report, Item 9790 A38075 (unpublished).

WILDE, S. A., 1980, The Jimperding Metamorphic Belt in the Toodyay area and the Balingup Metamorphic Belt and associated granitic rocks of the southwestern Yilgarn Block: Geological Society of Australia (Western Australia Division); 2nd International Archaean Symposium, Perth, Western Australia, 1980, Excursion Guide.

WILDE, S. A., and LOW, G. H., 1978, Perth, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes.

WILDE, S. A., and PIDGEON, R. T., 1986, Geology and geochronology of the Saddleback Greenstone Belt in the Archaean Yilgarn Block, southwestern Australia: Australian Journal of Earth Science, v. 33, p. 491–501.

WILDE, S. A., and WALKER, I. W., 1982, Collie, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes.

WILDE, S. A., and WALKER, I. W., 1984a, Pemberton–Irwin Inlet, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes.

WILDE, S. A., and WALKER, I. W., 1984b, Pemberton–Irwin Inlet, W.A. Sheet SI 50-10 and part Sheet SI 50-14: Western Australia Geological Survey, 1:250 000 Geological Series.

WILKINSON, D. 1990, A major new frontier in the West; Project Profile; Kemerton: Metals Gazette, v. 1, no. 20, p. 15–18.

WILLIAMS, S. J., WILLIAMS, I. R., CHIN, R. J., MUHLING, P. C., and HOCKING, R. M., 1983b, Mount Phillips, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes.

WILLIAMS, S. J., WILLIAMS, I. R., and HOCKING, R. M., 1983a, Glenburgh, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes.

WORLD HEALTH ORGANIZATION, 1997, Silica, some silicates, coal dust and para-aramid fibrils: IARC (International Agency for Research on Cancer) Working Group on the evaluation of carcinogenic risks to humans, World Health Organization, Geneva, Monograph 0250–9555, v. 68, 506p.

ZDUNCZYK, M. J., and LINKOUS, M. A., 1994, Industrial sand and sandstone, *in* Industrial Minerals and Rocks (6th edition) *edited by* D. D. CARR (Senior Editor): Littleton, Colorado, Society for Mining, Metallurgy, and Exploration, Inc., p. 879–891.

