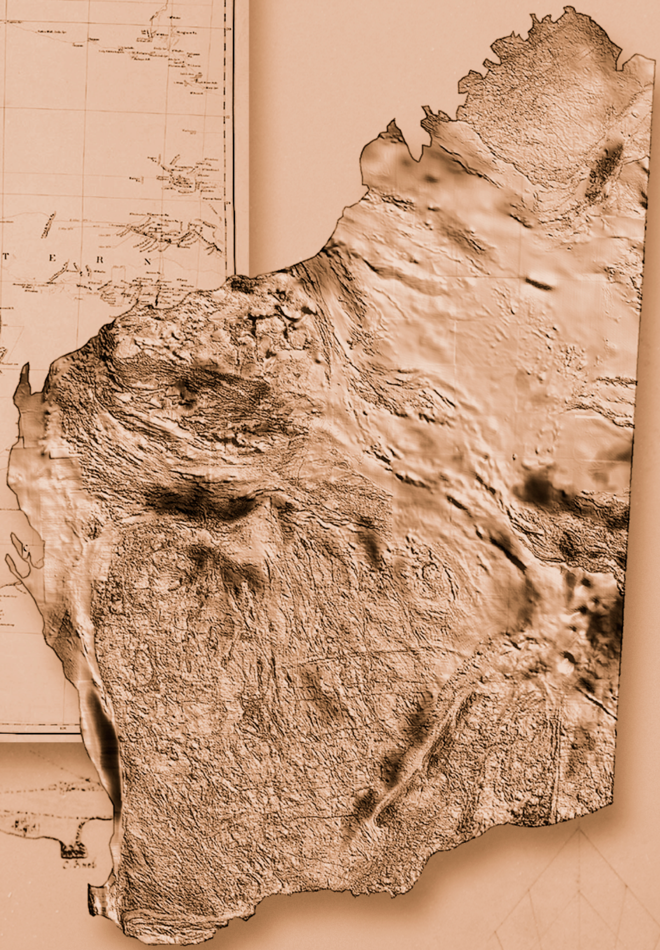
RECORD
2000/18

GOVERNMENT OF
WESTERN AUSTRALIA

REGOLITH–LANDFORM RESOURCES OF THE COWARAMUP–MENTELLE 1:50 000 SHEET

by J. R. Marnham, G. J. Hall, and R. L. Langford



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

Record 2000/18

REGOLITH–LANDFORM RESOURCES OF THE COWARAMUP–MENTELLE 1:50 000 SHEET

by
J. R. Marnham, G. J. Hall, and R. L. Langford

Perth 2000

MINISTER FOR MINES
The Hon. Norman Moore, MLC

DIRECTOR GENERAL
L. C. Ranford

DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
Tim Griffin

REFERENCE
The recommended reference for this publication is:
MARNHAM, J. R., HALL, G. J., and LANGFORD, R. L., 2000, Regolith–landform resources of the Cowaramup–Mentelle 1:50 000 sheet: Western Australia Geological Survey, Record 2000/18, 55p.

National Library of Australia Card Number and ISBN 0 7307 5661 0

Grid references in this publication refer to the Geocentric Datum of Australia 1994 (GDA94)

Printed by Quality Press, Perth, Western Australia

Copies available from:
Information Centre
Department of Minerals and Energy
100 Plain Street
EAST PERTH, WESTERN AUSTRALIA 6004
Telephone: (08) 9222 3459 Facsimile: (08) 9222 3444
www.dme.wa.gov.au

Contents

Appendices

Figures

Tables

Map

Regolith–landform resources of the COWARAMUP–MENTELLE 1:50 000 sheet

by

J. R. Marnham, G. J. Hall, and R. L. Langford

Abstract

Regolith–landform mapping of the COWARAMUP–MENTELLE 1:50 000-scale map sheet, located about 280 km south of Perth, has defined seven land systems, and provided a subdivision of the seabed materials and morphology. The onshore systems are the Cowaramup, Treeton, Caves Road, Yelverton, Abba, Spearwood, and Quindalup Systems. These are defined on the basis of the dominant underlying parent materials that range in age from Proterozoic though Cretaceous to Holocene, and landforms that include a dissected plateau, erosional shelves, and dunes.

The Cowaramup System consists of low hills and rises of residual materials and colluvial deposits overlying weathered rocks of the Proterozoic Leeuwin Complex. In the Treeton System the land surface comprises low hills and rises formed in weathered Cretaceous strata. The Caves Road System is an eroded land surface of probable Eocene age made up of residual coastal or fluvial deposits over the Leeuwin Complex. The Yelverton System is composed of residual materials underlain by sediments of probable Eocene age, and by rocks of the Cretaceous Leederville Formation. The Abba System is low-lying, gently undulating plain underlain by a series of alluvial, shoreline and coastal dune deposits. The Spearwood System is equivalent to the Pleistocene Tamala Limestone, and consists of a series of deflated dunes and swales composed of quartz sand overlying calcarenite, with some organic sandy soils in hollows or depressions. The Quindalup System is equivalent to the Safety Bay Sand, and consists of Holocene parabolic dunes, swales, and blowouts. The Marine System includes rock ridges and flats, mostly of Leeuwin Complex, nearshore and shoreface sand, and marine channels.

Each system has been divided into mapping units based on vegetation, landform elements and patterns, and regolith characteristics. These units, combined with knowledge of the subsurface geology, have been used to provide information on landuse, mineral potential, currently active and geologically active processes, and natural hazards. The most significant hazard in the area is coastal erosion causing cliff collapse, and heavy rainfall can create a hazard through flooding in local river systems.

Large areas of COWARAMUP–MENTELLE have landuses that preclude or restrict mineral extraction, in particular those areas used for national parks, state forests, and viticulture. The mineral resource potential is mostly limited to gravel and sand for use in road building and construction. Some heavy mineral sand concentrations have been recorded in the coastal and inland fluvial deposits, but none is currently considered to be economic or viable. Coal seams are present in the east of the sheet, but they are both deep and disrupted by numerous faults, making them subeconomic to mine.

KEYWORDS: Cowaramup, Cape Mentelle, Gracetown, Margaret River, Vasse, geomorphology, mineral resources, industrial minerals, coal, regolith–landform, landuse, land systems, natural hazards, viticulture.

Introduction

The COWARAMUP–MENTELLE* regolith–landform resources map will be of value in landuse planning, in the sustainable development of mineral resources, and in identifying natural hazards, both onshore and in shallow marine areas. This map will be of use to Government departments and agencies, local government and public utilities, the resource, construction, agricultural, and tourism industries, and the general public.

The map provides information on the regolith (engineering soils) and underlying rocks, on the landforms (landscape), topography and infrastructure, and on the mineral resources of COWARAMUP–MENTELLE. Land systems

* Capitalized names refer to standard map sheets

Figure 1. Location of COWARAMUP–MENTELLE in Western Australia

are defined as areas with recurring patterns of landform, regolith, and vegetation. Within each system there are discrete landform elements or materials. These regolith–landform units are related to geological and hydrogeological units, and can be used for identifying landuse and mineral resources potential.

The accompanying CD-ROM contains the data used to compile the map and report, the files necessary for viewing the data in a Geographical Information System (GIS) environment, and a self-loading version of the ArcExplorer™ software package.

Location

The COWARAMUP–MENTELLE 1:50 000-scale map sheet (1930 III and 1830 II) lies between latitudes 33°45' and 34°00'S, and longitudes 114°58' and 115°15'E (Fig. 1). The sheet lies in the South West Region of Western Australia, forming part of the Leeuwin–Naturaliste geographic region, a distinctive anvil-shaped promontory that lies at the southwesternmost tip of the Australian continent. This region is bounded to the north by Geographe Bay, to the west by the Indian Ocean, and to the south by the Southern Ocean, with state forest to the east. COWARAMUP–MENTELLE lies towards the north of this geographic region, and covers parts of both the Shire of Busselton and the Shire of Augusta–Margaret River.

The land area of the sheet is 667 km^2, and the offshore area is about 60 km^2. The population of the main town of Margaret River is around 3000, with about another 3000 inhabitants in the surrounding area. A gazetteer of named localities and features is given as Appendix 1. Perth, the capital city of Western Australia, lies about 280 km to the north.

Infrastructure

COWARAMUP–MENTELLE is accessed from Perth along the Old Coast Road through Mandurah and Bunbury, or inland along the South Western Highway through Armadale and Pinjarra, and then south from Bunbury via Busselton along the Bussell Highway. The Bussell Highway provides access to the townsites of Cowaramup and Margaret River (Fig. 2), and continues south to Augusta.

Caves Road runs parallel to the Leeuwin–Naturaliste Ridge, and two sealed roads off Caves Road provide access to Gracetown in the north (Cowaramup Road) and Prevelly (Wallcliffe Road) in the south. There is no rail

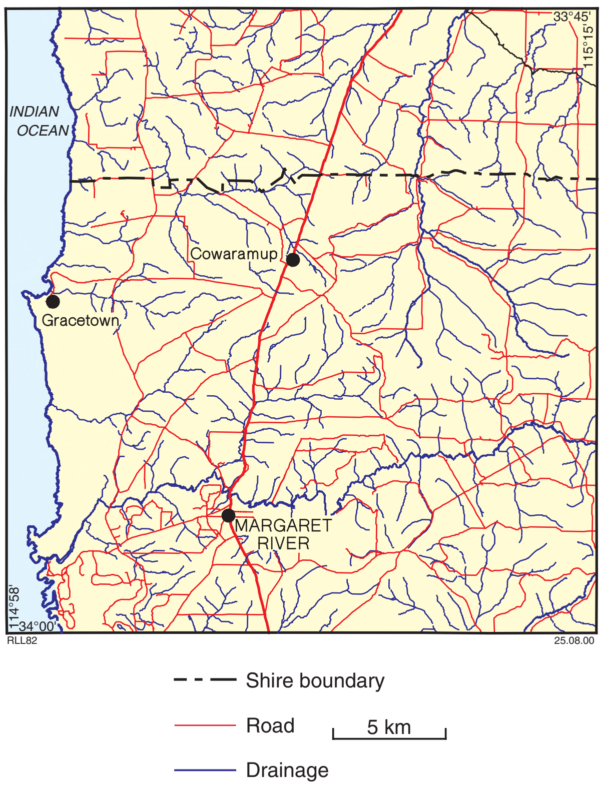


Figure 2. Infrastructure and drainage

link to the region, with the railway from Perth ending north of the area at Busselton. However, an abandoned railway line extends from Busselton to the town of Margaret River, and there are various railway reserves through some of the state forests. An airfield northeast of Margaret River townsite provides air services that link the region to Perth. Recreation reserves occupy large parts of the coastal belt, and state forest lies to the east.

There is an extensive network of sealed and unsealed roads serving the local farming community. For power supply the area forms part of the South West Interconnected System that serves the southwest corner of the State, with a high-voltage transmission line connecting to coal or heavy fuel-oil generating stations at Muja and Bunbury. Mobile telephone services cover much of the area, although the signal generally drops out close to the coast and in some valleys.

The area is supplied with potable water from the reservoir at Ten Mile Brook on a tributary of the Margaret River about 5 km east of Margaret River townsite. Water bores typically have low yields, and some water is stored in farm dams, particularly for use in the viticulture industry.

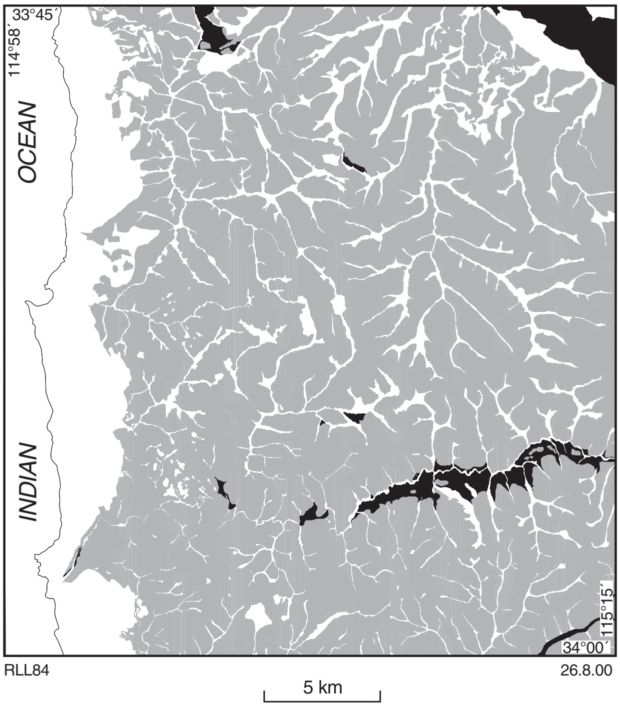


Figure 3. Land with high to very high capability for market gardening, vineyards and orchards. Most of the area shaded black (AbA_a, CoA_a, TrA_a) and some of the area shaded grey (*CoC*, *CoRf*, *TrC*, *TrRf*, *YvC*, *YvCq*, *YvRf*, YvR_pf, *YvRq*) (after Tille and Lantzke, 1990a)

Landuse

The Leeuwin–Naturaliste region was dominated by eucalypt forest when aboriginal people occupied the land. The first European settlers arrived in Augusta in 1830, and grazing, forestry, and fishing became important industries as land clearing advanced. The Group Settlement Scheme, which began in the 1920s, saw an increase in land clearing, and the expansion of the dairy industry. The first commercial vineyard was planted in 1967, and both vineyards and orchards have since become significant contributors to the local economy.

The dominant land uses in Cowaramup–Mentelle are viticulture, horticulture, grazing, forestry, low-density urban development, and recreation reserves. The area is a very popular tourist destination, with world-renowned surfing beaches, and many accessible caves. Urban development is centred on Margaret River townsite, with smaller settlements at Prevelly, Gracetown, and Cowaramup. The area between the Leeuwin–Naturaliste Ridge and the Bussell Highway is more intensely developed than coastal or inland areas.

Tille and Lantzke (1990a) provide a comprehensive study of the land capability of the Busselton–Margaret River–Augusta area, identifying those land system units related to hydrogeological and climatic factors that are most suitable for a range of primary industries. The correlation between the regolith–landform mapping units and agricultural potential is best demonstrated for horticultural land. Land with a high to very high capability for market gardening, vineyards, and orchards has been identified by Tille and Lantzke (1990a). Based on the criteria given by Tille and Lantzke (1990a), the area of high to very high capability for market gardening, vineyards, and orchards has been estimated to range from 19 to 510 km^2, depending on quality (Fig. 3).

Vegetation

The area lies in the Darling Botanical District (Southwest Forest Region) of the Southwest Botanical Province, and includes two botanical subdistricts. The relationships between vegetation and geology are summarized in Table 1 (Beard, 1990). The classification of vegetation used during mapping of Cowaramup–Mentelle is given in Appendix 2.

The Menzies Botanical Subdistrict (Southern Jarrah Forest Subregion), which covers most of Cowaramup–Mentelle, consists of jarrah on duricrust and loam soils, with marri–wandoo woodlands on drier laterite-free soils (Beard, 1990).

The Warren Botanical Subdistrict (Karri Forest Subregion) covers a strip along the coast that widens to the south and includes tall forests of karri on deep loams, with forests of jarrah–marri on leached sands (Beard, 1990). Paperbark and sedge swamps commonly grow in seasonally waterlogged valleys and drainage depressions (Beard, 1990). The coastal vegetation in the Leeuwin–Naturaliste National Park is mostly original, whereas most of the state forests are now regrowth.

Climate

The climate in the northern portion of Cowaramup–Mentelle is classified as Dry Mediterranean, character-

Table 1. Relationships between vegetation and geology (after Beard, 1990)

Vegetation type	*Dominant species*	*Height (m)*	*Geology*
Tall karri forest	Eucalyptus diversicolour	≤ 70	Deep reddish brown loam or sandy loam; well drained
Jarrah forest	*E. marginata*	10–30	Laterite
Jarrah–marri forest	*E. marginata–E. calophylla*	20–30	Leached sands; may be gravelly
Marri–wandoo woodland	*E. calophylla–E. wandoo*	10–30	Dry, laterite-free soils
Jarrah–banksia low woodland	*E. marginata–Banksia* spp.	≤ 10	On sand ridges in swamps
Paperbark low forest and thicket	*Melaleuca* spp.	≤ 10	Paperbark may cover or encircle swamps; some species cover flats of leached sand subject to seasonal flooding
Peppermint low woodland and scrub	*Agonis flexuosa*	≤ 10	Calcareous dune sand and understorey in karri forest
Acacia thicket	*Acacia* spp.	≤ 5	Coastal areas on calcareous dune sands
Coastal scrub heath and heath	*A. flexuosa, B. grandis, E. angulosa, Acacia* spp.	≤ 2	Dunes of calcareous sands or leached quartz sands
Jarrah low woodland	*E. marginata*	≤ 10	Poorly drained sands on watersheds

ized by mild wet winters and a warm to hot dry season of five to six months. To the south, the climate is Moderate Mediterranean, characterized by cool wet winters and a short dry season of three to four months (Beard, 1990).

Climatic averages* for temperature and rainfall are available for stations at Busselton (Table 2), Cape Naturaliste and Karridale, all of which lie outside COWARAMUP–MENTELLE. Rainfall ranges from 820 mm a year in the north, to 1190 mm a year in the south. January and February are the hottest months, with temperatures in the north reaching an average maximum of 28.5°C at Busselton, and 24.7°C to the south at Karridale. July is both the wettest and coldest month, with average temperatures reaching 16.1–16.3°C between the recording stations.

Previous investigations

The majority of geological publications covering COWARAMUP–MENTELLE are broad, regional studies. In the early 1900s, coal production in the Collie Coalfield prompted a geological reconnaissance survey of a portion of the South West Region in order to gain a better understanding of the extent of coal-bearing deposits. The area that was mapped and reported by Saint-Smith (1912) includes most of COWARAMUP–MENTELLE. The widespread blanket of residual material formed by weathering in situ of the underlying rock was noted, along with abundant limestone and gneissic granite outcropping along the coast.

More recently, several regional geological maps have been published that include COWARAMUP–MENTELLE. Lowry (1967) and Myers (1995) produced geological maps and explanatory notes of the BUSSELTON–AUGUSTA 1:250 000-scale sheet and the ALBANY 1:1 000 000-scale sheet respectively. Urban and Environmental Geology mapping extends only to the YALLINGUP 1:50 000-scale sheet to the north (Leonard, 1991). Playford et al. (1976) provided the regional framework for the stratigraphy of the Perth Basin, including the Leeuwin Complex. A study of the southern Perth Basin by Iasky (1993) used seismic, gravity, magnetic, and geothermal data to interpret the structures of the basin. Wilde and Murphy (1990) and Myers (1990a, 1994) undertook more specific geological research on the Leeuwin Complex.

The mineral resource potential of the ALBANY 1:1 000 000-scale sheet was assessed by Townsend (1994), and the subsurface coal resources were defined by Le Blanc Smith and Kristensen (1998). The Regional Forest Agreement was the impetus for the compilation of mineral occurrence data that allowed assessment of the mineral prospectivity of the South West Region; a report, 1:500 000-scale geological map, and digital dataset were

* Climatic data from Bureau of Meteorology website

Table 2. Annual monthly rainfall, rain days and temperature at Busselton, 1877–1996

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	***Total***
Rainfall, **mm**	10	11	21	42	118	174	167	116	74	52	25	13	**823**
Rain days	3	2	4	8	15	19	22	19	16	13	7	4	**132**
Max °C	28	28	26	23	19	17	16	18	20	24	26	22	**–**
Min °C	14	14	13	11	9	8	7	7	8	9	11	12	**–**

published (Hassan, 1998). Crostella and Backhouse (2000) assessed the results of petroleum exploration in the southern Perth Basin, and reviewed the stratigraphy.

A regional view of the plant life, including correlations with bedrock, soil, and landform, was provided by Beard (1990). The broad physiographic framework was defined by Bettenay (1983) and Jennings and Mabbutt (1986), and detailed descriptions were given by Playford et al. (1976), and Tille and Lantzke (1990a). The land capability and agricultural potential have been documented by Tille and Lantzke (1990a), who used the land systems methodology in their 1:50 000-scale soil and landscape maps.

Land systems methodology

Regolith–landform mapping in Cowaramup–Mentelle was completed between late 1998 and late 1999 using a mapping base of 1:10 000-scale 1 m resolution colour orthophotographs flown in 1996, combined with 5 m topographic contours. The offshore was mapped using the orthophotographs in shallow waters and enhanced Landsat TM imagery combined with 5 m resolution bathymetry in deeper water. The nearshore zone has not been bathymetrically surveyed in detail, and few of the contours are continuous. A total of 457 sites were documented in the area, at which 294 photographs and 128 soil or rock samples were taken. Hand augered soil samples accounted for 32 of the total samples collected.

The mapping system that was adopted relies on the principle of identifying soil catenas (Milne, 1935), which have also been described by Pain et al. (1994) as regolith toposequences. Pain et al. (1994) distinguished soil catenas from regolith toposequences on the basis of depth and complexity. This distinction is not applied in the regolith–landform mapping of Cowaramup–Mentelle, and regolith toposequences are seen as synonymous with regolith–landform systems.

Catenas are groups of soils or regolith types that are found together on the same parent material to form a land pattern. Mapping of regolith–landform units relies on the identification of catenas, and the resulting mapping units are therefore areas with a particular association of regolith materials, bedrock geology and landforms (Anand et al., 1993). The classification of landforms and slopes used for land surveys has been documented by McDonald et al. (1984). The terminology used for slopes is given in Appendix 3.

Land systems have been used in Cowaramup–Mentelle to define areas with recurring patterns of topography, soil and vegetation (Christian and Stewart, 1953). The system is hierarchical and divided into regions, provinces, zones, systems and subsystems. Cowaramup–Mentelle lies in the Western Region, which covers the western half of Western Australia (Bettenay, 1983; Tille and Lantzke, 1990a). The systems adopted by Tille and Lantzke (1990a) have been broadly applied and refined, with the emphasis on regolith material at depth, together with its relationship to the underlying bedrock in a specific landform context.