Appendix 1

Localities of silica deposits and occurrences referred to in text

Locality	*GSWA sample no.*	*Latitude (°S)*	*Longitude (°E)*	*Type of silica raw material*
Alexander Bay	164564	33°50'10"	122°44'29"	Silica sand
Andrew Bore	–	24°42'32"	116°22'55"	Pegmatite
Avon Valley	–	31°39'27"	116°10'54"	Quartz vein
Bilocupping	164588	30°39'01"	118°16'43"	Quartz vein
Bilocupping	164589	30°38'22"	118°13'45"	Quartz vein
Bon Accord Road	164549	34°56'05"	117°56'45"	Silica sand
Bonnie Rock	164591	30°33'53"	118°19'39"	Quartz vein
Bonnie Rock	–	30°36'38"	118°24'57"	Quartz vein
Boyanup	164515	33°26'34"	115°42'53"	Silica sand
Brunswick Junction	164510	33°12'14"	115°46'25"	Silica sand
Burekup	164512	33°20'56"	115°49'16"	Silica sand
Calcaling	–	30°55'01"	118°25'50"	Pegmatite
Canning Vale	–	32°04'51"	115°53'45"	Silica sand
Caves Road	164531	33°50'15"	115°02'06"	Silica sand
Collie (Williams Road)	164516	33°21'02"	116°12'08"	Silica sand
Condingup	164566	33°39'55"	122°32'45"	Silica sand
Condingup	164565	33°40'35"	122°36'10"	Silica sand
Condingup	164568	33°37'14"	122°24'51"	Silica sand
Condingup	164567	33°40'40"	122°28'56"	Silica sand
Coolgardie	164592	30°59'00"	120°57'43"	Silica sand
Cowaramup	164534	33°48'33"	115°07'10"	Silica sand
Crystal Brook	164555	34°44'59"	117°34'36"	Silica sand
Crystal Brook	–	34°45'37"	117°36'45"	Silica sand
Cubbine Hills	164575	31°53'01"	117°21'33"	Quartzite
Dalyup	164560	33°41'44"	121°29'54"	Silica sand
Dangin	164576	32°00'23"	117°18'37"	Quartzite
Dardanup	164513	33°24'50"	115°44'29"	Silica sand
Dardanup	164514	33°25'22"	115°43'49"	Silica sand
Donnybrook	164525	33°34'45"	115°51'09"	Silica sand
Donnybrook	164526	33°34'39"	115°52'16"	Silica sand
Dunn Rock Road	164563	33°52'26"	122°19'32"	Silica sand
Gnangara (Rocla)	117896–117900	31°47'08"	115°56'31"	Silica sand
Goomalling (Berring East Road)	164584	31°15'38"	116°58'46"	Silica sand
Goomalling (Ucarty Road)	164583	31°21'09"	116°55'59"	Silica sand
Goongarrie	145205	29°55'11"	121°07'26"	Silica sand
Grass Valley	164581	31°39'10"	116°50'39"	Quartzite
Grass Valley (Clydesdale Road)	164582	31°37'50"	116°51'27"	Silica sand
Harvey	164501–164502	33°03'32"	115°47'51"	Silica sand
Harvey	164503	33°03'14"	115°48'40"	Silica sand
Harvey	164504	33°05'45"	115°48'09"	Silica sand
Harvey	164505	33°05'23"	115°54'34"	Silica sand
Jandakot (Readymix)	117891–117895	32°07'26"	115°52'36"	Silica sand
Karloning	164586–164587	30°38'43"	118°06'27"	Pegmatite
Karratha (Location A)	145217	20°47'39"	116°52'03"	Quartz vein
Karratha (Location A)	145218	20°47'42"	116°52'01"	Quartz vein
Karratha (Location A)	145219	20°47'45"	116°52'00"	Quartz vein
Karratha (Location A)	145220	20°47'33"	116°52'12"	Quartz vein
Karratha (Location B)	145221	20°45'46"	116°57'39"	Quartz vein
Karratha (Location C)	145222	20°45'19"	116°59'59"	Quartz vein
Karratha (Location D)	145223	20°45'32"	117°06'32"	Quartz vein
Karratha (Location E)	145224	20°47'59"	116°49'16"	Quartz vein
Karratha (Location E)	145225	20°47'54"	116°49'22"	Quartz vein
Karratha (Mount Regal)	–	20°49'08"	116°45'50"	Chert
Kauring	164577	31°56'26"	117°03'01"	Quartzite
Kemerton	164506–164509	33°07'50"	115°47'09"	Silica sand
Kronkup	164551	35°02'23"	117°37'04"	Silica sand
Lake Culcurdoo	162524	27°23'12"	114°10'58"	Silica sand
Lake Don	164540–164541	34°42'05"	117°40'26"	Silica sand
Lake Don	164542	34°43'04"	117°39'53"	Silica sand
Lake Don	164543	34°43'15"	117°40'58"	Silica sand
Lake Lefroy	145201	31°07'31"	121°51'23"	Silica sand
Lake Lefroy	145202	31°23'47"	121°36'55"	Silica sand
Lake Lefroy	145203	31°30'04"	121°39'47"	Silica sand
Lake Seabrook	–	30°52'21"	119°35'26"	Quartz vein

Appendix 1 (continued)

Locality	*GSWA sample no.*	*Latitude (°S)*	*Longitude (°E)*	*Type of silica raw material*
Mandogalup	–	32°12'13"	115°52'15"	Silica sand
Manypeaks	164556	34°50'00"	118°11'21"	Silica sand
Manypeaks	164557	34°49'42"	118°11'33"	Silica sand
Marbellup Hill	–	33°54'45"	122°06'44"	Silica sand
Marbelup	164550	34°59'10"	117°43'04"	Silica sand
Margaret River	164529–164530	33°57'54"	115°02'53"	Silica sand
McLeod Creek	164536	34°07'38"	115°06'48"	Silica sand
Merivale	164561	33°49'34"	122°06'16"	Silica sand
Merivale	164562	33°50'10"	122°12'12"	Silica sand
Mindijup (AustSand)	164544–164548	34°46'09"	118°04'14"	Silica sand
Moora	145227–145237	30°31'02"	116°02'06"	Chert
Mount Burges	164597	30°48'39"	121°00'45"	Silica sand
Mount Burges	164596	30°48'23"	121°01'26"	Silica sand
Mount Curious	162171	27°24'09"	114°21'22"	Silica sand
Muja Powerhouse Road	164522	33°24'28"	116°11'33"	Silica sand
Muja Powerhouse Road	164520	33°26'23"	116°17'32"	Silica sand
Muja Powerhouse Road	164521	33°25'35"	116°15'39"	Silica sand
Mukinbudin	164585	30°53'32"	118°08'32"	Pegmatite
Nanutarra	145226	22°35'56"	115°26'56"	Quartz vein
Narrikup	164554	34°46'37"	117°42'05"	Silica sand
Noggerup	164523	33°32'51"	116°12'58"	Silica sand
Powlalup	164528	33°50'47"	115°51'11"	Quartzite
Pusey Road	164532	33°46'25"	115°03'36"	Silica sand
Quairading	164573	32°04'32"	117°29'01"	Quartzite
Queen Victoria Rock	164600	31°17'04"	120°48'37"	Silica sand
Queen Victoria Rock	164598	31°12'16"	120°56'30"	Silica sand
Queen Victoria Rock	164599	31°17'10"	120°52'52"	Silica sand
Red Hill Gully	164537	34°00'22"	116°15'31"	Quartz vein
Redmond West Road	164553	34°54'45"	117°34'17"	Silica sand
Redmond West Road	164552	34°54'55"	117°29'40"	Silica sand
Shaw River	145206–145207	20°48'37"	119°29'31"	Chert
Shaw River	145208	20°48'57"	119°29'38"	Chert
Shaw River	145209	20°49'01"	119°29'45"	Chert
Shaw River	145210	20°49'19"	119°31'02"	Chert
Shotts (2 km east)	164519	33°23'19"	116°18'07"	Silica sand
Shotts (3.5 km west-northwest)	164518	33°22'51"	116°14'48"	Silica sand
Shotts (Stockton Lake)	164517	33°23'04"	116°13'36"	Silica sand
Smith Dam	–	30°55'34"	121°24'22"	Silica sand
Snake Soak	–	30°35'19"	118°01'00"	Pegmatite
Stewart Siding	164593	30°54'51"	120°48'35"	Silica sand
Stewart Siding	164594	30°52'55"	120°45'49"	Silica sand
Stewart Siding	164595	30°51'16"	120°43'33"	Silica sand
Stokes Inlet	164559	33°49'06"	121°09'03"	Silica sand
Tonebridge	164538	34°15'02"	116°42'11"	Silica sand
Toodyay (Sandplain Road)	164580	31°36'18"	116°26'45"	Silica sand
Unicup Road	164539	34°22'05"	116°46'18"	Silica sand
Wabling Hill	–	31°23'55"	115°45'32"	Silica sand
Wellstead	164558	34°29'03"	118°37'02"	Silica sand
Whim Creek	145211	20°55'48"	117°51'29"	Quartzite
Whim Creek	145212	20°55'46"	117°51'37"	Quartzite
Whim Creek	145213	20°55'46"	117°51'40"	Quartzite
Whim Creek	145214	20°55'41"	117°51'48"	Quartzite
Whim Creek	145215	20°55'40"	117°52'06"	Quartzite
Whim Creek	145216	20°55'46"	117°51'16"	Quartzite
White Flag Lake	–	30°39'21"	121°14'13"	Quartz vein
White Hill	–	26°44'00"	116°22'56"	Quartz vein
Wialki	164590	30°28'18"	118°07'40"	Quartz vein
Widgiemooltha	145203	31°30'23"	121°43'42"	Silica sand
Winning	–	23°08'14"	114°31'52"	Windalia radiolarite
Wolyamup Hill	164571	33°31'46"	117°53'37"	Quartzite
Woodanilling	164572	33°34'54"	117°22'26"	Quartz vein
Yabberup	164524	33°32'19"	115°58'30"	Silica sand
Yarloop	164511	32°57'42"	115°55'06"	Silica sand
Yellowdine	–	31°11'00"	119°41'00"	Quartz vein
Yelverton Road	164533	33°44'17"	115°09'41"	Silica sand
York (Mount Hardy)	164578	31°53'25"	116°52'14"	Quartzite