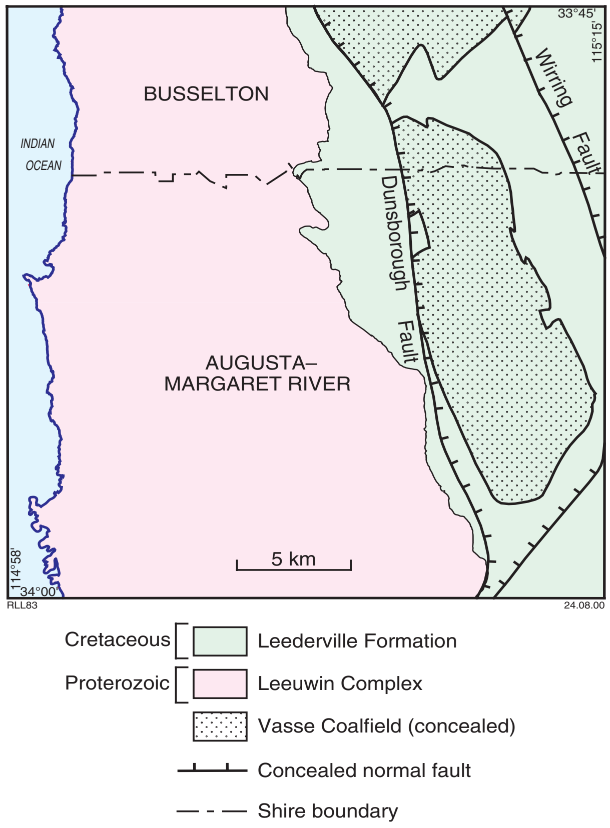


Figure 4. Interpreted onshore bedrock geology

The Leeuwin–Naturaliste region has been divided into five physiographic regions (Tille and Lantzke, 1990a): the Swan Coastal Plain in the north, the Blackwood Plateau to the east, the Margaret River Plateau and Leeuwin–Naturaliste coast to the west, and the Southern Coastal Plain. All these regions except the Southern Coastal Plain are represented on Cowaramup–Mentelle (Tille and Lantzke, 1990a, fig. 2), and form the basis of the division of the area into regolith–landform systems.

Geology and geomorphology

Proterozoic

The Leeuwin Complex (Fig. 4), exposed along the Leeuwin–Naturaliste coast and underlying the Margaret River Plateau west of the Dunsborough Fault, is a metamorphic complex within the Pinjarra Orogen (Myers, 1990b). The complex is exposed within the Cowaramup, Caves Road, and Quindalup Systems, and is probably the dominant lithology forming the offshore reefs and rock flats.

The ages of formation and subsequent deformation of the complex ranging from Mesoproterozoic to Neoproterozoic (1600–545 Ma*) are given by Compston and Ariens (1968), Fletcher et al. (1985), McCulloch (1987), Myers (1990a,b), Wilde and Murphy (1990), Fletcher and

* A list of abbreviations used in this report is given in Appendix 4

Libby (1993), Nelson (1996), and Tyler et al. (1998). Later peralkaline granite intrusion occurred around 535 Ma (Myers et al., 1996). The complex consists of intensely deformed plutonic igneous rocks, predominantly granite metamorphosed in granulite facies (Myers, 1990b) and amphibolite facies (Wilde and Murphy, 1990). Metamorphic grade increases progressively northward from amphibolite to granulite facies developed under low-pressure conditions (Wilde and Murphy, 1990).

The crystalline basement of the Perth Basin to the east of the Dunsborough Fault was formed and stabilized during an earlier phase of the Pinjarra Orogen than the Leeuwin Complex, between 2200 and 1100 Ma (Palaeoproterozoic to Mesoproterozoic) (Fletcher and Libby, 1993). Sm–Nd model ages are reported as 2018 and 2011 Ma from two discrete drillhole samples on the Vasse Shelf (Fletcher and Libby, 1993).

Palaeozoic

Palaeozoic strata do not outcrop on COWARAMUP–MENTELLE, and are restricted to the Permian Sue Group, which subcrops east of the Dunsborough Fault (Playford et al., 1976). The Sue Group conformably overlies the Stockton Group at depth, which in turn rests unconformably on Mesoproterozoic basement.

The Palaeozoic strata form part of a sequence in the Perth Basin that was deposited over the Pinjarra Orogen following rifting that started at about 420 Ma in the Silurian and continued intermittently until the Early Cretaceous at about 136 Ma (Myers, 1995; Hassan, 1998). The Sue and Stockton Groups relate to a phase of basin development within the southern part of the Perth Basin (Hassan, 1998).

Permian

The concealed Permian Sue and Stockton Groups contain coal-bearing strata (Vasse Coalfield) and lie unconformably below the Cretaceous Leederville Formation to the east of the concealed Dunsborough Fault, (Fig. 4; Le Blanc Smith and Kristensen, 1998). These coal-bearing strata were referred to by Playford et al. (1976) as a single unit, the Sue Coal Measures. The Permian is now divided into two groups comprising seven formations, summarized in Le Blanc Smith and Kristensen (1998) and Crostella and Backhouse (2000). The Permian strata are up to 4 km thick and dip west to northwest at 8–15° towards the Dunsborough Fault (Iasky, 1993; Le Blanc Smith and Kristensen, 1998; Crostella and Backhouse, 2000).

The Sue Group sits above the Stockton Group, and has been divided into six formations (Table 3) containing ten named coal seams: Wirring, Mowen, Chapman Hill, Osmington, Harmans, Fairfield, Lower and Upper Treeton, Jindong, and Anniebrook. Most of these seams form part of the Rosabrook Coal Measures; the Anniebrook seam forms part of the Redgate Coal Measures (Le Blanc Smith and Kristensen, 1998). Together, these seams form the Vasse Coalfield, in which the most extensive and thickest seam is the Osmington (see **Mineral resource potential**).

Mesozoic

The outcrop of Mesozoic strata on COWARAMUP–MENTELLE is restricted to the Cretaceous Leederville Formation, which overlies the Leeuwin Complex west of the Dunsborough Fault and Permian Sue Group strata east of the fault (Fig. 4; Playford et al., 1976).

The Mesozoic strata form part of a sequence in the Perth Basin that was deposited over the Pinjarra Orogen following rifting that started about 420 Ma in the Silurian and continued intermittently until the Early Cretaceous at about 136 Ma (Myers, 1995; Hassan, 1998). The Leederville Formation follows the final phase of rifting at the beginning of the Cretaceous (Hassan, 1998). In the deeper parts of the Vasse Shelf, the Leederville Formation unconformably overlies Jurassic strata, but on COWARAMUP–MENTELLE the Jurassic has not been recognized (Le Blanc Smith and Kristensen, 1998).

Cretaceous

The Leederville Formation is the only part of the Cretaceous sequence represented on COWARAMUP–MENTELLE, where it lies unconformably above Proterozoic and Permian rocks. Fairbridge (1953) introduced the name Leederville Formation for a Lower Cretaceous sandstone. Lowry (1967) noted an Early Cretaceous age for fluviatile sedimentary rocks found in wells 14 km east and northeast of Margaret River townsite (Edgell, 1963), and placed them in the Yarragadee Formation.

Playford et al. (1976) reviewed the Cretaceous stratigraphy of the Perth Basin, noting that on the Vasse Shelf the Leederville Formation rests unconformably on the Permian Sue Coal Measures. They also noted that stratigraphic relationships are indefinite between the various isolated natural exposures, of which the closest to COWARAMUP–MENTELLE is in the Blackwood River valley. Since the work of Playford et al. (1976) there has been no change to the assignation of these strata to the Leederville Formation. The most recent review of the stratigraphy of the Perth Basin is by Crostella and Backhouse (2000).

The Leederville Formation on the Vasse Shelf is an interbedded sequence of sandstone, siltstone, minor conglomerate, and thin seams of lignite of continental origin that is up to 300 m thick (Playford et al., 1976; Le Blanc Smith and Kristensen, 1998). Appleyard (1991) also recognized some distinctive glauconitic shales within the formation.

As well as unconformably covering the Permian, the formation also onlaps the Leeuwin Complex to the west of the concealed Dunsborough Fault (Fig. 4). There is only one exposure of the Leederville Formation noted on COWARAMUP–MENTELLE. This is in a road cutting on Bessell Road south of Rosa Brook Road (MGA 338080E

Table 3. Permian lithostratigraphy and coal seam names in the Vasse Coalfield (after Le Blanc Smith and Kristensen, 1998)

Group	*Formation*	*Seam names*
Sue Group	Willespie Formation	unnamed seamlets unnamed seamlets
	?hidden section	?hidden section
	Redgate Coal Measures	unnamed thin seamlets
		Anniebrook unnamed thin seamlets
	Ashbrook Sandstone	unnamed thin seamlets unnamed thin seamlets
	Rosabrook Coal Measures	unnamed thin seamlets
		Jindong Upper Treeton Lower Treeton Fairfield Harmans Osmington Chapman Hill Mowen Wirring
		unnamed thin seamlets
	Woodynook Sandstone	no seams
Stockton Group	Mosswood Formation	no seams
	(‘Cullens Diamictite’)	
	Proterozoic basement	

6242075N)*, where highly to completely weathered sandstone lies below weakly cemented colluvial gravel.

Cainozoic

The Cainozoic on Cowaramup–Mentelle includes both residual and transported materials. The transported deposits comprise colluvial (mass wasting), fluvial, eolian, coastal, and marine materials. The Cainozoic materials are spread over the entire sheet area, although they are mostly less than a few metres thick. They are thickest in the dunes of the coastal zone, where they reach a maximum thickness of 90 m.

The oldest materials are residual sands and duricrust gravels formed on a dissected plateau and adjacent shelves of weathered rock. These formed in situ through the weathering of the Proterozoic or Cretaceous bedrock, and this process may have started as early as the Middle to Late Eocene (49–34 Ma) (van de Graaff, 1983) when sea levels began to fall from highstands of up to 300 m above the present level.

The shelves of the Cave Road and Yelverton Systems range from 50 to 100 m AHD, and probably formed when the sea level was high during the Eocene. Southwestward downwarping on the Jarrahwood Axis has dropped the level of these features relative to areas to the north and east (Cope, 1972).

The morphology and distribution of duricrust on the plateau and shelves indicate that a dominant phase of duricrust formation post-dated features related to the presumed Eocene transgression. Hocking et al. (1987) suggested that, in the Carnarvon Basin, the important period of duricrust formation was mainly in the Oligocene (34–24 Ma), and it is proposed here that this was also the period when the duricrusts formed on the eroded and partially dissected plateau in the this region.

The last major transgression in the Miocene (24–5 Ma) created marine conditions over the area. The maximum age of the colluvial slopes is unknown, but they probably post-date this transgression. The dissection of the plateau forming the Treeton and Cowaramup Systems, producing the colluvial slopes and present-day drainage

* Locations mentioned in the text are referenced using Map Grid of Australia (MGA) coordinates, Zone 50. All locations are given to the nearest 5 m.

system, probably ranges in age from Pliocene to Early Pleistocene. The dissection appears to pre-date the deposition of eolian sands of Pleistocene (<1.8 Ma) age, because these locally overlie the slope deposits. The widespread preservation of mottling and induration of the colluvial slope deposits indicates that they have been weathered in situ, and that they may not have been significantly eroded since their formation.

The Pleistocene Tamala Limestone is confined to the Leeuwin–Naturaliste Ridge and some offshore reefs. Weathering of the formerly uniform calcareous dune sands of the Tamala Limestone has resulted in calcrete-capped calcarenite with an overlying residual quartz sand. The maximum thickness of these deflated dunes reaches about 90 m, although the overlying residual sand rarely exceeds 20 m in thickness.

The erosional channels that have developed in reefs and rock flats offshore from the mouth of the Margaret River and Wilyabrup Brook probably relate to a Pleistocene sea-level lowstand of around 30–40 000 years BP. The fluvial deposits in the Margaret River and Upper Chapman Brook formed after the deposition of the Pleistocene eolian sands, because the river valley that contains these deposits has also eroded the limestone near Prevelly to form cliffs. The younger fluvial deposits are probably Late Pleistocene to Holocene, as they have been incised by present-day river channels.

The youngest deposits in the region are eolian dunes and associated coastal deposits of the Safety Bay Sand. These are dominantly Holocene parabolic dunes, but they also include older, lithified dunes that have been subject to coastal erosion to form cliffs, such as those at Cape Mentelle and at Gracetown. There is no evidence of the known Holocene sea-level highstands on the steep slopes adjacent to the present-day beach. Dune and beach formation and erosion are both currently active.

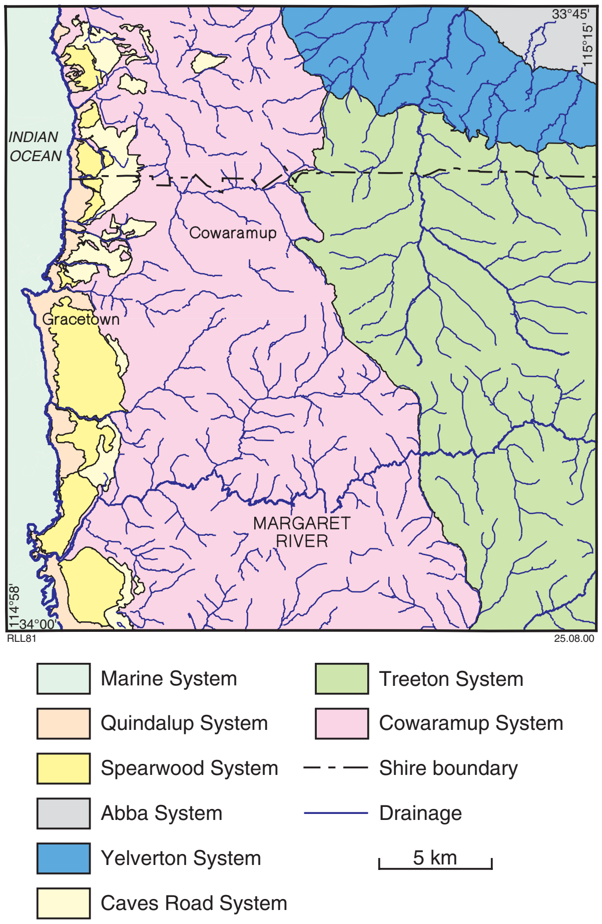


Figure 5. Distribution of land systems

Major geological structures

The major geological structure on COWARAMUP–MENTELLE is the Dunsborough Fault (Fig. 4). This fault lies east of the boundary between the Cowaramup and Treeton Systems, marking the concealed contact between Permian strata to the east and Proterozoic rocks to the west. The Wirring Fault lies on the eastern edge of COWARAMUP–MENTELLE, and has a small downthrow to the east. Crostella and Backhouse (2000) have interpreted a number of faults between the Dunsborough Fault and the Busselton Fault, including the Wirring Fault, with a combined downthrow to the east of less than a kilometre. The concealed Busselton Fault, which is located east of COWARAMUP–MENTELLE, marks the eastern edge of the Vasse Shelf and has a downthrow to the east in excess of 5 km.

Regolith–landform systems

COWARAMUP–MENTELLE has been divided into seven regolith–landform land systems, plus a marine system (Fig. 5). The land systems are based on those defined by Tille and Lantzke (1990a), with the emphasis on regolith material at depth, together with its relationship to the underlying bedrock in a specific landform context. There are several departures from the land systems employed by Tille and Lantzke (1990a), either with the same system being given a different name, or with systems combined to form larger units.

Cowaramup System (*Co*)

The Cowaramup System occupies 31 724 ha (44%) of COWARAMUP–MENTELLE (Fig. 6, Table 4) and consists of low hills and rises of residual materials and colluvial deposits overlying weathered rocks of the Leeuwin Complex. Hillcrests are commonly capped by colluvial gravel or duricrust, and outcrops of granulites of the Proterozoic Leeuwin Complex can also be seen throughout the Cowaramup System. The system is a source of gravel, which is used for road construction, and a minor source of quartz sand, which can be used for cement aggregate and landfill. There are numerous pits from which gravel has been removed, but only a few are currently operating.

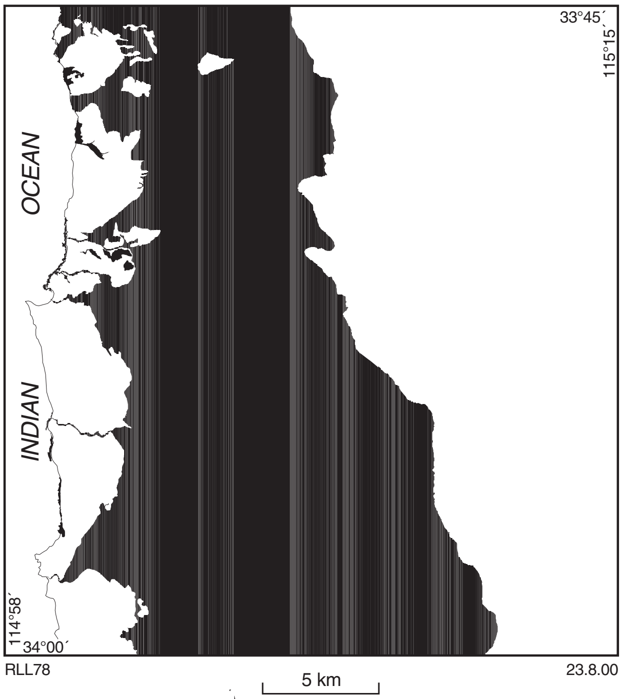


Figure 6. Distribution of Cowaramup System (*Co*)

Landform and distribution

The Cowaramup System, which is part of a much larger plateau, is characterized by low hills and rises with gently to moderately inclined slopes. These slopes become steep to precipitous and locally forming cliffs along waterways and near the coast. This system is the most extensive land system, forming a north–south corridor between the coastal Spearwood and Quindalup Systems to the west, and the Treeton System underlain by Cretaceous strata to the east.

In general, the elevation of the land system decreases towards the south. To the north, the plateau is incised around drainage depressions. However, broad, flat upland areas with very minor incision can be seen away from waterways (Fig. 7). Incision of waterways is preferentially along zones of mafic rocks.

The central part of the system, to the east of Gracetown, is cut by broad shallow depressions, and ranges in elevation from 90 m to 140 m AHD. This area is characterized by level to gently undulating rises, with some residual materials on hillcrests. The drainage depressions in this area are broad, with gently sloping sideslopes.

The southern part of the system is the most deeply incised around drainage depressions, in contrast to the central portion of the land system, which is only slightly incised. To the south, the land system is dominated by the Margaret River, which has deeply incised the plateau to form steep banks that become cliffed near the coast. Slopes are gentle to moderate, with low hills and rises capped by residual material.

Regolith and rock materials

The weathering and erosion in situ of the underlying Proterozoic Leeuwin Complex formed the regolith materials of the Cowaramup System. There are exposures of fresh to weathered, felsic to mafic granulite and granite, which become more common towards the coast. There are also minor outcrops of mafic granulite and anorthosite. Ferruginous duricrust (*CoRf*) is commonly exposed on hillcrests, and can be up to 2 m thick, and boulders of cemented duricrust are sometimes exposed on hillcrests. Residual bleached quartz sand (*CoRq*) derived from the weathering of the underlying ferruginous duricrust may also be developed on hillcrests.

Hillslopes are characterized by colluvial deposits of varying thicknesses (*CoC*). Colluvial materials are typically silty or gravelly sand overlying weathered bedrock. The thickness of the colluvium generally increases downslope. Mottling is a feature of most of the colluvial deposits, which indicates weathering in situ of the materials after deposition. Mottled clay, or completely weathered rock, lies below the colluvial materials. Road cuttings are usually the only sections to provide a view of the deeper parts of the regolith or weathered profile, and these exposures may show mottled clay with recognizable rock textures (highly to completely weathered rock) at depths of 2 m or more.

Swamps (CoA_w) are distributed sporadically within the Cowaramup System. These are waterlogged areas containing carbonaceous or peaty silty sand and commonly overlie a ferruginous hardpan. In places along the Margaret River, alluvial plains (CoA_a) of silty sand lie up to a few metres above the river channel. Alluvial channel deposits (CoA_c) consist of a range of materials from boulders to silty clayey sand, and fresh to slightly weathered bedrock is sometimes exposed.

Mineral resource potential

The Cowaramup System is a potential source of ferruginous pisolitic gravel, rammed earth, hard rock aggregate, and dimension stone. Numerous abandoned and operating gravel pits can be seen throughout the system, and gravel is generally extracted to the depth of the underlying mottled clay. The pisolitic gravel is used as aggregate for road construction. In places the gravel is concealed by residual quartz sand that, if thick enough, could potentially be a source of sand for landfill or construction purposes. Ferruginous pisolitic gravel is exposed on many hillcrests, where it may form a resistant feature above a slight break in slope.

Many of the gravel pits and reserves are within state forests. A number of gravel pits lie within state forest approximately 5 km north of Margaret River townsite, on each side of the Bussell Highway, and north of Tanah

Table 4. Components of the Cowaramup System

Regolith–landform unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Colluvium *CoC*/ЕmLE 18 642 ha (59%)	Colluvial Undivided slopes of low hills and rises; slopes are gentle to moderate, with some steep slopes; 20–160 m AHD Up to 1.5 m (thicker downslope) of gravelly sand grading downslope to silty sand over residual soil of mottled gravelly sandy clay (weathered Leeuwin Complex)	Northeast end of Burnside Road (MGA 318980E 6245095N) Two shallow pits excavated in a drainage ditch by the roadside to about 0.8 m total depth Colluvium over mottled soil; loamy gravel over sandy gravelly clay over sandy clay (weathered bedrock); yellowish brown 10YR 5/6gravelly and sandy silt; larger quartz clasts are subrounded and smooth (fluvial origin); duricrust nodules up to 1 cm also eroded and subrounded
Ferruginous duricrust *CoRf* 8 148 ha (26%)	Residual Hillcrests of low hills and rises; mostly gentle to moderate slopes; 60–160 m AHD Ferruginous duricrust overlying mottled soil (weathered Leeuwin Complex); may include small areas of relict leached quartz sand	State forest south of Rosa Brook Road (MGA 326015E 6238285N) Large gravel pit currently operating in up to 2 m of gravel; boulders are separated into waste piles; loose material is put through a screen to remove oversize (roots and cobbles) then by conveyor to a stockpile; veneer of gravel left on the site, being replanted at the southern end Cemented ferruginous duricrust and gravel
Drainage depression CoA_d 2 555 ha (8%)	Alluvial Drainage depressions; well drained narrow valleys with small stream channels to poorly drained broad swampy valleys; may be seasonally active; dominantly flat areas with level to moderate sideslopes; minor steep sideslopes; 0–160 m AHD Formed in weathered bedrock and slope deposits; generally silty clayey sand; alluvium is generally thin	Near Pusey Road, Wilyabrup (MGA 321260E 6261800N) Swampy drainage depression with 0.5 m alluvium over mottled alluvium or colluvium Pale yellow 2.5Y 7/4, mottled yellowish brown 10YR 5/8 and yellowish red 5YR 5/6, very silty clayey sand; slightly gravelly at 1.2 m depth; subrounded to rounded medium* quartz sand; fine sand opaque minerals <1%
Stream channel CoA_c 1 012 ha (3%)	Alluvial Stream channel; includes beds and banks; mostly level to moderate with rare steep and very steep slopes; 0–140 m AHD Sand, gravel and boulders, with some exposed bedrock; seasonally water filled	East of Caves Road; bridge over the Margaret River (MGA 316690E 6241640N) Stream channel incised into Leeuwin Complex Abundant boulders in the stream bed, plus exposures of banded felsic granulite
Proterozoic Leeuwin Complex ЕmLE 710 ha (2%)	Bedrock Stream beds, road cuttings and outcrops; covers 58% of system at shallow depth beneath *CoC*; also lies beneath *CoRf* and CoA_a; commonly exposed at the coast Fresh to completely weathered, undivided felsic granulite and gneiss; minor anorthosite	Near corner of Ellen Brook Road and Garstone Road (MGA 319945E 6249365N) Very large granitoid rock outcrop 40–50 m long and approx. 3–4 m high; another one of similar size on the other side of Ellen Brook Road Abundant, very coarse feldspar grains; contains some quartz; thin, discontinuous bands of biotite (about 2 mm wide), not present throughout the whole exposure; some linear alignment of the feldspar
Alluvial plain CoA_a 473 ha (1%)	Alluvial Plain; undulating surface, mostly level, poorly drained; 0–120 m AHD Thin alluvium (silty sandy clay); in places over weathered Leeuwin Complex (ЕmLE) at shallow depth	Near Pusey Road, Wilyabrup (MGA 321585E 6261920N) Flat, gently undulating alluvial plain; poorly drained Up to 1.5 m of slightly sandy clay over residual soil; pale yellow 2.5Y 8/2, mottled yellowish brown 10YR 5/8 and yellowish red 5YR 5/6; sandy fraction is subrounded to rounded medium quartz sand, with fine sand opaque minerals < 1%

Table 4. (continued)

Regolith–landform unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Swamp *CoA_w* 46 ha (<1%)	Alluvial Swamp; level to moderately sloping; 60–160 m AHD Overlies ferruginous hardpan	Adjacent to Bussell Highway, 4 km south of Margaret River townsite (MGA 323550E 6237650N) Closed depression with water dependent vegetation of low shrubs; seasonal, standing water at least 0.5 m deep
Quartz sand *CoRq* 9 ha (<1%)	Residual Low hills and rises; mostly moderate slopes; 90–100 m AHD Leached quartz sand	Northeast end of Burnside Road (MGA 318785E 6244730N) Auger in shallow hand dug pit to 1.2 m below surface Uniform residual sand over bedrock or duricrust; light grey 10YR 7/2, medium quartz sand; angular to subangular; glassy; minor iron oxide flecks

NOTES: * Grain-size ranges for regolith are given in Appendix 5

Marah Road (MGA 323000E 6247000N). These pits are operated intermittently to provide local shires with gravel for use as roadbase material. An active gravel pit lies within state forest to the south of Rosa Brook Road (MGA 326015E 6238285N). This large pit (Fig. 8) is operating in about 2 m of variably cemented duricrust. During excavation, large duricrust boulders are separated as waste, and the loose material is passed through a screen to remove oversize components, with the screened product stockpiled on site.