Appendix 2

Sample locations in Perth Metropolitan Area (Gozzard, 1987a,b)

Sample no.	Number in Gozzard (1987a,b)	Latitude (°S)	Longitude (°E)	1:50 000 sheet	Locality
1	(2034)4NE 51	31°32'09"	115°41'56"	YANCHEP	Yanchep National Park
2	(2034)4NE 49	31°32'53"	115°38'23"	YANCHEP	Yanchep Beach Road
3	(2034)4SE 39	31°42'00"	115°42'37"	YANCHEP	Waukolop Hill
4	(2034)4SE 40	31°42'36"	115°42'37"	YANCHEP	Waukolop Hill
5	(2034)4SE 38	31°43'10"	115°42'55"	YANCHEP	Burns Beach
6	(2034)4SE 41	31°43'41"	115°44'38"	YANCHEP	Burns Beach
7	(2034)4SE 37	31°41'28"	115°44'38"	YANCHEP	Neerabup National Park
8	(2034)1SW 24	31°41'00"	115°45'29"	MUCHEA	Wanneroo Road
9	(2034)1SW 25	31°43'08"	115°47'46"	MUCHEA	Clarkson Avenue
10	(2034)1SE 5	31°40'26"	115°57'29"	MUCHEA	Bullsbrook
11	(2134)4SW 1	31°43'52"	116°02'11"	MUCHEA	Walyunga
12	(2034)2NE 6	31°45'16"	115°56'38"	PERTH	Gnangara Road
13	(2034)2NW 37	31°45'20"	115°51'43"	PERTH	Lake Gnangara
14	(2034)2NW 21	31°45'36"	115°51'08"	PERTH	Rossi Street
15	(2034)2NW 16	31°46'33"	115°50'46"	PERTH	Badgerup Road
16	(2034)2NW 33	31°47'59"	115°46'19"	PERTH	Whitford Avenue
17	(2034)2NW 32	31°48'11"	115°46'57"	PERTH	Whitford Avenue
18	(2034)2NW 31	31°48'17"	115°47'37"	PERTH	Whitford Avenue
19	(2034)2NW 26	31°47'32"	115°47'49"	PERTH	Woodvale Avenue
20	(2034)2NW 25	31°48'22"	115°48'10"	PERTH	Whitford Avenue
21	(2034)2NW 30	31°48'14"	115°49'00"	PERTH	Hocking Road
22	(2034)2NW 29	31°48'16"	115°49'30"	PERTH	Gnangara Road
23	(2034)2NW 28	31°48'13"	115°50'05"	PERTH	Gnangara Road
24	(2034)2NW 22	31°47'42"	115°50'03"	PERTH	Franklin Road
25	(2034)2NW 41	31°48'02"	115°50'36"	PERTH	Gnangara Road
26	(2034)2NW 20	31°47'50"	115°50'32"	PERTH	Gnangara Road
27	(2034)2NW 17	31°48'38"	115°50'37"	PERTH	Kingsway
28	(2034)2NW 18	31°48'28"	115°50'56"	PERTH	Kingsway
29	(2034)2NW 40	31°47'57"	115°51'28"	PERTH	Gnangara Road
30	(2034)2NW 27	31°47'53"	115°52'10"	PERTH	Gnangara Road
31	(2034)2NW 19	31°47'43"	115°52'29"	PERTH	Uganda Road
32	(2034)2NW 34	31°47'27"	115°52'29"	PERTH	Lake Gnangara
33	(2034)2NE 23	31°47'50"	115°53'01"	PERTH	Gnangara Road
34	(2034)2NE 22	31°47'50"	115°53'44"	PERTH	Gnangara Road
35	(2034)2NE 21	31°47'51"	115°54'15"	PERTH	Gnangara Road
36	(2034)2NE 20	31°47'53"	115°54'51"	PERTH	Gnangara Road
37	(2034)2NE 19	31°47'53"	115°55'35"	PERTH	Gnangara Road
38	(2034)2NE 18	31°47'52"	115°56'19"	PERTH	Gnangara Road
39	(2034)2NE 17	31°47'54"	115°57'04"	PERTH	Gnangara Road
40	(2034)2NE 16	31°47'51"	115°57'32"	PERTH	Gnangara Road
41	(2034)2NE 8	31°48'55"	115°57'30"	PERTH	Park Street, Henley Brook
42	(2034)2NE 1	31°48'38"	115°56'25"	PERTH	Gnangara Road
43	(2034)2NE 15	31°47'54"	115°57'59"	PERTH	Gnangara Road
44	(2034)2NE 6	31°47'33"	115°58'26"	PERTH	Gnangara Road, Henley Brook
45	(2034)2NE 5	31°48'06"	115°58'32"	PERTH	Gnangara Road, Henley Brook
46	(2034)2NE 14	31°47'53"	115°59'10"	PERTH	Gnangara Road
47	(2134)3NW 8	31°47'28"	116°00'58"	PERTH	Burgess Crescent, Upper Swan
48	(2034)2NW 7	31°48'57"	115°58'50"	PERTH	Park Street, Henley Brook
49	(2034)2NE 11	31°49'34"	115°58'29"	PERTH	Woolcott Avenue, Henley Brook
50	(2034)2NE 9 & 10	31°49'39"	115°58'11"	PERTH	Woolcott Avenue, Henley Brook
51	(2034)2NE 13	31°49'50"	115°57'54"	PERTH	Woolcott Avenue, Henley Brook
52	(2034)2NE 12	31°50'02"	115°57'39"	PERTH	Woolcott Avenue, Henley Brook
53	(2034)2NE 4	31°51'01"	115°55'23"	PERTH	Beechboro Road. Ballajura
54	(2034)2NE 35 & 36	31°52'04"	115°55'05"	PERTH	North Beechboro
55	(2034)2NE 2	31°52'12"	115°54'46"	PERTH	Della Road, Beechboro
56	(2034)2NE 30	31°51'41"	115°53'12"	PERTH	Marshall Road, Malaga
57	(2034)2NE 28	31°51'58"	115°53'04"	PERTH	Victoria Road, Beechboro
58	(2034)2NE 27	31°51'18"	115°52'50"	PERTH	Marshall Road, Beechboro
59	(2034)2NW 15	31°51'59"	115°52'36"	PERTH	Victoria Road, Yirrigan
60	(2034)2NW 36	31°51'41"	115°52'03"	PERTH	Marshall Road, Malaga
61	(2034)2NW 35	31°51'01"	115°52'21"	PERTH	Harrow Street. Koondoola
62	(2034)2NW 23	31°52'23"	115°49'27"	PERTH	Stubbs Street, Balcatta
63	(2034)2NE 3	31°51'53"	115°56'22"	PERTH	James Street, Beechboro