Active processes and hazards

The most significant currently active agent driving landform processes in the Cowaramup System is rainfall. Erosion is the dominant active process, which can have marked effects on cleared areas during heavy rains. Heavy rainfall often results in flooding in hollows in the Cowaramup System. Channel erosion can occur during the wet season, especially along drainage channels within cleared farmland. Wind can also have a minor erosional effect, and gravity may induce downslope movement of materials on steeper slopes, or those with loose materials.

Landuse, vegetation, and drainage

Common landuses in the Cowaramup System include grazing, viticulture and olive growing, conservation, recreation, and tourism. Grapevines are often planted on slopes where colluvium contains some gravel (Fig. 9). Natural vegetation has been cleared from a large portion of the system, and there are only small remnant pockets in the north. Vegetation is often retained along watercourses, where water-tolerant plants such as reeds and paperbark trees grow. Within farmland, the crests of hills capped with duricrust are commonly covered in natural vegetation of low to medium forests of jarrah and marri (Appendix 6). In the south, there is a large area of state forest to the north and east of Margaret River townsite.

The two major waterways in the Cowaramup System are the Margaret River in the south and Wilyabrup Brook in the north. Other smaller watercourses include Cowaramup Brook, which reaches the coast at Gracetown, Miamup Brook to its north and Ellen Brook to its south. In general, waterways drain to the west in the Cowaramup System. Near the coast the waterways are more deeply incised, forming steep banks, which are cliffed in places. Farther inland, banks are more gently sloping and channels are broader.

Relationships

The Cowaramup System forms part of a dissected plateau that is underlain by residual and colluvial materials of the Proterozoic Leeuwin Complex. To the east, the Leeuwin Complex is onlapped in places by the Leederville Formation, which lies beneath the Treeton System. In the north lie the shelf sediments of the Yelverton System, which were deposited during a former sea level high. To the west, the sands of the Caves Road and Spearwood Systems overlie the Leeuwin Complex.

Geological history

The Cowaramup System is underlain by Proterozoic (1600–545 Ma) rocks of the Leeuwin Complex that were strongly deformed and recrystallized in granulite or

RLL61 22.8.00

Figure 7. Landform, landuse and vegetation on a colluvial slope (*CoC*) of the Cowaramup System near Moses Rock (MGA 317215E 6262420N)

RLL62 22.8.00

Figure 8. Active gravel pit in ferruginous lateritic duricrust (*CoRf*) within state forest south of Rosa Brook Road (MGA 326015E 6238385N). The pit is operating in about 2 m of gravel

Figure 9. Landform and landuse of the Cowaramup System (*Co*). Colluvial slopes are planted with grapevines, while hillcrests capped with duricrust retain natural vegetation. South of Metricup Road, near Sandalford Winery. 1:25 000-scale orthophotograph with contours at 5 m

amphibolite facies (Wilde and Murphy, 1990; Myers, 1990b). These rocks have been weathered and eroded to form a dissected plateau. The Proterozoic bedrock is now overlain by colluvial and alluvial materials of Cainozoic age (65–1.6 Ma), as well as a weathered rock profile of mottled clays. The dissection of the plateau forming the Cowaramup System, producing the colluvial slopes and present-day drainage system, probably took place from Pliocene to Early Pleistocene.

Treeton System (*Tr*)

Land of the Treeton System occupies 21 300 ha (30%) of Cowaramup–Mentelle (Fig. 10, Table 5) and comprises low hills and rises formed in weathered Cretaceous strata. The narrow valley floors are underlain by fertile soils. Cemented pisolitic duricrust and duricrust gravels on the summits and upper slopes are a source of gravel for road building. At depth, the older Permian strata are a potential source of coal through underground mining.

Landform and distribution

The Treeton System is located in the eastern part of the sheet, and is the second most extensive land system after the Cowaramup System. The system is dominated by low hills and rises with very gently to moderately inclined slopes.

The northern part of the system has a lower relief than the southern part, and is cut by broad swampy depressions that drain to the north onto the shelf of the Yelverton System. This part of the system is an undulating, near level plateau, mostly over 120 m AHD, dominated by residual materials. Below the duricrust-dominated hillcrests, most valley slopes are less than a kilometre wide, and the colluvial slopes pass downslope into poorly drained or swampy depressions (Fig. 11). The main drainage depression, the northward-flowing Carbunup River, is typically about 100 m wide, with no floodplain development.

The topography is more deeply incised in the south, with the valleys of the Margaret River and Upper Chapman Brook draining westerly and southwesterly into the adjacent Cowaramup System. Compared with the northern part of the system, the plateau landform pattern is not dominant, and the residual materials on the hillcrests are less areally extensive. The height of this degraded plateau rarely exceeds 120 m AHD, and the steeper colluvial sideslopes extend down to narrow streams as low as 50 m AHD (Fig. 12). In contrast to the drainage in the incised plateau to the north, drainage lines in the south can have well-developed alluvial plains ranging in width from 200 m to over 1 km. These plains are incised by present-day stream channels, and are relicts of terrace deposits formed at times when the climate was significantly wetter.

Regolith and rock materials

The regolith materials are derived from weathering and erosion of the sedimentary rocks of the underlying Cretaceous Leederville Formation. The low hills are characterized by extensive sideslopes of colluvial materials (*TrC*) below broad hillcrests of cemented pisolitic

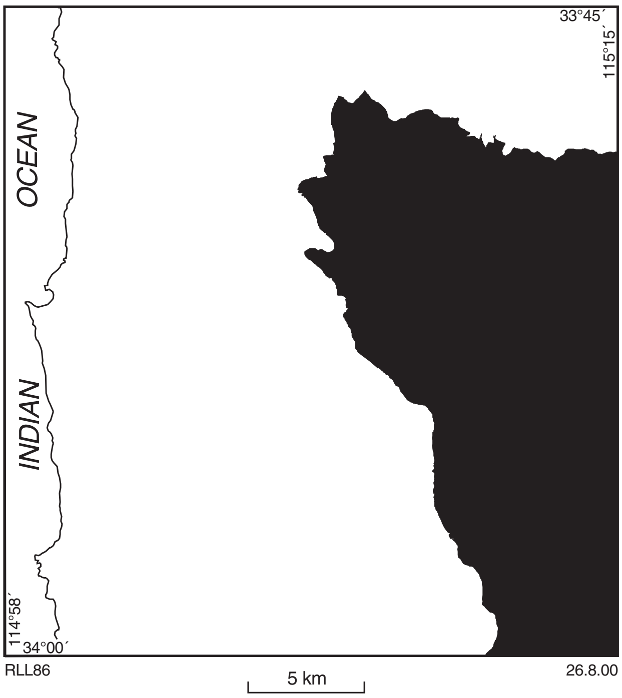


Figure 10. Distribution of Treeton System (*Tr*)

Table 5. Components of the Treeton System

Regolith–landform unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Colluvium *TrC* 10 500 ha (49%)	Colluvial Undivided slopes; mainly gentle slopes; 40–160 m AHD Silty or gravelly sand over mottled sandy clay; overlies Leederville Formation at shallow depths	Low Road (MGA 334770E 6239080N) Low hills with very gently inclined hillslope; profile below old road surface shows mottled soil (weathered bedrock), overlain by duricrust gravel, overlain by colluvial sand Duricrust forms an irregular surface 5–15 cm thick, passing up into lightly mottled colluvium about 30 cm thick; above is grey colluvial sand up to 0.8 m thick; downslope the colluvium is at least 1 m thick, with strongly mottled colluvium below red colluvium
Ferruginous duricrust *TrRf* 7 607 ha (36%)	Residual Hillcrests and upper slopes of low hills and rises; mostly gently sloping Ferruginous duricrust and gravel overlying mottled soil (weathered Leederville Formation)	State forest southeast of Bessell (MGA 338045E 6237290N) Duricrust exposures at the top of the hill; above a marked break in slope; boulders up to 0.8 m across and duricrust pavement exposed in the track Duricrust with reddish yellow 7.5YR 6/6 matrix and pale yellow 2.5YR 8/4 mottles; some clasts dark reddish brown 2.5YR 3/4; abundant subangular to subrounded smooth quartz grains up to 2 mm
Drainage depression TrA_d 1 790 ha (8%)	Alluvial Drainage depression; mainly level to moderate slopes; includes seasonally active channels; 40–140 m AHD Formed in weathered bedrock and slope deposits; silty sandy clay	Bessell Road south of Rosa Brook Road (MGA 338100E 6242520N) Narrow, alluvium filled valley; shallow auger hole to 0.4 m; waterlogged Strong brown 7.5YR 5/8, sandy silty clay
Alluvial plain TrA_a 658 ha (3%)	Alluvial Plain; mainly moderate slopes; 40–120 m AHD Silty sand	Jindong Treeton Road near the Margaret River (MGA 334350E 6244980N) Plain about 200 m wide between rises in ferruginous duricrust. Adjacent to narrow river channel
Drainage depression TrA_df 364 ha (2%)	Alluvial Drainage depression; slopes mainly level to moderate; 80–140 m AHD Overlies ferruginous hardpan	Kohlhagen Road, Vasse State Forest (MGA 337100E 6255285N) Seasonally dry stream bed formed in highly ferruginous, continuous hardpan Colours vary from dusky red 10R 3/2 to yellowish red 5YR 4/6; duricrust is composed predominantly of cemented ferruginous nodules that contain medium to fine, subangular to subrounded quartz; rarer clasts are composed of coarse sand to fine gravel of subrounded quartz
Stream channel TrA_c 306 ha (1%)	Alluvial Stream channel; includes stream beds and banks; slopes are level to moderate; 40–120 m AHD	Margaret River at Jindong Treeton Road (MGA 334240E 6245090N) Narrow stream channel about 40 m wide, with a bed about 20 m wide; permanent water and thickly vegetated banks; about 4 m depth below bridge
Swamp TrA_wf 55 ha (< 1%)	Alluvial Swamp; slopes mostly moderate; 80–140 m AHD Waterlogged, poorly drained depressions; overlies ferruginous hardpan	Swampy area east of Kohlhagen Road (MGA 337335E 6255120N) Shallow auger hole to 0.45 m in thin alluvium over ferruginous hardpan Yellowish brown 10YR 5/6, slightly silty sand

Table 5. (continued)

Regolith–landform unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Quartz sand *TrRq* 29 ha (<1%)	Residual Low hills and rises; slopes mostly gentle; 100–140 m AHD Bleached quartz sand overlying ferruginous duricrust	Bussel Highway opposite Taunton Farm (MGA 325965E 6257405N) Sandpit in 2–3 m thick residual sand White 10YR 8/1, gravelly, medium to coarse sand; subangular to subrounded quartz; medium gravel of subrounded to rounded quartz at a depth of 2.5–3 m; minor fine sand opaque minerals < 1%
Swamp *TrA_w* 1 ha (< 1%)	Alluvial Swamp; slopes are generally very gentle to moderate; around 65 m AHD Organic silty sand	Upper Chapman Brook (MGA 337730E 6238240N) Hollow with water-dependent vegetation on the lower slopes adjacent to the alluvial plain; probably associated with a spring
Cretaceous Leederville Formation Kll < 1 ha (< 1%)	Bedrock Subsurface; weathered; underlies *TrC* at shallow depths beneath 49% of the land system; rare, small outcrops Interbedded sandstones, siltstones, claystones, shales and conglomerates; quartz-rich	Bessell Road south of Rosa Brook Road (MGA 338080E 6242075N) Road cutting exposing up to 2 m of weathered sandstone below 0.6–0.8 m of weakly cemented duricrust gravel (colluvium); the hill to the east is covered in duricrust boulders; gravel pit to the northeast Yellow 10YR 7/8, mottled red 2.5YR 4/6; completely weathered to residual soil; ferruginous nodules in weathered profile; beds of coarse sandstone up to 10 cm; cm-scale bedded medium-grained sandstone dominant; well sorted subangular glassy quartz; bedding probably subhorizontal; possible cross-bedding in sandstone

duricrust and duricrust gravels (*TrRf*). There may be a slight break in slope below the residual duricrust on the hillcrest, but this is often poorly developed or absent. The hillslopes consist of colluvial materials that become progressively finer grained and increase in thickness downslope, ranging from gravelly sand to sand or silty sand. The colluvium may become mottled at depth, and it has formed over mottled residual soil that was derived from the weathering of the underlying sedimentary rocks.

Cemented pisolitic duricrust is sometimes exposed on the hillcrests, although it is more commonly covered by a veneer of residual quartz sand (*TrRq*) derived from the weathering of the underlying duricrust. Large boulders of cemented duricrust, up to 1 m across, can be seen amongst trees on many uncleared hillcrests. Piles of these boulders, produced as part of the land clearing process, can be seen at the edges of some paddocks.

Mass wasting deposits on the colluvial slopes range in thickness from 0.3 m to more than 1 m. The material on the proximal slopes may contain gravel from the hillcrest duricrust, and downslope the material grades to gravelly silty sand. Mottling is almost invariably present in the colluvium, indicating weathering in situ after deposition and making the transported deposits difficult to distinguish from the underlying residual soil. The presence of transported gravel in the colluvium is a distinguishing feature, and there is often a gravel layer at the colluvium–residual soil interface. The underlying weathered bedrock is mostly a residual soil composed of mottled sandy clay, and only very rarely is this deeply weathered rock identifiable as to silty sandstone (Kll), such as that seen in a recent road cutting on Bessell Road south of Rosa Brook Road (MGA 338080E 6242075N).

Mineral resource potential

The mineral resource potential of the Treeton System is for gravel, sand, rammed earth, coal, and heavy mineral sands. Only gravel is being extracted at present, with two viable, intermittently operating pits. There are a few small sandpits, none of which is currently operating. Coal and heavy mineral sand resources are described in detail in the section on mineral resources.

RLL92 25.8.00

Figure 11. Forested, gravelly hillcrest in the Treeton System (*Tr*) above colluvial slopes with poorly drained channels on the Carbunup River along Oldfield Road. 1:25 000-scale orthophotograph with contours at 5 m

There are a number of abandoned gravel pits scattered across the system. The largest operating gravel pit lies east of Bessell Road, on the eastern margin of the sheet (MGA 338200E 6242200N). The Shire of Augusta–Margaret River uses gravel from this pit for rebuilding unsealed roads in the vicinity. A second large, intermittently operating pit is located near the intersection of Gale Road and Carbunup Road South (MGA 330800E 6258800N), also within the Shire of Augusta–Margaret River.

Coal deposits (Vasse Coalfield) are known to lie at depth in Permian sedimentary rocks below the Cretaceous Leederville Formation that characterizes the Treeton System (Le Blanc Smith and Kristensen, 1998). Heavy mineral sands have been noted in the Upper Chapman Brook (Electrolytic Zinc Company of Australasia Ltd, 1971), probably derived from incised Cainozoic valley-fills.

Active processes and hazards

The Treeton System was formed by the weathering in situ and subsequent erosion of the underlying Cretaceous Leederville Formation. The processes of weathering, duricrust formation, and transport downslope are all now significantly less intensive than those which occurred during the main Pleistocene and pre-Pleistocene periods of landscape formation. Seasonal rainfall is now the only significant agent driving regolith–landform processes.

RLL63 22.8.00

Figure 12. Colluvial slope leading down to the Carbunup River, adjacent to Carbunup South Road (MGA 330430E 6258635N). Soil auger samples in the foreground comprise uniform, yellow 2.5Y 7/6, silty clayey medium sand

Small-scale erosion of soil can take place during heavy rainfall in those areas cleared of natural vegetation, and hill creep is evident in some places on the steeper slopes. Areas adjacent to fluvial channels and drainage depressions may become waterlogged during the winter, and the major channels show high flow rates during the winter wet season. Unstable slopes and localized flooding are the only natural hazards of note in the Treeton System.

Landuse, vegetation, and drainage

The Treeton System has been extensively cleared of natural vegetation for the principal landuses of grazing, viticulture, and orchards. The valley floors are often waterlogged, and contain swamp or water-tolerant vegetation (Fig. 13). There are areas of forest regrowth following timber extraction, and there are large areas of state forest that include both regrowth and remnant native forest. Small parts of the system are a source of gravel for road construction and sand for building.

In the north, the major drainage depressions are related to the northward-flowing Carbunup River, which passes through the Yelverton System into the alluvial plain of the Abba System. In the south, the valleys of the Margaret River and Upper Chapman Brook drain to the west and southwest into the adjacent Cowaramup System.

Relationships

The Treeton System forms part of a dissected plateau that includes the adjacent Cowaramup System. The Cretaceous strata underlying this system rest on top of the older Proterozoic metamorphic rocks that characterize the Cowaramup System. The same Cretaceous strata underlie the Yelverton System to the north, which is an erosional shelf backed by a palaeoshoreline at the edge of the Treeton System.

Geological history

The Treeton System is underlain by Cretaceous (146–65 Ma) sedimentary rocks that have been weathered and eroded to form a dissected plateau surface of Cainozoic age (65–1.6 Ma).

Some of the valley-fill deposits contain localized accumulations of heavy mineral sands. These deposits are not obviously colluvial or fluvial, and may relate to an Eocene sea-level highstand, at which time they would have been in part coastal, lagoonal or tidal. The maximum age of the colluvium is unknown, but probably post-dates the last major transgression in the Miocene (23–5 Ma). The mottling of these deposits indicates that they have been weathered in situ, and this is a process that is probably currently active. The alluvial plains in the valleys of the Margaret River and Upper Chapman Brook have been incised by Holocene channels, and formed after the last significant sea-level highstand in the Eocene.

RLL64 29.8.00

Figure 13. Swampy depression in a tributary of Upper Chapman Brook, near Rosa Glen Road (MGA 332980E 6236980N)

Caves Road System (*Cr*)

Land of the Caves Road System occupies 2130 ha (3%) of COWARAMUP–MENTELLE (Fig. 14, Table 6) and is an eroded land surface made up of residual eolian, coastal or fluvial deposits over the Leeuwin Complex. The thick podzolized sands of the system are composed almost entirely of quartz. They are commonly gravelly or coarse at the base, and are a possible source of aggregate for roadbase and landfill.

Landform and distribution

The Caves Road System is a level to gently inclined shelf ranging in height from 60 m AHD near the western coast to 100 m inland. The system can be found sporadically along the Leeuwin–Naturaliste Coast, generally west of Caves Road and east of the Spearwood System.

The surface of the system is gently undulating, with shallow hollows and rises; swamps and poorly drained depressions are also characteristic of the system.

In the northern area of the sheet, along Moses Rock and Matheson Roads, sandy residual materials form low rises over a gently undulating and locally flat surface of residual duricrust materials or Leeuwin Complex. Along Biljedup Beach and Cullen Roads, materials of the Caves Road System are thicker, with sands up to 5 m or more. These areas are more freely draining, but form swamps and poorly drained depressions in areas where materials of the underlying Leeuwin Complex are close to the surface.

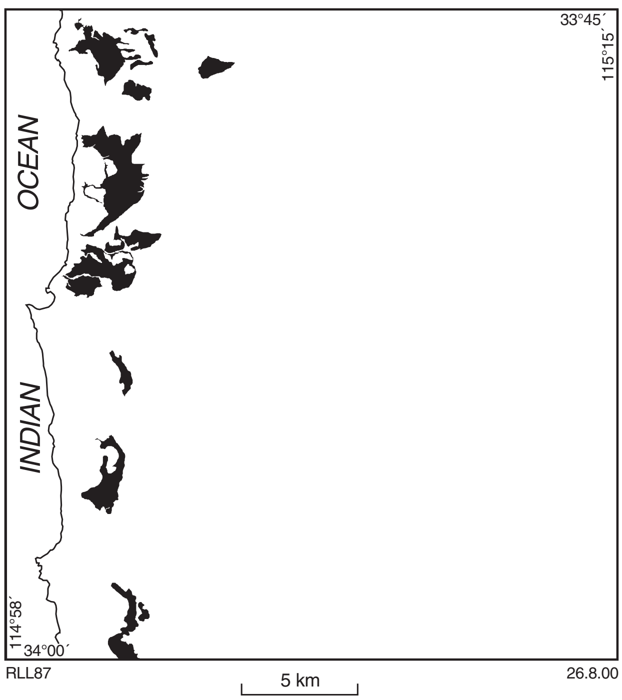


Figure 14. Distribution of the Caves Road System (*Cr*)

Regolith and rock materials

The dominant regolith material in the Caves Road System is residual leached quartz sand derived from Eocene sedimentary rocks (*CrRq*; Fig. 15). Grain size varies from fine gravel through to fine sand, with the most common fraction from medium to coarse sand. Grains are predominantly subrounded to rounded, probably indicating a sedimentary origin rather than a weathering product of the underlying Leeuwin Complex. McArthur (1991) attributed these sands to eolian processes. However, some areas of coarser sand are of alluvial or coastal origin.