Appendix 2 (continued)

Sample no.	*Number in Gozzard (1987a,b)*	*Latitude (°S)*	*Longitude (°E)*	*1:50 000 sheet*	*Locality*
64	(2034)2NE 29	31°52'26"	115°56'35"	Perth	Widgee Road, Beechboro
65	(2034)2NE 37	31°52'23"	115°57'29"	Perth	Widgee Road, Beechboro
66	(2134)3NW 3	31°51'08"	116°02'12"	Perth	Dunelg Road, Middle Swan
67	(2034)2SE 5	31°53'37"	115°58'13"	Perth	West Swan Road Guildford Road
68	(2034)2SE 2	31°54'28"	115°55'15"	Perth	King Street, Bayswater
69	(2034)2SE 9	31°56'49"	115°58'32"	Perth	Zante Road Newburn
70	(2034)2SE 10	31°57'05"	115°58'05"	Perth	Grogan Road Newburn
71	(2034)2SE 3	31°58'12"	115°58'17"	Perth	Victoria Street. Newburn
72	(2034)2SE 4	31°57'27"	115°59'35"	Perth	Wittenoom Road High Wycombe
73	(2134)3SW 5	31°57'31"	116°00'38"	Perth	Brand Road, High Wycombe
74	(2034)2SW 5	31°55'43"	115°48'48"	Perth	Herdsman Lake
75	(2034)2SW 6	31°55'59"	115°47'54"	Perth	Herdsman Lake
76	(2034)2SW 7	31°57'32"	115°47'05"	Perth	Brockway Road
77	(2033)1NE 8	32°00'52"	115°54'51"	Armadale	Armstrong Road, Wilson
78	(2133)4NW 4	32°01'23"	116°00'46"	Armadale	White Road, Orange Grove
79	(2133)4NW 2	32°01'38"	116°01'01"	Armadale	White Road, Orange Grove
80	(2133)4NW 1	32°01'39"	116°00'38"	Armadale	Kelvin Road, Orange Grove
81	(2133)4NW 3	32°01'32"	115°59'58"	Armadale	Clifford Road, Orange Grove
82	(2033)1NE 9	32°03'12"	115°54'13"	Armadale	Nicol Road, Willetton
83	(2033)1NE 4	32°03'58"	115°54'03"	Armadale	Bannister Road, Canning Vale
84	(2033)1NE 1	32°03'56"	115°56'32"	Armadale	Amhurst Road, Canning Vale
85	(2133)4NW 6	32°03'48"	116°01'15"	Armadale	Rushton Road, Gosnells
86	(2133)4NW 5	32°06'02"	116°01'06"	Armadale	Gosnells Avenue, Kelmscott
87	(2033)1NE 18	32°06'04"	115°55'16"	Armadale	Ranford Road, Jandakot
88	(2033)1NE 7	32°05'19"	115°53'52"	Armadale	Jandakot Airfield
89	(2033)1NE 10	32°05'16"	115°53'37"	Armadale	Johnson Road, Jandakot
90	(2033)1NE 3	32°04'52"	115°52'42"	Armadale	Melville Glades
91	(2033)1NE 6	32°05'58"	115°53'37"	Armadale	Acort Road, Jandakot
92	(2033)1NE 2	32°07'09"	115°54'35"	Armadale	Warton Road, Banjup
93	(2033)1SE 7	32°07'42"	115°53'53"	Armadale	Mason Road, Banjup
94	(2033)1SE 6	32°07'44"	115°54'21"	Armadale	Mason Road, Banjup
95	(2033)1SE 8	32°08'00"	115°54'08"	Armadale	Mason Road, Banjup
96	(2033)1SE 9	32°08'08"	115°53'01"	Armadale	Forrest Road, Jandakot
97	(2033)1SE 14	32°08'28"	115°53'56"	Armadale	Forrest Road, Forrestdale
98	(2033)1SE 13	32°08'56"	115°55'22"	Armadale	Forrest Road, Forrestdale
99	(2033)1SE 12	32°09'34"	115°58'36"	Armadale	Forrest Road, Armadale
100	(2033)1SE 15	32°11'31"	115°52'45"	Armadale	Bodeman Road
101	(2033)1SE 10	32°12'26"	115°53'34"	Armadale	Thomas Road
102	(2033)1SE 11	32°14'22"	115°54'36"	Armadale	Orton Road, Byford
103	(2033)1SE 16	32°14'29"	115°59'29"	Armadale	Stock Road
104	(2033)2NE 5	32°15'18"	115°58'22"	Serpentine	Hopkinson Road
105	(2033)2NE 1	32°15'41"	115°58'22"	Serpentine	Hopkinson Road
106	(2033)2NE 2	32°16'48"	115°57'55"	Serpentine	Hopkinson Road
107	(2033)2NE 27	32°15'46"	115°55'07"	Serpentine	Boomerang Road
108	(2033)2NE 26	32°15'29"	115°53'25"	Serpentine	Banksia Road
109	(2033)2NE 7	32°20'00"	115°55'46"	Serpentine	Lowlands Road
110	(2033)2NE 4	32°15'12"	115°59'12"	Serpentine	Soldiers Road
111	(2033)2NE 6	32°16'34"	115°59'19"	Serpentine	Soldiers Road
112	(2033)2SE 1	32°22'56"	115°52'51"	Serpentine	Yangeti Road
113	(2033)2SE 2	32°23'06"	115°58'38"	Serpentine	Hall Road
114	(2033)2NE 3	32°15'35"	115°59'06"	Serpentine	Soldiers Road

Appendix 3

Index of silica localities in Western Australia