The podzolized sand is underlain by a ferruginous duricrust (*CrRf*), which may be exposed at the surface in places where the sand has been eroded. The duricrust is characteristically gritty, with cemented coarse sand composed of rounded grains of quartz, as seen along Cullen Road (MGA 316960E 6257795N) and Moses Rock Road (MGA 316485E 6262495N).

Duricrust within the Caves Road System may also be derived from the Leeuwin Complex and form cemented pisolitic duricrust. The two different duricrusts may occur alongside each other and in close proximity to exposed Leeuwin Complex. In one location off Cullen Road (MGA 318025E 6256165N), there is a very thin remnant of the Caves Road duricrust, overlying Leeuwin Complex granulite, which contains traces of calcium carbonate material adhered to its surface. This indicates that the Caves Road material was deposited in a coastal environment, possibly beach or eolian.

On Matheson Road (MGA 316455E 6261880N) there is a thin deposit of a poorly indurated weathered sandstone (Czs) lying beneath a thin duricrust from which the overlying sand has been largely eroded. Mottling occurs beneath the duricrust and grades down to a white weathered sandy material, which at depth overlies Leeuwin Complex. The clasts are mostly coarse quartz and minor feldspar, with local gravel up to 15 cm across. The gravel and sand clasts are rounded, indicating abrasion through fluvial processes. The sandstone is likely to be part of a fluvial sequence that has been poorly preserved along the Leeuwin–Naturaliste Coast, and which is the protolith for much of the residual sand materials seen in the Caves Road System.

Mineral resource potential

The Caves Road System provides a source of sand, and has a potential for gravel and heavy mineral sand extraction. White sand, referred to as ‘grit’ by the Shire of Augusta–Margaret River, is used as aggregate for roadbase and landfill purposes. Deposits of this clean white sand can be more than 5 m thick, and it is extracted from a few small pits in the area (Fig. 15). The residual duricrusts of this system have a tendency to be cemented rather than forming loose pisoliths, reducing their potential as sources of gravel. However, there may be areas of locally pisolithic materials suitable as a source of gravel. Mid-East Minerals NL (1972) undertook drilling in the early 1970s and found some heavy mineral anomalies within the Caves Road System.

Table 6. Components of the Caves Road System

Regolith–landform unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Quartz sand *CrRq* 1 716 ha (81%)	Residual Hillcrests of rises and low hills or degraded dunes; mostly moderate slopes; 20–120 m AHD Original deposit emplaced either fluvially, or by beach or shallow marine processes; lateritized and eroded to form thick leached quartz sand over duricrust	Matheson Road off Caves Road (MGA 317655E 6261955N) Thick residual leached sand up to 5 m thick, over duricrust and granulite at depth Light grey 10YR 7/2, coarse to medium sand; subangular to subrounded quartz; minor fine sand opaque minerals Sand and duricrust commonly not related to underlying granulite; duricrust contains well rounded, coarse quartz sand
Ferruginous duricrust *CrRf* 153 ha (7%)	Residual Hillcrests of rises and low hills or degraded dunes; mostly gentle slopes; 65–105 m AHD Ferruginous duricrust with quartz sand of fluvial or coastal origin	Biljedup Beach Road (MGA 316965E 6257820N) Thick residual duricrust outcropping at surface; ferruginous cemented gritty quartz; rounded coarse quartz sand; some up to fine gravel
Swamp CrA_w 123 ha (6%)	Alluvial Swamp; mostly level to moderate slopes; 40–120 m AHD Waterlogged silty sand	Private land, Moses Rock Road (MGA 314995E 6262265N) Characterized by perennial swamp and includes small areas prone to intermittent inundation Underlain by silty sand over Leeuwin Complex; surrounding land supports pasture
Drainage depression CrA_d 88 ha (4%)	Alluvial Drainage depression; includes seasonally active channels; slopes are mostly level to moderate, with some steep slopes in places; 0–140 m AHD Silty clayey quartz sand	Cullen Road (MGA 316750E 6256240N) Small channel in alluvium over ferruginous hardpan, with seasonally stagnant water and strong flow after heavy rain; sedges in the channel area Yellowish red 5YR 4/6, grading to strong brown 7.5 YR 5/8, gravelly very silty clayey medium sand; subrounded to rounded quartz, stained with iron oxides; minor ferruginous gravel up to 1 cm
Proterozoic Leeuwin Complex ⱣmLE 44 ha (2%)	Bedrock Stream beds, road cuttings and outcrops; also lies at shallow depth below *CrRq* over 24% of the system Fresh to weathered, undivided felsic granulite and granite; minor mafic granulite and anorthosite	Matheson Road (MGA 317450E 6261930N) Rock outcrop; small rise on plain; poor exposure Anorthosite; black to grey rock speckled with weathered feldspar (white) and hornblende (black); minor quartz pyroxene and opaque minerals; medium to coarse grained; granoblastic; weak mineral lineation in amphiboles
Colluvium *CrC* 7 ha (< 1%)	Colluvial Undivided slopes; mostly gentle slopes; overlies Czs; 75–85 m AHD Silty sand over mottled soil	Matheson Road (MGA 316015E 6261955N) Colluvial slope planted in vines Gravelly silty sand overlying weathered Eocene deposits and Leeuwin Complex granulite
Weathered sandstone Czs (lies beneath *CrRq* and *CrC*)	Undivided coastal or fluvial Subsurface, with rare exposures; outcrops below the surface of 4% of the system	Matheson Road (MGA 316455E 6261880N) Roadcut drain; upper slope near the edge of a broad undulating plateau

Table 6. (continued)

Regolith–landform unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Weathered sandstone (cont.)	Quartz-rich, with minor clay	Grey 2.5Y 6/1, mottled reddish yellow 7.5YR 6/8 and yellow 2.5Y 7/6, slightly clayey coarse sand; rounded quartz; minor feldspar and clay; larger clasts of rounded to subrounded quartz up to 15 cm; no mafics; ferruginous nodules in upper 1 m; thin lateritized sedimentary deposit overlying Leeuwin Complex; overlain by residual sand

Active processes and hazards

Rainfall and wind drive the current regolith–landform processes in the Caves Road System. Vulnerability to water and wind erosion is a factor on cleared slopes near the coast (Fig. 16) where there are strong prevailing southwest winds. Flat areas often have poor drainage. If the upper sand is thick, water will infiltrate easily and the soil will generally be free draining. However, if the sand is thin, then the underlying duricrust or Leeuwin Complex rocks, with a comparatively low porosity, will prevent free drainage and seasonal waterlogging will occur. Small swamps form within the Caves Road System, notably along Moses Road near the coast, and also west of Daleep (Fig. 17).

Colluvial processes are of minor significance in the Caves Road System, since the dominant landforms are flat to gently sloping. These processes are only apparent on the sides of low hills within the system adjacent to deeply incised streams of the Cowaramup System.

Landuse, vegetation, and drainage

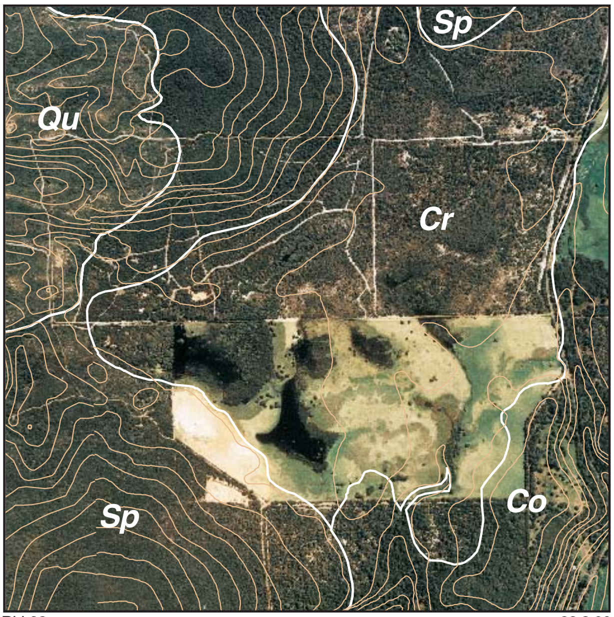
Only a minor proportion of the land of the Caves Road System has been cleared of vegetation. Landuses include conservation, grazing, sand and gravel extraction, forestry, and viticulture. The are no major watercourses in the Caves Road System, and all the narrow incised creeks, such as the Biljedup Brook, lie in materials of the adjacent Cowaramup System.

The Caves Road System is particularly subject to inundation in the winter months, and includes numerous

Figure 15. Small sand pit in leached sand (*CrRq*) of the Caves Road System, Wilyabrup Reserve (MGA 320355E 6261240N)

RLL66 29.8.00

Figure 16. Caves Road System is prone to erosion by water and wind on cleared slopes (MGA 315435E 6257885N)



RLL93 28.8.00

Figure 17. Caves Road System (*Cr*) near Daleep is characteristically flat, with swamps and poorly drained depressions. Between Spearwood System (*Sp*) and Cowaramup System (*Co*), with Quindalup System (*Qu*) to the west. Much of the natural vegetation of this system remains intact. 1:25 000-scale orthophotograph with contours at 5 m

swamps and poorly drained depressions. Although the dominant material is sand, the thickness of this sand can affect the drainage characteristics of the soil. Also, thick sand drains freely and provides a local aquifer where water has percolated downwards and collected over impervious rocks of the Leeuwin Complex or a thick duricrust horizon. A number of small springs, such as Forrest Spring, have developed in this way.

Relationships

The Caves Road System lies adjacent to the Cowaramup System, and extends along the Leeuwin–Naturaliste coast in remnant pockets immediately east of the Spearwood System. Materials underlying the Caves Road System are older than those of the Spearwood System.

Geological history

The Caves Road System is an eroded shelf lying on the edge of an older plateau formed over rocks of the Proterozoic (1600–545 Ma) Leeuwin Complex. Materials underlying the system were part of a coastal sequence deposited when sea levels were higher. The shelf of the Cave Road System ranges from 60 to 100 m AHD, predating the Pleistocene eolian deposits of the Spearwood System, and probably formed during an Eocene sea-level high. However, an exact age for the deposition of these materials is uncertain because the remnants are thin, highly leached, and poorly exposed.

The morphology and distribution of the duricrust on the plateau and shelf indicate a dominant phase of duricrust formation that post-dates the presumed Eocene erosion. The important period of duricrust formation is mostly during the Oligocene (34–24 Ma) (Hocking et al., 1987). Formation of the colluvial slopes and present-day drainage system within the Treeton and Cowaramup Systems probably occurred from the Pliocene to Early Pleistocene.

Yelverton System (*Yv*)

The Yelverton System occupies 5586 ha (8%) of COWARAMUP–MENTELLE (Fig. 18, Table 7) and is composed of residual materials underlain by sediments of probable Eocene age and Cretaceous rocks of the Leederville Formation. The system may be a resource of sand and gravel for construction purposes, and may also contain heavy mineral sand deposits.

Landform and distribution

The Yelverton System comprises coastal and fluvial materials deposited on an incised shelf, formed in weathered Leederville Formation. The shelf, which is in the northeast of the area, is around 6 km wide. The elevation of the shelf decreases northerly towards the coast from 90–60 m AHD. The shelf has been incised and predominantly forms rises and some low hills, with broad swampy drainage depressions (Fig. 19).

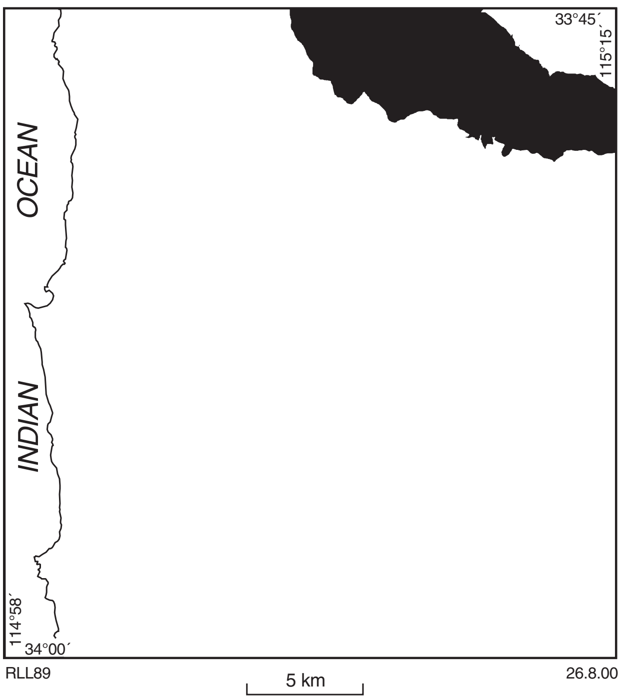


Figure 18. Distribution of the Yelverton System (*Yv*)

The northern and southern boundaries of the Yelverton System have an arcuate topographic expression. The northern boundary is known as the Whicher Scarp (Fairbridge, 1949; Lowry, 1967; Playford et al., 1976), and the southern boundary may correlate with the 'middle escarpment shoreline' of Welch (1964), although this was not extrapolated to COWARAMUP–MENTELLE. These features suggest that a major influence in shelf formation was marine erosion during a sea-level high. The sporadic presence of remnant coastal sediments confirms importance of marine processes, and these sediments are also known to extend to the northeast.

The Carbunup River is the main drainage feature within the system, and it is more deeply incised than other streams. Landforms adjacent to the river are low hills with moderately to very gently inclined hillslopes. Compared with hillcrests in the Treeton System to the south, those in the Yelverton System are less prominent because of the draping effect produced by the overlying leached sand. Streams are typically meandering, with distinct narrow channels that are incised into a duricrust surface. The presence of this lower duricrust surface indicates that watertable levels have been slightly higher than at present in the valley floors. This low duricrust feature protrudes into the northern area of the Treeton System for about 5 km.

Regolith and rock materials

The materials of this system have a complex history of Cainozoic deposition, erosion, and weathering related to fluctuation of eustatic sea levels and climates changes. Ferruginous duricrust and pisolitic gravel are common on hillcrests (Fig. 20), and may be extracted as a source of gravel. Sideslope colluvium overlies weathered Leederville Formation (mottled soil), and grades downslope from colluvial gravelly sand to sand or silty sand.

There are two distinct levels of duricrust, found either on hillcrests, or near the base of drainage depressions. Areas of thick quartz sand (*YvRq*) overlying the hillcrest duricrust are also common. This sand is the weathered residue of duricrusted younger deposits of probable Eocene age that may have been coastal or fluvial in origin, and which overlie the Leederville Formation. The sand is susceptible to colluvial processes and is found on sideslopes (*YvCq*). In some areas the sand has been completely eroded, leaving either an exposed flat duricrust surface (*YvR$_a$f*), or a low hillcrest capped by duricrust (*YvRf*) developed over thin coastal sediments or Leederville Formation.

Mineral resource potential

The Yelverton System is a potential source of ferruginous pisolitic gravel and, like the Treeton System to the south, is also underlain at depth by Permian coal-bearing strata. There are two large gravel extraction sites operated by the Shire of Busselton (Gibb Road, MGA 331920 6262410) and CALM (Yelverton Road, MGA 324255E 6263560N). Numerous smaller, abandoned and intermittently operating

Table 7. Components of the Yelverton System

Regolith–landform unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Ferruginous *YvRf* 1 633 ha (29%)	Residual Hillcrests of rises and low hills; slopes are level to moderate; 40–100 m AHD Up to 2 m of ferruginous duricrust and gravel overlying mottled soil (weathered Leederville Formation); may include areas of relict leached sand	Gravel reserve at the corner of Gibb Road and Payne Road (MGA 331920E 6262410N) Gravel pit in duricrust on broad, flat-crested, low hills and rises; duricrust is massive and forms an almost continuous sheet Colours are brownish yellow 10YR 6/8, with pale yellow 2.5Y 8/2 patches; small nodules, up to 1 cm, of red 10R 4/8 ferruginized wood; the rest of the duricrust contains abundant medium to coarse, rounded to subrounded quartz sand
Colluvium *YvC/*Kll 1 420 ha (26%)	Colluvial Undivided slopes of rises and low hills; mostly gentle to moderate slopes; 40–100 m AHD Silty or gravelly sand over mottled sandy clay (weathered Leederville Formation); colluvium usually gravelly in upper slope region grading to silty sand in lower slope region; overlies QpY in places	Near Gibb Road (MGA 332380E 6262615N) Shallow auger hole to 1.2 m in thin colluvium over weathered rock, on a track cut into the side of the hill, with a 0.5 m high section of colluvial gravelly sand Pale brown 10YR 6/3, mottled brownish yellow 10YR 6/6, slightly clayey gravelly medium sand; subangular to rounded quartz; minor ferruginous nodules up to 3 cm across at 0.4 m depth White 5YR 8/1, mottled light reddish brown 2.5YR 6/4, slightly sandy clay below colluvium
Drainage depression YvA_df 1 209 ha (22%)	Alluvial Drainage depression with small active channels; includes poorly drained shallow depressions with swampy floors; mostly level slopes, to moderate; 40–100 m AHD Channels often formed in ferruginous hardpan; alluvium generally clayey sand and thin	Near Payne Road (MGA 333440 6262845) Damsite excavation has uncovered duricrust at shallow depth above pallid clay (weathered Leederville Formation) On top of the duricrust is strong brown 7.5YR 5/8, gravelly sand with ferruginous nodules; clasts of duricrust and ferruginized charcoal Duricrust colours range from strong brown 7.5YR 5/8 to red 2.5YR 4/6; contains medium to coarse quartz sand, and some fine gravel; subangular to rounded Underlying duricrust is light greenish grey 7/10Y, sandy silty clay; possibly Yoganup Formation
Quartz sand *YvRq* 732 ha (13%)	Residual Mainly hillcrests of rises and low hills; mostly gentle to moderate slopes; 40–100 m AHD Podzolized profile of deeply leached quartz sand overlying ferruginous duricrust	End of Beckett Road (MGA 327500E 6263565N) Thick residual podzolized sand covers hillcrest and extends to upper slope areas Light grey 10YR 7/2 medium to fine quartz sand; subangular to subrounded; minor coarse quartz sand, and <1% fine sand opaque minerals
Alluvial plain YvR_pf 417 ha (7%)	Residual Plain; mostly level and moderate slopes; 60–100 m AHD Ferruginous duricrust	As for *YvRf* Flat area with continuous sheet of ferruginous hardpan at or close to the surface; not incised by streams
Swamp *YvAw* 134 ha (2%)	Alluvial Swamp; dominantly level, to moderate slopes; 40–100 m AHD	Beckett Road, off Bussell Highway (MGA 327800E 6263440N) Dam site in elevated swampy area with very dense tall shrubs and medium trees; excavation of a dam has uncovered

Table 7. (continued)

Regolith–landform unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Swamp (cont.)	Silty clayey sand over ferruginous duricrust	Leederville Formation at shallow depth beneath the organic quartz sand and ferruginous hardpan Sediments range from very carbonaceous dark grey to black clayey sand, to pinkish grey 7.5YR 6/2 slightly carbonaceous sandy clay, to quartz and feldspar-rich, poorly sorted gravels; abundant dark carbonaceous material; clasts are subangular to rounded and up to 6 cm; feldspars are white to dull grey; quartz is more angular than feldspars; minor fine sand opaque minerals
Quartz sand *YvCq* 37 ha (1%)	Colluvial Undivided slopes; mainly moderate slopes; 40–80 m AHD Bleached quartz sand	East of Bussell Highway (MGA 329780E 6263165N) Colluvial slope between sandy plateau and tributary of the Carbunup River Thick transported white sand
Cretaceous Leederville Formation Kll (lies at shallow depth beneath *YvC*)	Bedrock Subsurface; underlies 26% of the system Weathered, interbedded sandstones, siltstones, claystones, shales, and conglomerates; quartz-rich	Bussell Highway (MGA 328315E 6262670N) 1.5 m roadcut with 0.5 m of colluvial gravel over poorly developed duricrust over mottled soil; formed in Leederville Formation bedrock Gravelly, very sandy clay; contains abundant rounded clasts of vein quartz gravel; fine gravel up to 4 cm across
Yoganup Formation QpY (lies at shallow depth beneath *YvC*)	Coastal Subsurface; underlies < 1% of the system Sand, silt and clay; local heavy mineral enrichment	Jindong Treeton Road (334580E 6261835N) Colluvial materials from the Yelverton System have been transported off the edge of the system and overlie deposits of the Yoganup Formation on the border with the Abba System White sandy clay beds, with coarse sand to fine gravel; subangular to subrounded quartz; localized occurrences of heavy mineral-enriched beds; fine to medium sand opaques

gravel pits can be seen throughout the system. Gravel up to 1.5 m thick is generally extracted to the underlying mottled clay, and is used as aggregate for road construction. The gravel is commonly concealed by residual quartz sand that, if thick enough, could potentially be a source of sand for landfill or construction purposes. Ferruginous pisolitic gravel is exposed on many hillcrests, where it commonly forms a resistant feature above a slight break in slope.

This system may also have potential for heavy mineral sand extraction. In the early 1970s, Mid-East Minerals NL (1972) drilled RAB holes and intersected anomalous heavy mineral concentrations. CRA Exploration Pty Ltd (1992) later drilled three RC holes, but no significant intersections were found.

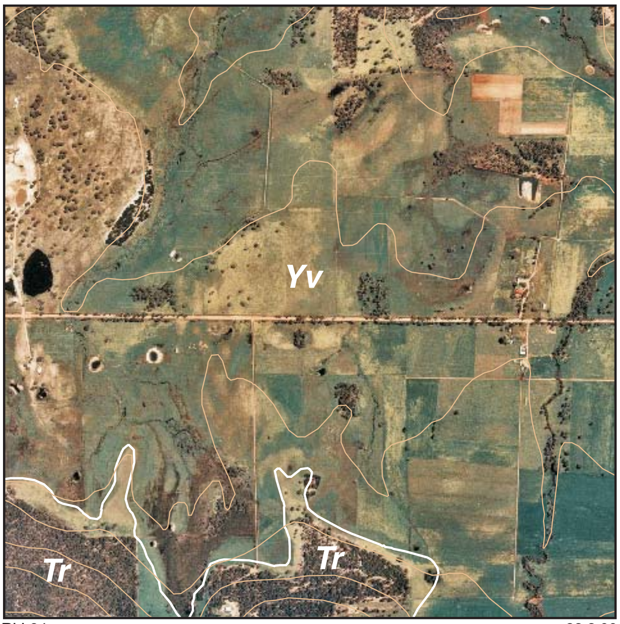
Coal occurs as concealed deposits (Vasse Coalfield) in Permian rocks beneath the Cretaceous Leederville Formation that underlies the Yelverton System (Le Blanc Smith and Kristensen, 1998). Coal resources are described in detail in the section on mineral resources.

Active processes and hazards

The weathering in situ and subsequent erosion of the underlying rock (Eocene sediments and Leederville Formation) formed the Yelverton System. The current processes of weathering, duricrust formation, and transport of materials downslope are much weaker than those which characterized the main Pleistocene and pre-Pleistocene periods of landscape formation. Seasonal rainfall is now the only significant agent controlling regolith–landform processes, and may cause soil erosion on cleared sandy slopes. Much of the Yelverton System has broad swampy drainage depressions underlain by duricrust. These areas may impede drainage and become waterlogged in winter.

Landuse, vegetation, and drainage

The Yelverton System is largely cleared of natural vegetation and is used intensively for grazing cattle. Some



RLL94 28.8.00

Figure 19. Yelverton System (*Yv*) is a flat shelf (compare with the Treeton System, *Tr*) with sandy rises and broad swampy drainage areas. 1:25 000-scale orthophotograph with contours at 5 m

of the gravelly sideslopes have more recently been exploited for viticulture. Other uses include sand and gravel extraction (Fig. 21), forestry, horticulture, and smallholdings.

Relationships

The Yelverton System lies between the Abba System to the north and the Treeton System to the south. To the west, where the shelf is underlain by Proterozoic rocks, the Yelverton System gives way to the Cowaramup System.

Geological history

The Yelverton System is formed on an erosional surface that was cut into Cretaceous (141–65 Ma) sedimentary rocks of the Leederville Formation during a sea-level highstand. Deposition of undivided sand and sandy clay, coastal and fluvial sediments took place on top of the Leederville Formation. These have since been extensively eroded, lateritized, and leached to produce deposits of podzolized sand overlying a ferruginous duricrust layer. This surface has been incised, and mainly forms rises and some low hills, with broad swampy drainage depressions.

The shelf of the Yelverton System predates the Pleistocene eolian deposits of the Spearwood System. Based on relative height of the Yoganup Formation within

RLL67 23.8.00

Figure 20. Ferruginous duricrust commonly forms hillcrests of the Yelverton System (Beckett Road, MGA 327805E 6262985N)

RLL68 23.8.00

Figure 21. Gravel extraction area in the Yelverton System also used as a motorbike racing track, Gibb Road (MGA 332200E 6263455N)

the Abba System, which lies at heights of around 45 m AHD, the shelf also predates the Pliocene Yoganup Formation. The erosional surface ranges from 50 to 90 m AHD, and may therefore relate to an Eocene sea-level high.

The morphology and distribution of the duricrust on the adjacent plateau and shelf indicate a dominant phase of duricrust formation that post-dates the presumed Eocene features. The important period of duricrust formation is mostly during the Oligocene (34–24 Ma) (Hocking et al., 1987). Extensive leaching of the lateritized deposits probably occurred during the Pliocene (5.32–1.78 Ma), which was a time when the climate was significantly wetter.

Abba System (*Ab*)

The Abba System occupies 1253 ha (2%) of COWARAMUP–MENTELLE (Fig. 22, Table 8) and has two physiographic components. Along its southern boundary there is a topographic feature known as the Whicher Scarp. This was referred to by Fairbridge (1949) as the Whicher Fault, but is now thought to have formed by marine erosion during a sea-level high of the early Pleistocene or late Tertiary (Lowry, 1967; Playford et al., 1976). Northwards from the Whicher Scarp, extending to the Dunsborough coast, lies the Swan Coastal Plain (Saint-Smith, 1912). This is a low-lying, gently undulating plain underlain by a series of alluvial, shoreline, and coastal dune deposits. The system may be prospective for heavy minerals, with known economic deposits found in the laterally equivalent Yoganup Formation to the northeast of the sheet.

Landform and distribution

The Abba System occupies the northeastern corner of the sheet around Jindong and Kaloorup. The dominant form of the system is a level to gently inclined plain, ranging in altitude from 45 m AHD inland, to 10 m AHD nearer the northern coast (outside COWARAMUP–MENTELLE). The surface of the plain is gently undulating, with shallow hollows and slight rises. Narrow meandering fluvial channels, emanating from land systems to the south, cut into the Abba System. These channels become less distinct towards the northern edge of the sheet as the grade of the slope decreases northwards towards the coast. These extensive flat areas are subject to water-logging during winter months. Numerous artificial drains have been installed to help mitigate drainage difficulties.

Several eroded foredunes take the form of discontinuous, low ridges. They parallel the southern boundary of the system but are not continuous to the eastern edge of the sheet (Fig. 23). Immediately north of the dunes, the ground is flat with small areas of swamp and larger areas subject to seasonal inundation (Fig. 24).

Regolith and rock materials

The Abba System has been formed by alluvial and shoreline deposition of silt, clay and sand since the late

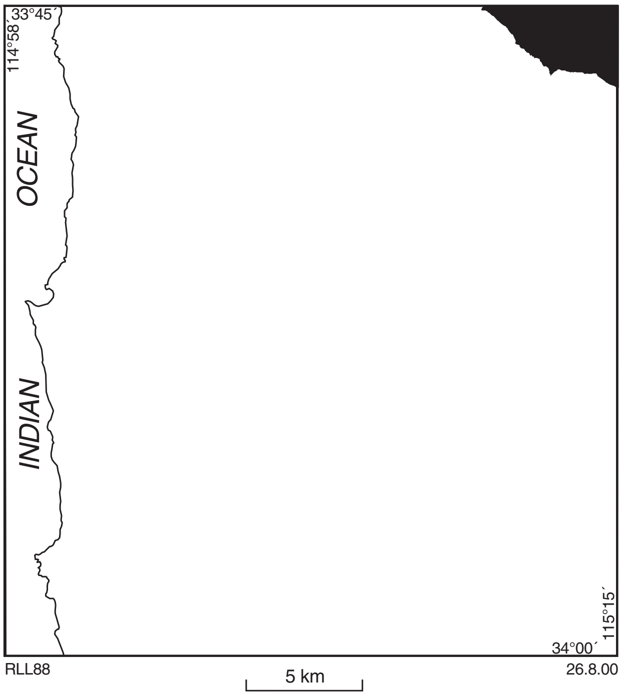


Figure 22. Distribution of the Abba System (*Ab*)

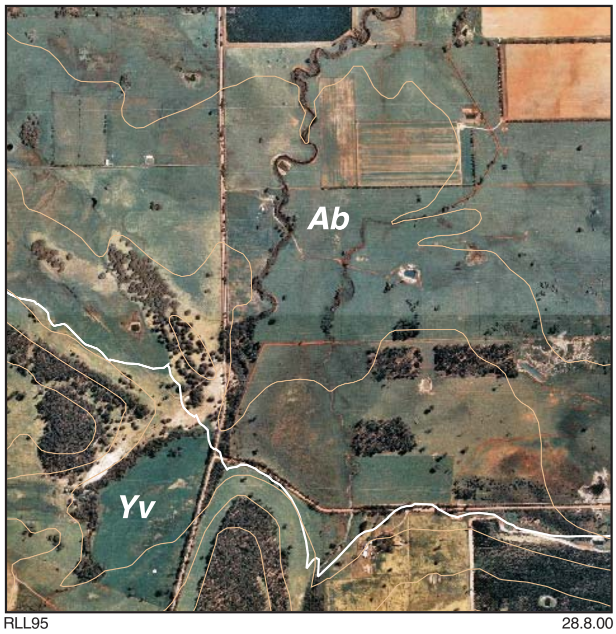


Figure 23. Southern edge of the Abba System (*Ab*), marking the Whicher Scarp and the edge of the Swan Coastal Plain, has remnant foredune landforms and is underlain by a ferruginous hardpan. Yelverton System (*Yv*) to the south. 1:25 000-scale orthophotograph with contours at 5 m

Figure 24. Landform and vegetation of a flat swampy area (*AbA$_w$q*) in the Abba System (MGA 333600E 6263835N) with pools of stagnant water and a small flowing channel in the foreground. The surface is underlain by a ferruginous hardpan formed in the Yoganup Formation. Looking south towards the edge of the Yelverton System

Table 8. Components of the Abba System

Regolith–landform unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Alluvial plain *AbA$_a$* 740 ha (59%)	Alluvial Plain; dominantly level, to moderately inclined, gently undulating surface; 30–40 m AHD Up to 2 m of sand and clayey sand overlying ferruginous hardpan at depth	Corner of Payne Road and Kaloorup Road, Jindong (MGA 336525E 6263975N) 1.1 m of alluvium over ferruginous hardpan Pale yellow 5Y 8/2, mottled brownish yellow 10YR 6/8, very silty clayey, fine to medium subangular quartz sand; slightly gravelly at the base; minor fine sand opaque minerals <1%; ferruginous nodules up to 1 cm; nodules have no cutans and contain fine quartz sand
Swamp *AbA$_w$q* 391 ha (31%)	Alluvial Swamp; dominantly level, to moderately inclined plain, with swampy, poorly drained depressions; 35–40 m AHD Up to 1.5 m of leached quartz sand overlying ferruginous hardpan; sand sometimes absent	Jindong Treeton Road (MGA 334740E 6262160N) 1.1 m of residual sand over ferruginous hardpan; formed on fluvially reworked Yoganup Formation Pale yellow 2.5Y 8/3 medium to fine sand; subangular to subrounded quartz; minor rounded coarse quartz sand; slightly gravelly at the base; fine sand opaque minerals <1%; moderately weak* ferruginous nodules at the base, up to 6 mm across; hardpan below 1.1 m
Swamp *AbA$_w$f* 65 ha (5%)	Alluvial Swamp; dominantly level, to moderately inclined plain with swampy, poorly drained depressions; 30–35 m AHD Thin alluvium, sandy silt, and clay; up to 1 m overlying ferruginous hardpan; alluvium sometimes absent; numerous artificial drains	Payne Road (MGA 336820E 6264045N 0.5 m of alluvium over ferruginous hardpan Yellowish brown 10YR 5/4, mottled yellowish brown 10YR 5/6, slightly sandy clayey silt; slightly gravelly at the base; minor fine sand opaque minerals 1%
Degraded foredune *AbB$_d$* 27 ha (2%)	Coastal Beach; degraded foredunes; mostly gentle to moderate slopes; discontinuous elongate ridges of low relief; 40–60 m AHD Leached quartz sand; no trace of carbonate	Jindong Treeton Road (MGA 334670E 6261960N) Leached residual sand on degraded foredune of the Yoganup Formation Pale yellow 2.5Y 7/3, medium to coarse sand; subrounded to rounded; minor fine sand opaque minerals <1%
Quartz sand *AbCq* 20 ha (2%)	Colluvial Undivided slopes of rises and low hills at the edge of the Yelverton System; slopes are mostly gentle to moderate; 40–60 m AHD Leached quartz sand (Yoganup Formation) of variable thickness over mottled sandy clay (weathered Leederville Formation)	Payne Road (MGA 333200E 6263240N) Reworked, podzolized Yoganup Formation Light grey 10YR 7/2, medium to fine sand; subangular to subrounded quartz; minor rounded coarse quartz sand and fine sand opaque minerals
Drainage depression *AbA$_d$*/QpY 10 ha (1%)	Alluvial Drainage depression or swamp; slopes dominantly moderate and gentle Silty sand overlying ferruginous hardpan; formed on the Yoganup Formation	Jindong Treeton Road (MGA 334500E 6262060N) Dam excavated in valley floor; alluvial silty sand over weakly formed ferruginous hardpan; beds of white sandy clay below hardpan Clay with coarse sand to fine gravel; subangular to subrounded quartz; localized enrichment of subrounded to rounded, fine to medium sand opaque heavy minerals

NOTES: * Field classification of rock material strength is given in Appendix 6

Figure 25. 1.2 m auger sample of pale yellow 2.5YR 7/3 sand from a highly leached foredune (*AbB*$_d$) on the southern border of the Abba System (MGA 334680E 6261950N)

Tertiary. Much of the surficial material is now underlain by a secondary ferruginous hardpan.

On the southern boundary with the Yelverton System there is a degraded shoreline (AbB_d) that can be correlated with the Yoganup Formation of Low (1971). Deflated foredunes on this palaeoshoreline consist of podzolized quartz sand (Fig. 25). Excavation of a dam in a drainage depression behind the dunes (MGA 334480 6262065) has uncovered white, sandy clay and clayey sand, with sandy beds beneath the near-surface ferruginous hardpan containing local concentrations of heavy minerals. Immediately north of the foredunes, sheetwash and alluvial processes have transported the dominantly bleached quartz sand onto the plain (AbA_a). Farther north, where the remnant coastal environment is not preserved at the surface, the dominant materials are silty clayey sands lying above a continuous hardpan surface that has formed from a series of Quaternary alluvial deposits. Small floodplain areas exist near currently active waterways and, as they have good drainage characteristics, are mostly underlain by very fertile loamy soils (Marybrook Soils; Tille and Lantzke, 1990a).

Mineral exploration drillholes in the area have shown that there are up to 10 m of Quaternary material overlying the Cretaceous rocks of the Leederville Formation, which in turn overlie the Permian Sue Group containing coal-bearing strata.

Mineral resource potential

Along the southern border of the Abba System there is a strandline that has been exploited for heavy mineral sands to the northeast at Yoganup and Yoganup Central mines. Mid-East Minerals NL (1972) completed RAB and RC drilling between 1969 and 1972 but there has been no further exploration.

Le Blanc Smith and Kristensen (1998) have evaluated the extent of subsurface coal deposits in this area. Coal seams of the Sue Group lie some 250–300 m below the surface, and are described in detail in the section on mineral resources.

Active processes and hazards

Many of the processes that originally formed the Abba System are now relict. Sea level is now about 45 m lower, and the alluvial processes that formed much of the inland Swan Coastal Plain north of the strandline are now greatly reduced. River action is currently confined to narrow channels and adjacent small overbank areas, and sediment supply from the hinterland is minimal.

Rainfall is the most significant agent controlling the current regolith–landform processes, and the most obvious effects are erosion and deposition in streams, and flooding.

In the Abba System, flat areas become waterlogged and are commonly underlain by relatively impervious hardpans. These hardpans form at or near the watertable and, in turn, reduce drainage characteristics of the land even further. Hardpan formation in the area is believed to be a currently active process.

Landuse, vegetation, and drainage

Areas with adequate drainage and fertility sustain a market-gardening industry, mostly growing potatoes. Flat, sandy and duricrusted areas typically have poor quality soils and are used for grazing cattle. Other minor landuses in the area include viticulture and small forestry plots. Natural vegetation has been extensively cleared in the region to facilitate these landuses.

There are several narrow channels draining the Abba System. The Buayanyup River is described as a major creek by Pen (1997), and Iron Stone and Dawson gullies, tributaries of this creek, have their confluences to the north of the sheet. These creeks are intermittent waterways, with little or no water present in the summer months. During winter, large areas become boggy and waterlogged, particularly those with a hardpan close to or at the surface. Some areas are not suitable for year-round cropping because of this, but may be suitable for summer crops.

Relationships

The Abba System was probably formed at times when the climate was significantly wetter than at present, and is largely a relict system currently subject to modification by comparatively small-scale alluvial and weathering processes in situ. At its southern boundary it is likely that the Abba System materials onlapped the Yelverton System materials. However, more recent sheetwash and colluvial processes have transported material from the Yelverton System onto the Abba System, concealing the geological boundaries and mixing the materials.

Geological history

The Abba System lies on the Swan Coastal Plain, extending northwards from the foot of the Whicher Scarp, and is underlain by shoreline and alluvial deposits. The shoreline deposits, and associated reworked materials, occupy a narrow strip of land up to 1 km wide in the study area. They are part of the Yoganup Formation, defined by Low (1971), and were mapped as the Ridge Hill Dune System by Lowry (1965) and as Pleistocene podzolized beach ridges and foredunes by Lowry (1967).

The Yoganup Formation rests unconformably on Cretaceous Leederville Formation, as observed in drillholes (Baxter and Hamilton, 1981) and exposures at the base of heavy mineral sand openpits. The formation is unconformably overlain by yellow sand (Baxter, 1977). Baxter (1981) interprets it as a paralic sequence, in which the sandy units represent barrier sheets, whereas the clay beds represent interdunal or estuarine deposits. Precise dating of the formation is difficult as there are no fossils. The unit is variably lateritized and generally less than 6 m thick. Baxter and Hamilton (1981) interpret the Ascot Formation and the Yoganup Formation as facies equivalents. The Ascot Formation is a Pliocene, fossil-rich calcarenite that interfingers with the Yoganup Formation in the northern Perth Basin. Therefore, a Pliocene age is assigned to the Yoganup Formation.

The Yoganup Formation has undergone extensive weathering, erosion and reworking since its deposition. Original carbonates have been leached, and there has been hardpan formation at or near the watertable. Outwash from the Yoganup Formation has mixed with the Quaternary alluvial deposits.

The Swan Coastal Plain has experienced a series of sea-level fluctuations as well as changes in climate during the Quaternary. Beyond the extent of the Yoganup Formation materials, the dominant process of land formation throughout the rest of the Abba System has been alluvial deposition. This alluvium is variable in age and consists of sand, silt and clay. Low (1971) assigned the alluvium to the Guildford Formation, and it is referred to as the Pinjarra Plain by McArthur and Bettenay (1960).

Spearwood System (*Sp*)

The Spearwood System occupies 3142 ha (4%) of COWARAMUP–MENTELLE (Fig. 26, Table 9) and consists of a series of deflated dunes and swales composed of quartz sand overlying eolian calcarenite, with some organic sandy soils in hollows or depressions. The system is

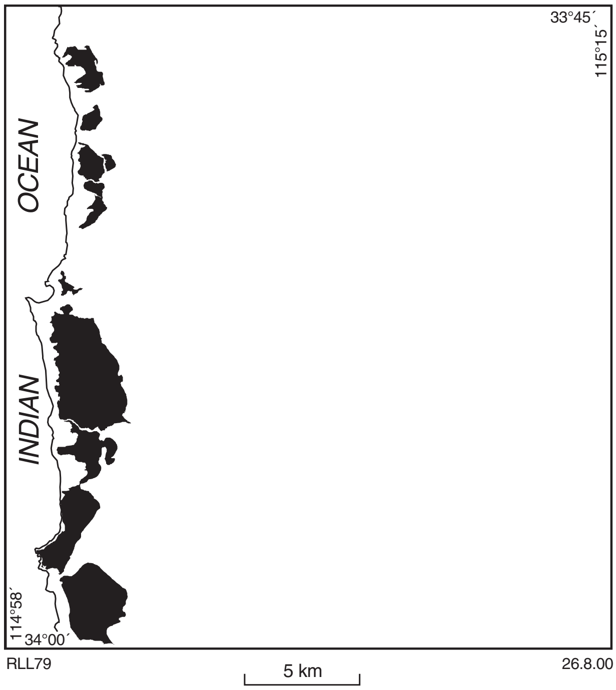


Figure 26. Distribution of the Spearwood System (*Sp*)

Table 9. Components of the Spearwood System

Regolith–landform unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Deflated parabolic dunes SpE_a 2 594 ha (82%)	Eolian Low hills and rises of deflated parabolic dunes; mostly gentle to moderate slopes, with some steep dune faces; mostly 40–140 m AHD, with one dune reaching 196 m AHD Brown residual quartz sand over calcarenite	Track in the forest about 300 m north of Spring Road (MGA 316435E 6246565N) Red sand pit at the crest of the dune; several other larger pits within this property; some limestone float in the paddock Strong brown 7.5YR 4/6, slightly silty clayey medium to coarse sand; subangular to subrounded quartz; minor fine sand mafic grains; calcarenite at 0.55 m depth
Calcareous eolianite *SpEk* 536 ha (17%)	Eolian Dunes; slopes are mostly gentle to moderate, with some steep slopes; 20–100 m AHD Calcrete above well indurated shell and quartz sand	Limestone pit on the top of a dune in Leeuwin–Naturaliste National Park (MGA 316285E 6247605N) Friable calcarenite with large-scale bedding, dipping 20° towards 145° Cream-coloured, coarse-grained calcarenite, with equidimensional and elongate grains composed of shell fragments; minor quartz sand; grains are mostly rounded and smooth
Swampy swales SpE_w 7 ha (< 1%)	Eolian Poorly drained depressions; slopes are generally moderate to gentle; 40–100 m AHD Waterlogged organic soil over red residual quartz sand	0.8 km east of Dallip Spring (MGA 315200E 6242800N) Swamp vegetation in a hollow down to 43 m AHD, behind younger dunes of the Quindalup System; yellow sand here and in the pit to the east contrast with the older white sand of the Caves Road System
Blowout SpE_b 4 ha (< 1%)	Eolian Dunes; mostly moderate to gentle slopes, with some steep slopes; 20–100 m AHD Actively eroding quartz sand and calcarenite	Spring Road, Ellenbrook (MGA 314439E 6246026N) Dune devoid of vegetation Exposed, leached, residual quartz sand
Doline SpR_d 2 ha (< 1%)	Residual Doline; mostly gentle to moderate slopes; 20–100 m AHD Formed in calcarenite by erosional processes	Near the mouth of Wilyabrup Brook (MGA 315570E 6259090N) Small rounded depression; solution doline; identified on aerial photography; formed in Spearwood System calcarenite

equivalent to the Pleistocene Tamala Limestone, and is a source of limestone and building sand in the area, with a number of limestone quarries providing roadbase material.

Landform and distribution

The Spearwood System is a discontinuous ridge composed of a series of deflated dunes and swales that were formed during the Pleistocene by the predominantly southwesterly winds of the region. The dunes, which have been leached and eroded over time, are located along the Leeuwin–Naturaliste Coast in a northerly direction. To the west are eolian sands of the Quindalup System and, to the east, the older sediments of the Caves Road System and the dissected plateau of the Cowaramup System.

The Spearwood System is up to 3 km wide, but is absent in places along the coastline. The dune slopes are gently to moderately inclined, with rare steep to precipitous rocky slopes or cliffs that overhang in places (Fig. 27). The limestone ridge of the Spearwood System is characterized by large-scale eolian cross-bedding, and contains many caves and areas of karst topography (Tille and Lantzke, 1990b). Most of the caves are lie within the Leeuwin–Naturaliste National Park.

Regolith and rock materials

The dunes of the Spearwood System (SpE_a) were formed by dominantly eolian processes, and have been modified over time by groundwater. The dunes now consist of

RLL71 23.8.00

Figure 27. Landform and vegetation of the deflated parabolic dunefield (*SpE$_a$*) of the Spearwood System. Bedded limestone (*SpEk*) has been weathered to create small caves and an overhang in cliffs at Joeys Nose, Kilcarnup Beach (MGA 314530E 6241925N)

RLL72 23.8.00

Figure 28. Landform, landuse and vegetation of the Spearwood System. Gently inclined slope with outcrops of calcarenite (*SpEk*) at the end of Wilyabrup Road (MGA 315725E 6257170N)

residual sand over limestone (*SpEk*). Leaching of the originally calcareous eolian dune sands has produced these residual sands, which are red to brown, slightly silty quartz sand.

Limestone was formed within the cores of the dunes by the precipitation of calcium at depth in the profile. The limestone includes many rhizomes and solution pipes, which formed around tree roots at a time when forest was widespread over the system. The limestones of the Spearwood System are more strongly cemented than those of the younger Quindalup System, and karstic weathering has created features such as caves and dolines (SpR_d). In places, limestone outcrops through the overlying residual sand (Fig. 28). Swales between the dunes (SpE_w) can become waterlogged, and may contain more organic or clayey soils.

Mineral resource potential

The Spearwood System is a source of limestone and sand. Nearly all areas of the system are underlain by limestone (calcrete and calcarenite) at depth, but the most prospective areas are those where the limestone is exposed or is close to the surface. These areas are generally on or near hillcrests and steep scarps, and are often covered in remnant vegetation. There are a number of quarries in the system that contain limestone with varying degrees of lithification, ranging from very friable to strongly lithified. Red residual quartz sand with a slightly silty content is widespread throughout the system (Fig. 29) and is used for construction purposes, principally pads for buildings.

Active processes and hazards

The processes that are active in the Spearwood System are rainfall and wind. These processes erode the residual quartz sand and, where it outcrops, the limestone. The sinkholes, cave entrances, limestone outcrop, and cliffs associated with karst topography adversely affect most landuses and create an obstacle for machinery. Hidden cave entrances are a hazard for stock, machinery, and people. All areas underlain by limestone can potentially contain caves, and these are sometimes expressed as sinkholes and dolines at the surface. These limestone areas may be prone to subsidence and cave collapse. Overhangs formed in the limestone cliffs are mostly stable, but can be prone to collapse (Fig. 30). If westerly slopes are cleared of vegetation, blowouts may be formed and migrating sand may become a minor hazard.

Landuse, vegetation, and drainage

The Spearwood System lies predominantly within the Leeuwin–Naturaliste National Park. As such, the system is renowned for its natural beauty and much of it is used for conservation, tourism, and recreation, including caving and rock climbing. Small areas have been cleared for grazing and urban development.

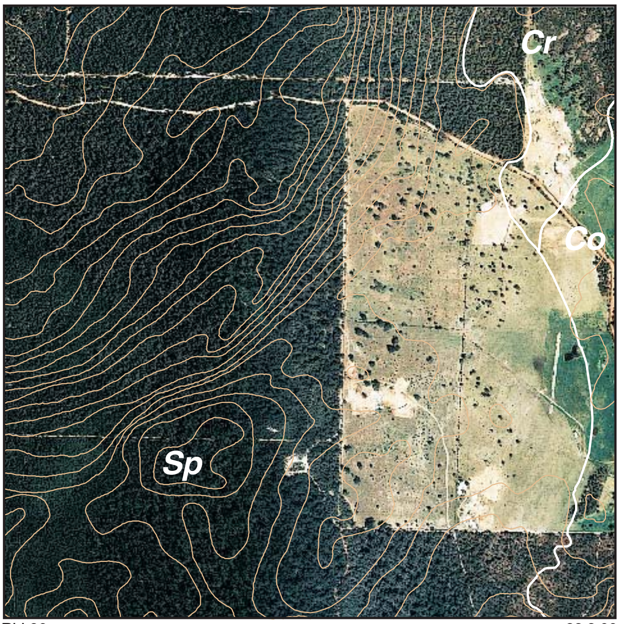


Figure 29. Steep eastern slope of a dune in the Spearwood System (*Sp*), with deflated dune sands being excavated for building sand. A small pit near the crest of the large dune has removed friable, bedded limestone for use as roadbase. West of Caves Road (*Cr*) and Cowaramup (*Co*) Systems. 1:25 000-scale orthophotograph with contours at 5 m

The western slopes of the ridge are exposed to strong, salt-laden coastal winds, which restrict the vegetation to heath to scrub heath plants that are low growing and salt tolerant. Farther inland, in areas more protected from the wind, and where the soils are older and deeper, vegetation is medium to tall forest. Karri grows on well-drained loamy soils, and marri and jarrah forests grow on leached sands and in areas underlain by duricrust. In areas of poor drainage, these jarrah and marri trees can become stunted and form low forests (Beard, 1990).

The quartz sand of the dunes is well drained, and there is generally no surface drainage on the dunes. Stream channels are, however, incised between dunes in places, for example the Margaret River, and Cowaramup and Wilyabrup Brooks. Dunes that are underlain by limestone often contain subsurface waterways. Swales can become filled with water during winter.

Relationships

The eolian deposits of the Spearwood System are overlain by the younger dunes of the Quindalup System to the west. The dunes were deposited over the weathered granulites of the Leeuwin Complex, or over shelf deposits of the Caves Road System to the east.

Geological history

The Spearwood System comprises a succession of lithified dunes of varying ages, which were formed as sea levels

Figure 30. Landform and landuse of the Spearwood System. Climbers scale the strongly lithified calcarenite (*SpEk*) cliff face, which has been weathered to form small caves and an overhang. South side of the Margaret River near Prevelly (MGA 314505E 6239095N)

fluctuated during the Late Pleistocene. The dunes have a weathering profile of leached quartz sand over a hard, indurated limestone caprock (Abeysinghe, 1998). These dunes were originally calcareous, but leaching by acidic groundwater has modified them over time, reducing the volume of the dunes by dissolving out calcium carbonate, which is then precipitated within the core of the dunes to form hard limestone (Lowry, 1967). The overlying residual sand has in places been removed by wind erosion to expose the limestone, which is in turn weathered to expose softer limestone (Abeysinghe, 1998).

The limestone of the Spearwood System is equivalent to the Tamala Limestone (Playford et al., 1976), which was originally referred to as Coastal Limestone (Seddon, 1972). A feature of the Tamala Limestone is well-developed dune bedding, and in places the roots of trees have been calcified, creating tubular rhizomorphs (Lowry, 1967). The Tamala Limestone was deposited in a shoreline environment above the Wadjemup Formation and the Rockingham Sand (Playford et al., 1976), both of which disconformably overlie Oligocene and Miocene shallow-marine and coastal deposits (Cockbain, 1990).

Quindalup System (*Qu*)

The Quindalup System occupies 1560 ha (2%) of COWARAMUP–MENTELLE (Fig. 31, Table 10) and consists of parabolic dunes, swales, and blowouts. The younger parabolic dunes are gently to very steeply sloping, and older deflated dunes are cliffed in coastal sections. Materials are dominantly calcareous sand and weakly lithified calcarenite, with organic sandy soils in swales. The system is a source of limesand for agricultural purposes, limestone for roadbase, and sand for construction.

Distribution and landform

The Quindalup System is the westernmost land system on COWARAMUP–MENTELLE. The system occupies a belt up to about 2 km wide along the Leeuwin–Naturaliste Coast, overlying the older Tamala Limestone or rocks of the Leeuwin Complex. The western margin of the Quindalup System is a beach, backed by a foredune. In places the beach is dominated by boulders of limestone and granulite, and may be backed by cliffs of calcarenite or bluffs of granulite. The dunes of the Quindalup System are often parabolic (Fig. 32), with swampy swales filled with organic sandy soils where drainage has been blocked by the dunes. Blowouts can be formed in these currently active dunes, leaving areas of loose sand with no cover of vegetation (Fig. 33). This loose calcareous sand may be eroded to expose the hard surface of the calcarenite in the cores of the dunes.

The Quindalup System slopes broadly west, although locally the slopes of the parabolic dunes vary widely. A few small beaches face northeast, for example in

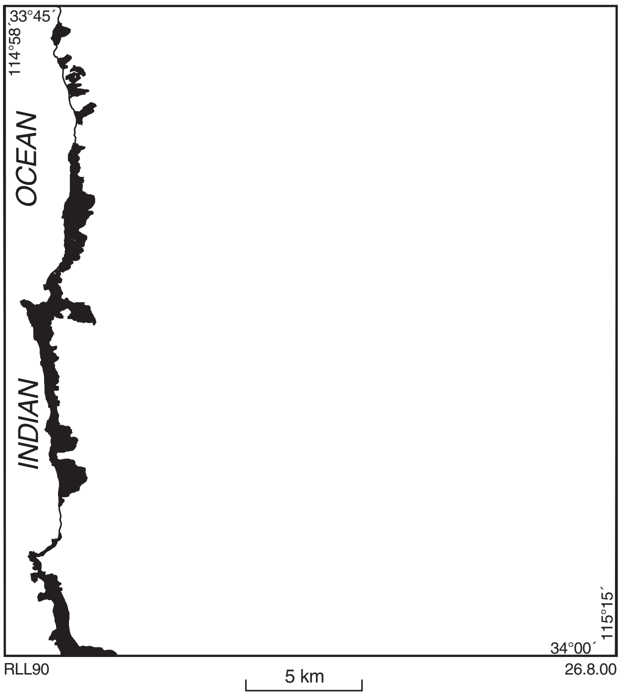


Figure 31. Distribution of the Quindalup System (*Qu*)

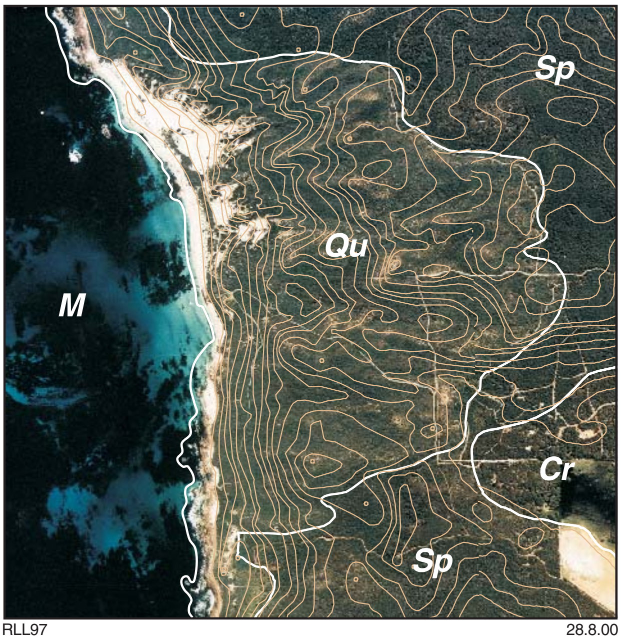


Figure 32. Parabolic dunes of the Quindalup System (*Qu*) overlie Spearwood System dunes (*Sp*), 3 km north of Cape Mentelle. Adjacent to Marine System (*M*), with Caves Road System (*Cr*) inland. 1:25 000-scale orthophotograph with contours at 5 m

Figure 33. Landform and vegetation of the Quindalup System. Blowout (*QuE$_b$*) on a dune at the end of Wilyabrup Road (MGA 315345E 6259270N)

Table 10. Components of the Quindalup System

Regolith–landform unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Parabolic dunefield *QuE_a* 863 ha (55%)	Eolian Dunes; mostly moderate and gentle slopes, with some very steep slopes; overlies ᴾmLE at shallow depths in places 0–140 m AHD Shell and quartz sand	Kilcarnup Beach to Gnoocardup Beach (MGA 314545E 6243300N) Shallow trench to 0.8 m in eolian sand Very pale brown 10YR 7/4, medium shell and quartz sand; trace of pink garnet
Calcareous eolianite *QuEk* 500 ha (32%)	Eolian sand Dunes; mainly gentle and moderate slopes, with some very steep slopes; includes coastal rock platform; overlies ᴾmLE in places; 0–100 m AHD Lithified dunefield; weakly lithified shell and quartz	Cape to Cape CALM walking track, west of Moses Rock (MGA 313920E 6262255N) 1–2 m high calcarenite cliff at approximately 20 m AHD, with a very steep talus slope; nodular calcareous rubble near surface; calcarenite has a calcrete surface, but is otherwise weakly cemented Very pale brown 10YR 7/4, porous calcarenite; contains rounded medium sand shell fragments and < 5% subrounded to rounded quartz; abundant calcified root structures (rhizomes) in cliff face
Beach *QuB_b* 102 ha (6%)	Coastal Beach and foredune; mostly moderate slopes, minor precipitous slopes; 0–5 m AHD Marine shell and quartz sand; eolian in part	Dunes north of Cape Mentelle (MGA 314190E 6240690N) Eroded seaward face of dune behind foredune Very pale brown (10YR 8/4) medium sand; abundant shell clasts; elongate flat and equidimensional; minor quartz is subrounded and glassy; traces of garnet
Blowout *QuE_b* 57 ha (4%)	Eolian Dunefield; most slopes are moderate, with some very steep slopes; 0–80 m AHD Actively eroding shell and quartz sand	Coastal end of Wilyabrup Road (MGA 315345E 6259270N) Top of blowout in mobile sand Pale brown 10YR 4/3 calcareous coarse sand; subrounded to rounded shell fragments ~90%; minor medium to fine sand opaque minerals
Swampy swale *QuE_w* 4 ha (< 1%)	Eolian Poorly drained depression; mostly level to moderate slope; around 5 m AHD Waterlogged organic soil over shell and quartz sand	Gnarabup Swamp, Prevelly (MGA 314450E 6238450N) Area of swampy vegetation, partially drained, about 160 m long and 80 m wide; one of a number of depressions with standing water or water-dependent vegetation
Proterozoic Leeuwin Complex ᴾmLE 3 ha (< 1%)	Bedrock Stream beds and along the coast; exposed at beach level and as cliffs along the coast; mostly gentle to moderate slopes, very steep in places; 0–120 m AHD Underlies *QuE_a*, *QuEk* and *QuE_d* at shallow depths in places	South of the Margaret River mouth (MGA 313950E 6239065N) Abundant exposures of banded granulite below the beach; tidally inundated Granulite includes numerous veins, segregations and shear zones; banding typically 5–10 mm wide, mostly planar, dipping 16° towards 061°
Boulder beach *QuB_o* 2 ha (< 1%)	Coastal Beach; slopes are mostly moderate to steep, occasionally precipitous; 0–10 m AHD Waterlogged organic soil over eolian shell and quartz sand	Cowaramup Bay, Gracetown (MGA 313448E 6250947N) Narrow beaches of shell and quartz sand, covered with boulders of varying size; boulders are composed of both limestone and granulite

Table 11. Particle-size distribution for samples from the Quindalup System

Map code	*GSWA sample no.*	*Location*	*Sample description*	*Gravel (%)*	*Coarse sand (%)*	*Medium sand (%)*	*Fine sand (%)*	*Silt/clay (%)*
QuEa	161669	Wilyabrup Road (MGA 315345E 6259270N)	Pale brown 10YR 4/3, coarse calcareous sand, with minor quartz and opaques and rare garnet	2.3	90.8	6.8	0.1	0.0
QuEa	161672	Wilyabrup Road (MGA 315545E 6259445N)	Medium sand, with opaques and garnet	0.0	1.0	33.8	63.5	1.8

Cowaramup Bay. The beaches have low relief and are generally gently to moderately sloping. Dune slopes are mostly gently to steeply inclined, and locally they are very steep to precipitous. Older deflated dunes are cemented and eroded, forming cliffs and rocky headlands that are overhanging in places. Dunes of the Quindalup System reach up to 110 m AHD, with heights generally increasing towards the east.

Regolith and rock materials

The dominant material in the Quindalup System is calcareous eolian (Table 11) sand composed of shell fragments, quartz, and minor garnet and other heavy minerals. The loose calcareous sand overlies a core of weakly lithified calcarenite (*QuEk*). The shell material is sourced from the marine environment, transported by marine and coastal processes into the dominantly eolian environment of the beach and dunes. Beach sands (*QuB$_b$*) tend to be coarser grained than the adjacent eolian deposits, and can include beach rock, which is a lithified beach deposit found at or slightly above the zone of dominant wave action. Beach rock platforms of calcarenite are exposed at both current sea level and old sea level stands, and may be unconformably overlain by lithified dune sand (Fig. 34). Outcrops of Proterozoic granulite are also common along the coast.

The eolian sands are dominantly unconsolidated to weakly lithified, well-sorted calcareous coarse sand. Carbonate clasts are rounded, smooth, flat to elongate shell

RLL75 29.8.00

Figure 34. Thinly bedded dune sand (*QuEk*) unconformably overlying strongly lithified beach rock, south of Prevelly (MGA 314385E 6236795N)

fragments, and the quartz is subrounded and glassy. The source of these clasts is both reworked marine shell and fluvial quartz sand. Many of the sands contain minor amounts of subrounded pink garnet, which is sourced mainly from weathered Proterozoic rocks of the inland systems.

The dunes have varying degrees of lithification at depth, depending in part on their age. The younger parabolic dunes (QuE_a) can have very weak calcarenite cores, whereas the older, deflated dunes are composed of calcareous soils over moderately weak limestone. The calcium carbonate content typically varies considerably in the Holocene sands, ranging from 50% to over 90%. One sample from a blowout surface (QuE_b) at the end of Wilyabrup Road (MGA 315345E 6259270N) has been analyzed at 68.7% $CaCO_3$.

Mineral resource potential

The Quindalup System is a potential source of limesand for agricultural applications. Sands in the system can also be used for construction. Two quarries located southwest of Margaret River townsite provide lithified calcarenite from the cores of the dunes for use as roadbase. There is some potential for heavy mineral sands within the beach and dune sands of the system.

Active processes and hazards

Eolian processes dominate on the dunes, and both eolian and coastal processes are dominant on the beaches. An important process in the system is the eolian transport of dune sand by prevailing winds, which are predominantly southwesterly. Eolian transport is most active in blowouts or areas where the vegetation has been damaged or removed. Marine transport of reworked shell and quartz is the dominant process in the coastal zone, resulting in seasonal deposition and erosion of beaches and river bars. This process is most active during storms, when there is often a significant increase in the erosion of coastal deposits. Beach regeneration is usually a naturally occurring seasonal process.

Collapse or subsidence of material, particularly overhanging cliffs, is a significant hazard along the coast, and has resulted in fatalities in recent years. The collapse of overhangs is an unpredictable, natural process that is more likely to happen after storms or heavy rain. Migrating sand from blowouts and steeper dune faces is a minor hazard. Waterlogging can take place in the depressions between dunes during winter.

Landuse, vegetation, and drainage

Much of the Quindalup System includes the Leeuwin–Naturaliste National Park, so conservation plays an important role in the area. Recreation and tourism are also common landuses. Some urban development has occurred along the coast at Prevelly Park. Grazing is a minor landuse in the Quindalup System.

Along the coast the vegetation consists of low-growing, salt-tolerant plants. Most commonly the vegetation is heath and scrub heath, as the plants are slow to regenerate after burning. Grey-leaved plants, acacias, and other low shrubs characterize the shrubland on mobile sand dunes and blowouts. Scrub heath can be found on stable dunes, with larger shrubs such as peppermint (*Agonis flexuosa*), banksia (*B. grandis*), and some eucalypts (*E. angulosa*), which are often stunted by the strong salt-laden winds. The climax vegetation is peppermint low woodland, but this is now found only in a few protected places (Beard, 1990).

Alluvial channels reach the coast at numerous points along the coast. They incise channels between dunes, sometimes eroding down to the underlying granulites of the Leeuwin Complex. Closer to the coast, the valley sides can be very steep, but farther inland the stream banks are generally gently sloping. There are no channels on the dune slopes, as the sands of the dunes are well drained.

Relationships

The Quindalup System trends in a northerly direction along the Leeuwin–Naturaliste Coast. Eolian sands of the system overlie the Proterozoic rocks of the Leeuwin Complex, which are exposed in places along the coastline. To the east these sands overlie the older dunes of the Spearwood System (Tamala Limestone), and in places also overlie the shelf deposits of the Caves Road System.

Geological history

The Quindalup System is underlain by the Safety Bay Sand, which was deposited during the Holocene (< 40 000 years BP). The system is defined as coastal sand dunes and shallow marine to littoral sands (Passmore, 1967, 1970). The older dunes have been leached over time by acidic groundwater and have become deflated. They consist of calcareous soils over moderately weak calcarenite. The younger dunes have cores of very weak calcarenite. Deposition of the dunes of the Quindalup System continues today, together with their erosion by the prevailing winds and rain.

Marine System (*M*)

The Marine System occupies 5983 ha (8%) of COWARAMUP–MENTELLE (Fig. 35, Table 12) and includes the nearshore rock ridges and flats, nearshore sand plain, marine channels, reef or rock flat, and shoreface seabed. The shallow waters have the potential to be a source of limestone, sand, and limesand. Reef and rock flat occupy a significant proportion of the Marine System.

Morphology and distribution

The Marine System is composed of level to gently inclined nearshore seabed and level to very gently inclined shoreface. The system includes all seabed materials and

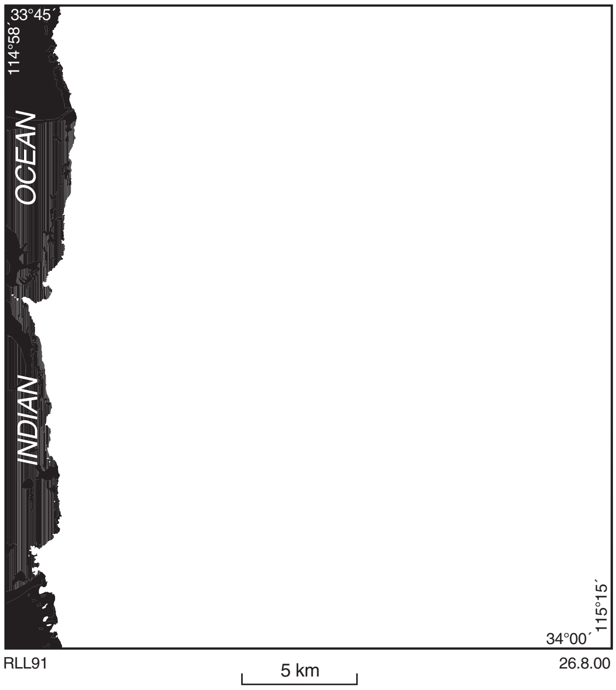


Figure 35. Distribution of the Marine System (*M*)

morphological features up to Chart Datum (CD), which is the level of the lowest astronomical tide. The major components of the Marine System are nearshore reefs or rock flats. These reefs and rock flats can be exposed in the littoral zone between high and low tide, as inshore or nearshore rock platforms. Erosional channels offshore from Gnarabup Beach and Woodlands are relicts of fluvial palaeochannels associated with the Margaret River and Wilyabrup Brook during lower sea levels (Fig. 36).

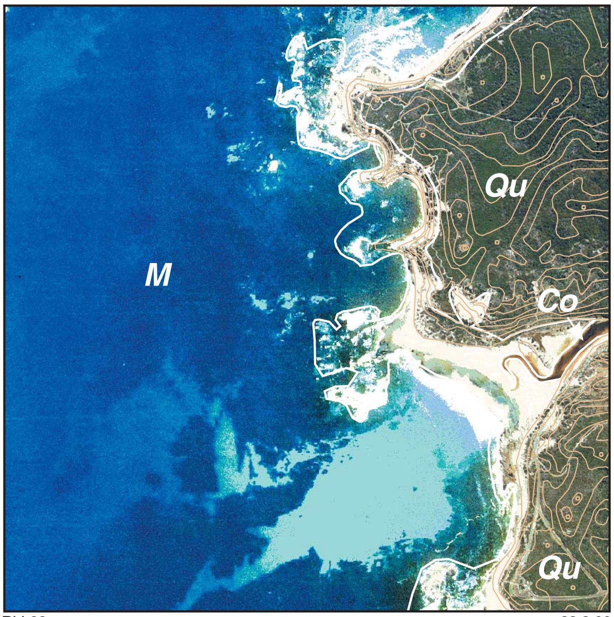
Seabed materials

The seabed is dominantly covered with rocky platforms and reefs composed of Leeuwin Complex granulite and granite, and calcarenite of eolian or beach origin (M_r). Some rocky platforms and reefs are partially emergent in the shoreface region (Fig. 37). Although most reefs or rock flats are composed of granulite and granite, the calcarenite is mostly Tamala Limestone of eolian origin.

Sandy areas within the system are composed of mainly calcareous shell fragments and quartz grains. The sand has come from a number of sources, including fluvial channels, which have brought materials from weathered rocks farther inland. The sand is also made up of grains

Table 12. Components of the Marine System

Regolith–landform unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence (based on bathymetry and enhanced Landsat TM imagery)*
Reef or rock flat M_r 5 075 ha (85%)	Marine Minor sandy areas; can be exposed at low tide; found down to –22 m CD Undivided Leeuwin Complex and eolian calcarenite	South of the mouth of the Margaret River at Prevelly (MGA 313800E 6238800N) Exposures of granulite and calcarenite extend offshore into rock flats on the seabed
Nearshore sandplain and sandy hollows M_n 517 ha (9%)	Marine Level to gently inclined; -10 to -18 m CD Shell and quartz sand; minor rock ridges and flats	Southwest of Cowaramup Point, Gracetown (MGA 312800E 6249500N) Sharp change in phototone from the nearshore rock flats to the adjacent sand plain
Shoreface M_s 245 ha (4%)	Marine Mostly gentle slopes; 0 to -12 m CD Shell and quartz sand; minor rock platform	North of the mouth of Wilyabrup Brook (MGA 314400E 6259900N) Sharp change in phototone from pale sand on the shoreface to the adjacent the nearshore rock flats
Channel M_v 143 ha (2%)	Marine Sand filled palaeochannel in shoreface and nearshore sediments; level to gently inclined; 0 to -22 m CD Shell and quartz sand	West of the mouth of Wilyabrup Brook (MGA 314000E 6258800N) Sand-filled channel feeding from the mouth of the brook, extending offshore into deeper water as a broad erosional channel



RLL98 28.8.00

Figure 36. Marine palaeochannel in Marine System (*M*) off the mouth of the Margaret River, adjacent to sandy hollow in the rock-dominated nearshore plain, west of Cape Mentelle. 1:25 000-scale orthophotograph with contours onshore at 5 m

from the weathering of marine reefs and rocks, as well as from biogenic activity. Narrow terrestrial palaeochannels (M_v), which were incised during lowered sea levels, are now infilled with sand from the current active drainage systems. This sand has been reworked in the nearshore marine environment.

Mineral resource potential

The Marine System is a possible source of limestone, sand or limesand that could be used for agricultural applications, construction, beach rebuilding, or reclamation. Much of the offshore area on COWARAMUP–MENTELLE is covered by water in excess of 10 m depth, and the sea conditions are often difficult, both of which significantly reduce the potential for dredging.

Geologically, the offshore area is the source of sand for beaches and foredunes, which is then modified by eolian processes to form the coastal dunes. The nearshore sands are a suitable source of material for beach reconstruction, as this sand most closely matches that found in existing beaches.

Active processes and hazards

The Marine System is the most active of all the systems on COWARAMUP–MENTELLE, with constantly active processes that include erosion and deposition by tides, currents, and wave action. The impact of wave action is increased because of the rocky coastline, shallow reefs, and rapidly deepening water offshore (Fig. 38).

RLL76 23.8.00

Figure 37. Calcarenite rock platform extending into the shoreface region, with waves breaking on partially submerged rocks further offshore, south of Prevelly (MGA 314385E 6236795N)

Figure 38. Strong wave action on the coast at Gracetown (MGA 313500E 6250980N), with erosion of the cliffs visible in the foreground

Rapid deposition and erosion of coastal deposits can take place during storms, and cliff collapse can be induced by a combination of heavy rainfall and storm action. Longshore drift from south to north is constantly modifying the inshore shore face, as well as the adjacent beach in the Quindalup System. Regeneration of the shoreface and adjacent beach is usually a naturally occurring seasonal process.

Seabed use

The nature of the seabed has a significant impact on shipping, the local fishing industry, and recreation. The location of reefs and the bathymetry are important factors in determining the formation of surfing waves (Figs 37 and 38).

Geological history and relationships

The seabed is a currently active regime that is dominantly underlain by undivided older reefs composed of the Leeuwin Complex metamorphic rocks. The age of the veneer of loose seabed materials lying above the rock and in hollows between the reefs is predominantly Holocene. The age and formation of these loose materials is closely linked to the coastal and eolian processes in the adjacent Quindalup System.

Mineral resource potential

Overview

The mineral resource potential of COWARAMUP–MENTELLE is limited to a small range of construction and industrial minerals (Fig. 39), coal, and heavy mineral sands. Construction materials in the area include basic raw materials such as sand, limestone, limesand, gravel, rammed earth, aggregate, and dimension stone. The occurrence of coal in the area forms part of the Vasse coalfield (Fig. 4), which is part of the Permian Sue Coal Measures. Titanium, zirconium, or garnet mineral sand concentrations have been identified in an alluvial deposit east of Margaret River townsite and in a coastal deposit north of Gracetown.

Construction material resources may contribute significantly to the local urban and industrial development of an area, making their distribution of interest to landuse planners. Knowledge of the distribution and supply of these resources will help to keep construction costs low, avoid future landuse conflicts, and thus provide benefits to the whole community.

Gravel

The ferruginous duricrust and transported gravels that cover many of the hilltops in the Cowaramup and Treeton

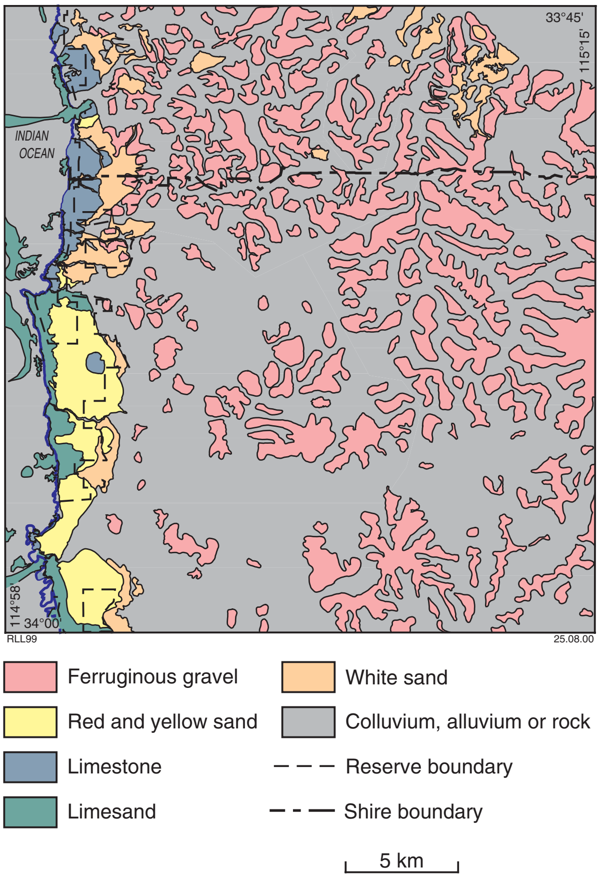


Figure 39. Construction and industrial mineral resource potential of COWARAMUP–MENTELLE

Systems (Fig. 39) range from strongly cemented to loose, and overlie mottled residual soil. This soil may be a suitable material to use as rammed earth in building construction. The duricrust and soil are formed by weathering of the underlying bedrock, which in this area includes Proterozoic metamorphic rocks and Cretaceous sedimentary rocks. The looser gravels are preferred for road building, as they can be easily excavated and require no further processing. These gravels are typically less than 0.5 m thick over large areas, but locally can be up to 2.5 m thick. They are used for roadbase, constructing farm tracks, and unsealed shire roads.

Extracting gravel resources is limited by a number of factors, principally land ownership and conservation requirements. The typically well-drained gravelly soils are preferred for a range of primary industries, notably viticulture, but where the soil profile includes well-cemented duricrust the land is commonly still under natural vegetation or forest regrowth. Road or track access to suitable occurrences is not difficult, but distance from the market may be a significant limiting factor. If the duricrust is strongly cemented it may prove difficult to extract gravel for road building, and if the looser parts of a deposit are less than 1 m thick, their extraction may prove uneconomic.

Sand

Weathering of calcareous sand in the Spearwood System (Fig. 39) has formed thick deposits of yellow and red sand. The resulting quartz-rich sand is discoloured by small amounts of iron oxide-rich clay; goethite produces a yellow to brown colour, and hematite gives a distinctive red colour. The slightly more clayey red sands are preferred for building pads. The resource is widespread throughout the Spearwood System, and is typically over 2 m thick above calcrete and calcarenite (limestone).

Limestone

Limestone can be used in the building and construction industry, as raw material in the manufacture of cement, and as dimension stone. Low-grade material is suitable as aggregate or roadbase. Limestone can be crushed and used in the agricultural industry to neutralize acidic soils and promote structure, nutrient availability, and encourage soil organisms such as worms. Limestone is also the principal source of lime, which has a wide variety of industrial applications. Lime or quicklime (CaO) is produced by thermal dissociation of high-calcium limestone. Slaked lime $Ca(OH)_2$ is produced by reacting quicklime with water.

The Tamala Limestone, part of the Spearwood System, comprises calcrete over calcarenite. The younger Safety Bay Sand, part of the Quindalup system, includes weak calcarenite. Calcarenites in these two units are generally referred to as limestone (Fig. 39). Abeysinghe (1998) reviewed the limestone resources of the Cape Leeuwin–Cape Naturaliste region. In COWARAMUP–MENTELLE the only use of limestone is as an aggregate for roadbase and concrete.

Limesand

Limesand is commonly used to correct soil deficiencies, as it helps to neutralize acidic soils or solutions, which in turn promotes nutrient availability in the soil and also encourages the earthworm population. Limesand can also be used as a source of lime. Sometimes 'lime' is used incorrectly to describe calcareous products such as agricultural limesand.

Limesand is composed of comminuted shell fragments of marine origin, with minor quantities of quartz and other minerals derived from weathering and erosion of rocks inland. The calcium carbonate content of the loose sands that form the Quindalup System is typically over 50%. The preferred locations for limesand operations are in blowouts in the mobile dunes, followed by sites in the vegetated dunes (Fig. 39). There are no limesand pits on COWARAMUP–MENTELLE, although the Quindalup System is used as a source of limestone.

Aggregate and dimension stone

The Leeuwin Complex, which is composed of fresh granulite and granite at shallow depths, is a potential source of crushed rock aggregate and dimension stone. There is one recorded proposal for a quarry in granite gneiss to be used as dimension stone (Wilyabrup Black Granite, MGA 317090E 6259730N).

Coal

The possibility of significant coal resources lying below the surface in the area south of Busselton was first documented by Saint-Smith (1912), who notes the opinion of Assistant Government Geologist H. P. Woodward that there may be a very extensive coal basin west of the Leeuwin–Naturaliste Ridge. The Vasse Shelf coalfield, part of the Permian Sue Group, was discovered in 1967 when the Mines Department drilled a line of water bores (Wharton, 1981; Kristensen and Wilson, 1986; Townsend, 1994).

The coal resource potential of the Vasse Shelf was estimated by Kristensen and Wilson (1986) to be 230 Mt in the Treeton area for seams exceeding 1.3 m thickness, at depths of 180 to 450 m. The coal potential was recently reviewed by Le Blanc Smith and Kristensen (1998), who concluded that the inferred resource of Class 1 coal in the Vasse coalfield is 500 Mt. They identified eight principal coal seams over 1.5 m thick (Fig. 4), with the best coal deposit east of Margaret River townsite at Rosa Brook. The thickest and most extensive seam is the Osmington, which is up to 4.5 m thick in the southern part of the deposit.

The coal is of a quality suitable for steam raising, with coal ash from 7 to 15%, and sulfur contents less than 1% (Kristensen and Wilson, 1986). Le Blanc Smith and Kristensen (1998) state that the seams are too deep for opencut mining, but should be accessible by underground mining.

Titanium, zirconium, and garnet

The eolian and coastal sands in the Swan Coastal Plain contain minor amounts of heavy minerals, with the most important economic deposits located to the northeast of COWARAMUP–MENTELLE in the Capel and Yoganup shorelines (Baxter, 1977). Lowry (1967) reported accumulations of heavy minerals, notably garnet, ilmenite and zircon, in a number of places in the foredunes and beach ridges along the Leeuwin–Naturaliste Coast. There are also heavy mineral concentrations in fluvial valley-fill deposits on the plateau adjacent to the Leeuwin–Naturaliste Ridge.

Two significant occurrences have been noted in COWARAMUP–MENTELLE; Woodlands, about 9 km north of Gracetown, and Upper Chapman, about 12 km east-southeast of Margaret River townsite.

Baxter (1977) described the Woodlands occurrence under its old name of the Ensor Prospect. The occurrence is located in Holocene dunes of the Quindalup System up to 24 m thick, overlying limestone and yellow sand of the Spearwood System. Baxter (1976) reports exploration by Busselton Minerals N. L. as identifying heavy mineral concentrations in zones between 6 and 20 m thick, with up to 25% heavy minerals.

The Upper Chapman occurrence was identified during field mapping and reconnaissance auger drilling by the Electrolytic Zinc Company of Australasia Ltd (1971). Mapping identified heavy mineral or ilmenite occurrences in a few localities. Auger holes were located at approximately half-mile (0.8 km) intervals along all existing roads, but failed to identify a potential resource.

Hydrogeology

Six groundwater regions in the Busselton–Margaret River–Augusta area have been identified as having differing availability of groundwater (Hirschberg, K., pers. comm. *in* Tille and Lantzke, 1990b), and these are summarized below. These regions closely correlate to physiographic regions, and four of the regions (Swan Coastal Plain, Blackwood Plateau, Margaret River Plateau, and Leeuwin–Naturaliste Coast) can be found on COWARAMUP–MENTELLE. Moore (1990) summarizes the total availability of renewable groundwater resources underlying the study area.

The Abba System (Swan Coastal Plain) is covered by a veneer of predominantly clayey regolith commonly of less than 10 m thickness, containing unconfined groundwater, with the watertable generally at very shallow depth. Yields are usually only small to moderate because of the clayey nature of the sediments. The salinity of the shallow groundwater increases from about 500 mg/L total dissolved solids (TDS) near the Whicher Scarp to more than 1000 mg/L TDS towards the coast, and the iron content is commonly high.

Large groundwater supplies are generally available from sandy sections within the Leederville Formation underlying the Abba System. The salinity of the confined groundwater is generally less than 500 mg/L TDS, with a slight increase towards the coast, and the iron content is commonly high. Upward hydraulic heads may cause bores to flow.

Within the Treeton and Yelverton Systems (Blackwood Plateau), the Leederville Formation outcrops at, or close to, the surface. A thin cover of sand and duricrust gravel is common on the slopes and in the valleys. Small to moderate supplies of shallow, fresh groundwater are locally available from the sand and duricrust. The iron content is typically high.

The Cowaramup System (Margaret River Plateau) is formed of Leeuwin Complex metamorphic rocks that are commonly weathered to a mottled clay sequence to depths that may reach 50 m. Groundwater is usually brackish to saline, and either confined to faults and fractures that are difficult to locate from the surface, or located at the contact of weathered and fresh bedrock. Yields from bores are generally very small, or more commonly, bores in this system are dry.

The Quindalup and Spearwood Systems (Leeuwin–Naturaliste Coast) consists of eolian sand and Tamala Limestone over granitic or gneissic bedrock of the Leeuwin Complex. Because of rapid channel flow in the limestone, a watertable is often not developed. Groundwater supplies from the sand and limestone are restricted to a few favourable locations, including town supplies for Yallingup and Gracetown.

References

ABEYSINGHE, P. B., 1998, Limestone and limesand resources of Western Australia. Western Australia Geological Survey, Mineral Resources Bulletin 18, 140p.

ANAND, R. R., CHURCHWARD, H. M., SMITH, R. E., SMITH, K., GOZZARD, J. R., CRAIG, M. A., and MUNDAY, T. J., 1993, Classification and atlas of regolith-landform mapping units. Exploration perspectives for the Yilgarn Craton: Australia, CSIRO Division of Exploration and Mining, Restricted Report 440R (unpublished).

APPLEYARD, S. J., 1991, The geology and hydrogeology of the Cowaramup borehole line, Perth Basin, Western Australia: Western Australia Geological Survey, Report 30, Professional Papers, p. 1–12.

AUSTRALIAN SURVEYING AND LAND INFORMATION GROUP, 1990, Atlas of Australian Resources, Third Series, Volume 6, Vegetation: Canberra, Commonwealth Government Printer, 64p.

BAXTER, J. L., 1976, Limestone — Western Australia, *in* Economic geology of Australia and Papua New Guinea, Volume 4. Industrial minerals and rocks *edited by* C. L. KNIGHT: Australasian Institute of Mining and Metallurgy, Monograph 8, p. 205–207.

BAXTER, J. L., 1977, Heavy mineral sand deposits of Western Australia: Western Australia Geological Survey, Mineral Resources Bulletin 10, 148p.

BAXTER, J. L., 1981, Geology of mineral sand deposits in Western Australia, *in* Selective reference papers for mineral-sand mining: Perth, Western Australia School of Mines and WAIT.

BAXTER, J. L., and HAMILTON, R., 1981, The Yoganup Formation and the Ascot Beds as possible facies equivalents: Western Australia Geological Survey, Annual Report 1980, p. 42–43.

BEARD, J. S., 1990, Plant life of Western Australia: Kenthurst, NSW, Kangaroo Press, 319p.

BETTENAY, E., 1983. Western Region (II), *in* Soils: an Australian viewpoint: Division of Soils, CSIRO, p. 179–187 (CSIRO:Melbourne/Academic Press:London).

CHRISTIAN, C. S., and STEWART, G. A., 1953. General report on the survey of Katherine–Darwin region, 1946: CSIRO Land Research Series No. 1.

COCKBAIN, A. E., 1990, Perth Basin, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 495–524.

COMPSTON, W., and ARRIENS, P. A., 1968, The Precambrian geochronology of Australia: Canadian Journal of Earth Science, v. 5, p. 561–583.

COPE, R. N., 1972, Tectonic style in the Southern Perth Basin: Western Australia Geological Survey, Annual Report 1971, p. 46–50.

CRA EXPLORATION PTY LTD, 1992, Cowaramup coal/mineral sands exploration, Partial Surrender Report: Western Australia Geological Survey, M-Series, A 38582, I6834.

CROSTELLA, A., and BACKHOUSE, J., 2000, Geology and petroleum exploration of the central and southern Perth Basin: Western Australia Geological Survey, Report 57, 85p.

EDGELL, H. S., 1963, Pleistocene mollusca from the vicinity of Busselton: Western Australia Geological Survey, Palaeontology Report no. 8/1963 (unpublished).

ELECTROLYTIC ZINC COMPANY OF AUSTRALASIA LTD, 1971, Margaret River Project, Western Australia. Interim Report: Western Australia Geological Survey, M-Series, A3385 I1276 (unpublished).

FAIRBRIDGE, R. W., 1949, Preliminary report on the geology of the coastal plain and other sedimentary areas between Busselton and Geraldton, Western Australia: Richfield Oil Company, USA: Western Australia Geological Survey, Open File Report, 19/1948, 73p.

FAIRBRIDGE, R. W., 1953, Australian stratigraphy: Perth, University of Western Australia, Text Books Board, 516p.

FLETCHER, I. R., and LIBBY, W. G., 1993, Further isotopic evidence for the existence of two distinct terranes in the southern Pinjarra Orogen, Western Australia: Western Australia Geological Survey, Report 34, p. 81–83.

FLETCHER, I. R., WILDE, S. A., and ROSMAN, K. J. R., 1985, Sm–Nd model ages across the margins of the Archaean Yilgarn Block, Western Australia, III — The western margin: Australian Journal of Earth Sciences, v. 32, p. 73–82.

GEOTECHNICAL CONTROL OFFICE, 1988, Guide to rock and soil description: Hong Kong, Civil Engineering Services Department, Geoguide no. 3, 189p.

HASSAN, L. Y., 1998, Mineral occurrences and exploration potential of southwest Western Australia: Western Australia Geological Survey, Report 65, 38p.

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.

IASKY, R. P., 1993, A structural study of the southern Perth Basin, Western Australia: Western Australia Geological Survey, Report 31, 56p.

JEANS, D. N. (editor), 1986, The natural environment, Australia, a geography, Vol. 1, second edition: Sydney, New South Wales, Sydney University Press, 347p.

JENNINGS, J. N. and MABBUTT, J. A., 1986, Physiographic outlines and regions, *in* Australia — a geography, volume 1, The natural environment *edited by* D. N. JEANS: Netley, SA, Sydney University Press, p. 80–96

KRISTENSEN, S. E., and WILSON, A. C., 1986, A review of the coal and lignite resources of Western Australia, *in* Geology and exploration, Publications of the 13th CMMI Congress, volume 2 *edited by* D. A. BERKMAN: 13th Congress of the Council of Mining and Metallurgical Institutions and The Australasian Institute of Mining and Metallurgy: Parkville, Victoria, p. 87–97.

LE BLANC SMITH, G., and KRISTENSEN, S. E, 1998, Geology and Permian coal resources of the Vasse River Coalfield, Perth Basin, Western Australia: Western Australia Geological Survey, Record 1998/7, 49p.

LEONARD, E. L., 1991, Yallingup sheet 1930 IV and part Sheet 1830 I: Western Australia Geological Survey, 1:50 000 Environmental Geology Series.

LOW, G. H., 1971, Definition of two new Quaternary formations in the Perth Basins: Western Australia Geological Survey, Annual Report 1970, p. 33–34.

LOWRY, D. C., 1965, Geology of southern Perth Basin: Western Australia Geological Survey, Record 1965/17 (unpublished).

LOWRY, D. C., 1967, Busselton and Augusta, Western Australia: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 22p.

McARTHUR, W. M., 1991. Reference soils of Western Australia: Agriculture Western Australia, 265p.

McARTHUR, W. M., and BETTENAY, E., 1960, The development and distribution of the soils of the Swan Coastal Plain, Western Australia: Australia CSIRO, Soil Publication 16.

McCULLOCH, M. T., 1987, Sm–Nd isotopic constraints on the evolution of Precambrian crust in the Australian continent, *in* Proterozoic lithospheric evolution *edited by* A. KRONER: American Geophysical Union, Geodynamics Series, v. 17, p. 115–130.

McDONALD, R. C., ISBELL, R. F., SPEIGHT, J. G., WALKER, J., and HOPKINS, M. S., 1984, Australian soil and land survey field handbook. Inkata Press, Melbourne, 160p.

MID-EAST MINERALS NL, 1972, Busselton region mineral sands exploration, 1969–1972: Western Australia Geological Survey, M-Series, A3440, I1270.

MILNE, G., 1935, Some suggested units of classification and mapping particularly for East African soils: Soil Research, 4, No. 3.

MOORE, G., 1990, Potential for horticulture study: stage 1 — Moore River to Dunsborough: Western Australian Department of Agriculture Division of Resource Management Technical Report no. 105.

MYERS, J. S., 1990a, Geological note: Anorthosite in the Leeuwin Complex of the Pinjarra Orogen, Western Australia: Australian Journal of Earth Sciences, v. 37, p. 241–245.

MYERS, J. S., 1990b, Pinjarra Orogen, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 264–274

MYERS, J. S., 1994, Late Proterozoic high-grade gneiss complex between Cape Leeuwin and Cape Naturaliste: Geological Society of Australia ,WA Division, Excursion Guidebook, no. 6, 23p.

MYERS, J. S., 1995, Geology of the Albany 1:1 000 000 sheet, W.A. Sheet SI 50: Western Australia Geological Survey, 1:1 000 000 Geological Series Explanatory Notes, 9p.

MYERS, J. S., SHAW, R. D., and TYLER, I. M., 1996, Tectonic evolution of Proterozoic Australia: Tectonics, v. 15, p. 1431–1446.

NELSON, D. R., 1996, Compilation of SHRIMP U–Pb zircon geochronology data, 1995: Western Australia Geological Survey, Record 1996/5, 167p.

PAIN, C. F., WILFORD, J. R., and DOHRENWEND, J. C., 1994, Regolith–landform of the Ebagoola 1:250 000 Sheet Area (SD54-12) North Queensland: Australian Geological Survey Organisation, Record 1994/7, 38p.

PASSMORE, J. R., 1967, The geology, hydrology and contamination of shallow coastal aquifers in the Rockingham district, Western Australia: University of Western Australia, PhD thesis (unpublished).

PASSMORE, J. R., 1970, Shallow coastal aquifers in the Rockingham District, Western Australia: Water Research Foundation of Australia, Bulletin 18, 83p.

PEN, L., 1997, A systematic overview of environmental values of the wetland, rivers and estuaries of the Busselton–Walpole region: Water and Rivers Commission, Water Resource Allocation and Planning Series, Report No. WRAP 7, 125p.

PLAYFORD, P. E., COCKBAIN, A. E., and LOW, G. H., 1976, Geology of the Perth Basin, Western Australia: Western Australia Geological Survey, Bulletin 124, 311p.

SAINT-SMITH, E. C., 1912, A geological reconnaissance of a portion of the South-West Division of Western Australia. Western Australia Geological Survey, Bulletin 44, 80p.

SEDDON, G., 1972, Sense of place; a response to an environment, the Swan Coastal Plain, Western Australia: Perth, University of Western Australia Press, 274p.

STANDARDS AUSTRALIA, 1993, Australian Standard, Geotechnical Site Investigation: Standards Australia, Homebush, NSW, 38p.

TILLE, P. J., and LANTZKE, N. C., 1990a, Busselton–Margaret River–Augusta land capability study: Western Australian Department of Agriculture, Land Resource Series No. 5.

TILLE, P. J., and LANTZKE, N. C., 1990b, Busselton–Margaret River–Augusta land capability study; methodology and results, volume 1. Western Australian Department of Agriculture, Resource Management Division Technical Report no. 109.

TOWNSEND, D. B., 1994, Mineral deposits of the Albany 1:1 000 000 sheet: Western Australia Geological Survey, Record 1993/4, 80p.

TYLER I. M., PIRAJNO, F., BAGAS, L., MYERS, J. S., and PRESTON, W. A., 1998. The geology and mineral deposits of the Proterozoic in Western Australia: AGSO Journal of Australian Geology and Geophysics, 17 (3), p. 223–244.

van de GRAAFF, W. J. E., 1983, Silcrete in Western Australia — geomorphological settings, textures, structures, and their genetic implications*, in* Residual deposits — surface related weathering processes and materials *edited by* R. C. L. WILSON: (Geological Society of London); Oxford, Blackwell Scientific Publications, p. 159–166.

WELCH, B. K., 1964, The ilmenite deposits of Geographe Bay: Australasian Institute of Mining and Metallurgy, Proceedings, v. 211, p. 25–48.

WHARTON, P. H., 1981, The geology and hydrology of the Quindalup borehole line: Western Australia Geological Survey, Annual Report 1980, p. 27–35.

WILDE, S. A., and MURPHY, D. M. K., 1990, The nature and origin of late Proterozoic high-grade gneisses of the Leeuwin Block, Western Australia: Precambrian Research, v. 47, p. 251–270.

Appendix 1

Gazetteer of named localities on Cowaramup–Mentelle

Name	Easting	Northing
10 Mile Brook	327100	6240100
A-Alla Homestead	325200	6246900
Adina Homestead	329200	6263500
Arundell Homestead	331600	6244000
Ashbrook	319900	6258000
Augusta–Margaret River Shire	322600	6241600
Baligah Kia Homestead	329900	6249800
Ban-Y-Gloe Homestead	330200	6244900
Bardfield Homestead	317800	6256900
Basildene Homestead	320100	6240900
Big Rock surf spot	313100	6250000
Big Valley Homestead	329600	6238000
Biljedup Brook	315000	6257900
Biljedup Brook	316100	6257500
Blackboy Hollow Cave	316200	6236400
Boat Ramp surf spot	313600	6237300
Bombie surf spot	313500	6238000
Boodjidup Brook	326100	6237800
Bramley	321600	6246700
Bramley Brook	322600	6245100
Brandon Homestead	325100	6251000
Broadvale Homestead	320300	6236400
Brookland Valley	317100	6258800
Burnside	318100	6242800
Cambalup Farm	338000	6241700
Cape Mentelle	313400	6240300
Cape Mentelle	318600	6239700
Carbunup Brook	330100	6252500
Chateau Xanadu	319400	6239400
Chelita Homestead	328600	6253200
Clovermoor Homestead	334400	6256400
Cobblestones surf spot	313200	6249900
Collins Firetower	315600	6248300
Cow Rock	312500	6240500
Cowaramup townsite	323800	6252600
Cowaramup Bay	313500	6251300
Cowaramup Brook	314100	6251100
Cowaramup Brook	319100	6250300
Cowaramup East	324500	6252900
Cowaramup Point	312900	6251100
Cowaramup Reef	311200	6254700
Creed Barnes Memorial	313900	6238600
Cullens	318500	6256200
Daleep	316500	6243100
Dallip Spring	314400	6243000
Dawson Gully	333500	6258100
Dingville Homestead	318000	6237100
Elberton Homestead	318900	6253400
Ellen Brook	314100	6246100
Ellen Brook	319100	6247200
Ellensbrook surf spot	313900	6246700
Ellensbrook Homestead	314300	6245900
Elmhurst Homestead	324900	6254700
Evans and Tate	318400	6259600
Fairfield Homestead	328400	6254800
Fairview Homestead	332900	6253500
Fermoy Estate	320000	6260000
Firegully Farm	320000	6261300
Forrest Spring	320500	6260900
Freycinet Estate	320400	6236400
Gallows surf spot	314600	6256400
Glen Aire Homestead	330400	6251600
Glenbourne Homestead	316200	6245500
Gleneyle Homestead	318000	6236700
Glengary Homestead	324800	6240700
Glenluce Homestead	321500	6255400
Gnarabup Beach	314300	6237700
Gnarabup Swamp	314700	6238400
Gnarawary Homestead	321300	6237100
Gnoocardup	314500	6244000
Gnoocardup Beach	314300	6244000
Gracetown	313800	6250600
Gralyn	317800	6257800
Guillotine surf spot	314400	6255500
Harmans	325600	6258200
High Jolly Homestead	323400	6249800
Honeycombs surf spot	313900	6261100
Hope Valley Homestead	330100	6253200
Huzzawooee	313700	6251200
Innishargie Homestead	334200	6253500
Ironstone Gully	336100	6256500
Island Brook	328000	6263100
Jessica Homestead	336400	6243400
Jilyara Homestead	320900	6261200
Joeys Nose	314500	6241900
Juniper Homestead	316400	6253800
Kachana Homestead	328100	6253000
Kaloorup	334100	6260100
Karendale Homestead	319300	6263500
Karriview Homestead	316000	6250600
Keenan	323100	6245300
Kilcarnup	314500	6242300
Kilcarnup Beach	314400	6241900
Kilcarnup Springs	314600	6241600
Leecroft Homestead	326000	6263000
Leeuwin Homestead	321000	6250000
Lefthanders surf spot	313400	6248500
Lenton Brae Homestead	318200	6260400
Lindross Homestead	322600	6262900
Margaret River	313800	6239400
Margaret River townsite	322100	6241100
Margaret River Main surf spot	313700	6238600
Margaret River Montessori School	321800	6240300
Margaret River Pre-School	322000	6241300
Margaret River Primary School	322100	6241200
Margaret River Senior High School	322000	6241200
Meekadarribee Falls	315800	6245500
Metricup	327100	6261100
Miamup Brook	314400	6253600
Miamup Brook	317100	6254100
Miamup Swamp	317500	6253400
Montrave Farm	323000	6258400
Morrisons	321100	6258600
Moses Rock	314400	6263000
Moses Rock surf spot	313800	6262800
Moss Brothers	318200	6260800
Mosswood	318200	6260000
Mouquet Homestead	317300	6245000
Mowen townsite	333100	6243100
Mowen Homestead	333300	6243300
Mundaringa Homestead	334200	6249600
Na-Gillah Homestead	333700	6243700
Nargon Homestead	321400	6238900
New Kerry Homestead	327900	6257700
Newlands Homestead	324700	6258000
Noisies	313400	6248700
Noojee Homestead	328300	6260100
North Point	313500	6251700

Appendix 1 (continued)

Name	*Easting*	*Northing*	*Name*	*Easting*	*Northing*
Nowheres	313600	6247900	Tanridge Homestead	336300	6259300
Ocean Valley Homestead	316800	6260100	Taunton Farm	326600	6257200
Osmington	335700	6245900	Tea Lake	316900	6239200
Pembridge Homestead	320900	6251900	The Scented Garden Homestead	333500	6248100
Pierro	317800	6258800	The Womb surf spot	313700	6247200
Pine Place Homestead	331200	6244600	Trastevere Homestead	319500	6255800
Prevelly townsite	313600	6238100	Treeton	333100	6251800
Quininup Brook	316100	6263700	Treeton Park Homestead	336100	6256000
Rainbow Cave	315300	6238000	Upper Chapman Brook	337100	6237600
Red Gully	320100	6257600	Vasse Felix	319400	6255700
Ribbon Vale	318100	6258400	Veryiuca Brook	314400	6254300
Rivermouth surf spot	313800	6239300	Veryiuca Brook	315600	6254300
Robbies Reef	314300	6254800	Walburra	324600	6259600
Rolling Plains Homestead	321800	6250200	Walburra Nature Reserve	325800	6259100
Rosa Brook	332100	6241900	Wallcliffe Cave	315000	6239200
Rosa Brook Estate	321700	6239300	Wallcliffe House	314900	6239300
Rosa Glen	332100	6236600	Warralea Homestead	324600	6256100
Rosa Park	329800	6241600	Warwick Glen Homestead	323400	6249900
Roseway Homestead	336300	6259000	Wayup Downs Homestead	335400	6254900
Roslyn Homestead	331500	6261800	Willespie	320600	6259200
Rutland Gate Homestead	334700	6245500	Wilyabrup	319100	6258800
S.S. Georgette Memorial	322000	6241300	Wilyabrup Brook	314700	6259300
Sandalford	319500	6259900	Wilyabrup Brook	317100	6258800
Settarah Park	323800	6252600	Wirring	328700	6248700
Shekinah Homestead	325300	6245800	Wongaburra Homestead	321800	6242600
Snowbridge Homestead	331300	6262500	Woodlands	317600	6259800
South Park Homestead	320300	6239500	Woodlands	317500	6259600
South Point surf spot	312700	6251000	Woodlands Brook	318900	6260100
Southward Park Homestead	334500	6253200	Woody Nook	322200	6260600
Stockwell Homestead	328600	6248700	Wrights	319500	6255600
Stone Haven Homestead	337600	6241900	Yalgardup Brook	320000	6241100
Sussex District	323000	6245600	Yangedung	314600	6242500
Tallyho Homestead	325700	6251500	Yelverton	325800	6263900
Tanah Marah	324300	6247100			

SOURCE: Department of Land Administration (Western Australia)

Appendix 2

Classification of vegetation
(Australian Surveying and Land Information Group, 1990)

Tall trees (>30 m)	
T2	Tall woodland
T3	Tall open forest
T4	Tall closed forest
Medium trees (10–30 m)	
M1	Open woodland
M2	Woodland
M3	Open forest
M4	Closed forest
Low trees (<10 m)	
L1	Low open woodland
L2	Low woodland
L3	Low open forest
L4	Low closed forest
Tall shrubs (>2 m)	
S1	Tall open shrubland
S2	Tall shrubland
S3	Open scrub
S4	Closed scrub
Low shrubs (<2 m)	
Z1	Low open shrubland
Z2	Low shrubland
Z3	Open heath
Z4	Closed heath
Hummock grasses	
H2	Hummock grassland
Tussocky or tufted grasses and graminoids	
G1	Sparse open tussock grassland
G2	Open tussock grassland
G3	Tussock grassland or sedgeland
G4	Closed tussock grassland or sedgeland
Other herbaceous plants	
F1	Sparse open herbfield
F2	Open herbfield
F3	sown pasture
F4	Dense sown pasture
Other	
NIL	No significant vegetation
LIT	Littoral complex
HOR	Horticultural complex
URB	Urban complex

Appendix 3

Slope classification system
(McDonald et al., 1984)

Slope (degrees)	*Slope symbol*	*Slope name*
0 – 0.6	LE	level
0.6 – 1.75	VG	very gently inclined
1.75 – 5.75	GE	gently inclined
5.75 – 18	MO	moderately inclined
18 – 30	ST	steep
30 – 45	VS	very steep
45 – 72	PR	precipitous
72 – 90	CL	cliffed

Appendix 4

Abbreviations

AHD	Australian Height Datum (mean sea level)
BP	Before present
CD	Chart Datum (lowest astronomical tide)
ka	Thousands of years (kilo anna)
Ma	Millions of years (mega anna)
MGA	Map Grid of Australia
Mt	Millions of tonnes

Appendix 5

Grain-size ranges for field classification and particle-size determination of regolith
(Geotechnical Control Office, 1988; Standards Australia, 1993)

	Size range (mm)	*Sieve size range (mm)*
boulders	>200	
cobbles	200 – 60	
coarse gravel	60 –20	>2.36
medium gravel	20 – 6	
fine gravel	6 – 2	
coarse sand	2 – 0.6	0.6 – 2.36
medium sand	0.6 – 0.2	0.212 – 0.6
fine sand	0.2 – 0.06	0.075 – 0.212

Appendix 6

Classification of rock material strength

(Geotechnical Control Office, 1988; Standards Australia, 1993)

	TEST METHOD				
STRENGTH	*Hand*	*Thumbnail*	*Pocket knife*	*Geological pick*	*Hand specimen*
EXTREMELY WEAK	easily crumbled	indented deeply			
VERY WEAK	crumbled with difficulty	scratched easily	peeled		
WEAK	broken into pieces	scratched	peeled	deep indentations (<5 mm)	broken by single light hammer blow
MODERATELY WEAK	broken with difficulty	scratched with difficulty	difficult to peel but easily scratched	shallow indentations easily made	usually broken by single light hammer blow
MODERATELY STRONG			scratched	shallow indentations with firm blow	usually broken by single firm hammer blow
STRONG				superficial surface damage with firm blow	more than one firm hammer blow to break
VERY STRONG					many hammer blows required to break
EXTREMELY STRONG					only chipped by hammer blows

Appendix 7

Mineral occurrence definitions

The Geological Survey of Western Australia's (GSWA) Western Australian Mineral Occurrence database (WAMIN) contains geoscience attribute information on mineral occurrences in Western Australia. The database includes textual and numeric information on the location of occurrences, accuracy of the locations, commodities, mineralization classification, the resource tonnage, estimated grade, mineralogy of ore, gangue mineralogy, details of host rocks, and both published and unpublished references.

The WAMIN database uses a number of authority tables to constrain the essential elements of a mineral occurrence, including the operating status, commodity group, and style of mineralization. In addition, there are parameters that dictate whether the presence of a mineral or analysed element is sufficiently high to rank occurrence status; this Report deals only with mineral occurrences. Other attributes were extracted from reports provided by mineral exploration companies or from authoritative references.

Those elements of the database that were used to create the mineral occurrences symbols and tabular information displayed on the COWARAMUP–MENTELLE 1:50 000-scale map are:

- operating status (number style);
- commodity group (symbol colour);
- mineralization style (symbol shape);
- position (symbol position).

Operating status

The database includes mineralization sites ranging from small but mineralogically significant mineral occurrences to operating mines. The classification takes into account all deposits and mines with established resources in the Department of Minerals and Energy (DME) mine and mineral deposits information database (MINEDEX; Townsend et al., 2000). All occurrences in the WAMIN database are assigned a unique, system-generated number. The style of this number (**bold**, *italicized*, and so on) is used as the coding to indicate operating status, both on the map and in the accompanying table. The system used is:

- mineral occurrence — any economic mineral exceeding an agreed concentration and size found in bedrock or regolith (italic, serif numbers, e.g. *5*);
- prospect — any working or exploration activity that has found subeconomic mineral occurrences, and from which there is no recorded production (italic, serif numbers, e.g. *3175*);

Table 7.1. WAMIN authority table for commodity groups

Commodity group	*Typical commodities*	*Symbol colour*
Precious mineral	Diamond, semi-precious gemstones	
Precious metal	Ag, Au, PGE	
Steel-industry metal	Co, Cr, Mn, Mo, Nb, Ni, V, W	
Speciality metal	Li, REE, Sn, Ta, Ti, Zr	
Base metal	Cu, Pb, Zn	
Iron	Fe	
Aluminium	Al (bauxite)	
Energy mineral	Coal, U	
Industrial mineral	Asbestos, barite, kaolin, talc	
Construction material	Clay, gravel, limestone	

Table 7.2. Modifications made to the Mining Journal Ltd (1997) commodity classification

Commodity group (Mining Journal Ltd, 1997)	*Commodities*	*Changes made for WAMIN commodity group*
Precious metals and minerals	Au, Ag, PGE, diamonds, other gemstones	Diamond and other gemstones in precious minerals group Au, Ag, and PGE in precious metals group
Steel-industry metals	Iron ore, steel, ferro-alloys, Ni, Co, Mn, Cr, Mo, W, Nb, V	Fe in iron group
Specialty metals	Ti, Mg, Be, REE, Zr, Hf, Li, Ta, Rh, Bi, In, Cd, Sb, Hg	Sn added from major metals
Major metals	Cu, Al, Zn, Pb, Sn	Cu, Pb, and Zn into the base metals group Al (bauxite) into aluminium group Sn in speciality metals
Energy minerals	Coal, U	No change
Industrial minerals	Asbestos, sillimanite minerals, phosphate rock, salt, gypsum, soda ash, potash, boron, sulfur, graphite, barite, fluorspar, vermiculite, perlite, magnesite/magnesia, industrial diamonds, kaolin	No change

Table 7.3. WAMIN authority table for mineralization styles and groups

Mineralization style	*Typical commodities*	*Group symbol*[(a)]
Kimberlite and lamproite intrusions	Diamond	☆
Carbonatite and alkaline igneous intrusions	Nb, Zr, REE, P	
Orthomagmatic mafic and ultramafic — undivided	PGE, Cr, V, Ni, Cu	✚
Orthomagmatic mafic and ultramafic — komatiitic or dunitic	Ni, Cu, Co, PGE	
Pegmatitic	Ta, Li, Sn, Nb	⬡
Greisen	Sn	
Skarn	W	
Disseminated and stockwork in plutonic intrusions	Cu, Mo	
Vein and hydrothermal — undivided	Au, Ni, Cu, Pb, Zn, U, Sn, F	◇
Vein and hydrothermal — unconformity	U	
Stratiform sedimentary and volcanic — volcanic-hosted sulfide	Zn, Cu, Pb, Ag, Au	△
Stratiform sedimentary and volcanic — volcanic oxide	Fe, P, Cu	
Stratiform sedimentary and volcanic — undivided	Pb, Zn, Cu, Ag, Au, Fe	
Stratiform sedimentary and volcanic — sedimentary-hosted sulfide	Pb, Zn, Cu, Ag	
Stratabound — undivided	Pb, Ba, Cu, Au	□
Stratabound — carbonate-hosted	Zn, Pb, Ag, Cd	
Stratabound — sandstone-hosted U	U	
Sedimentary — undivided	Mn	
Sedimentary — banded iron-formation	Fe	
Sedimentary — residual to eluvial placers	Au, Sn, Ti, Zr, REE, diamond	
Sedimentary — alluvial to beach placers	Ti, Zr, REE, diamond, Au, Sn	
Sedimentary — calcrete	U, V	○
Sedimentary — basin	Coal	
Residual and supergene	Al, Au, Fe, Ni, Co, V	▭
Undivided	Various	▽

NOTE: (a) The white symbol colour used in this table does not indicate the commodity group in Table 7.1

- mineral deposit — economic mineral for which there is an established resource figure (serif numbers, e.g. 33);
- abandoned mine — workings that are no longer operating or are not on a care-and-maintenance basis, and for which there is recorded production, or where field evidence suggests that the workings were for more than prospecting purposes (bold, italic, sans serif numbers, e.g. ***181***);
- operating mine — workings that are operating, including on a care-and-maintenance basis, or that are in development leading to production. (bold, sans serif numbers, e.g. **37**).

The name of an occurrence and any synonyms that may have been used are derived from the published literature and from company reports. As some occurrences will not have been named in the past, these appear without names in the WAMIN database — no attempt has been made to provide names where none is currently recognized. The name that appears in MINEDEX database is used where possible, although there may be differences because MINEDEX reports on production and resources whereas WAMIN notes individual occurrences.

Commodity group

The WAMIN database includes a broad grouping based on potential or typical end-use of the principal commodities constituting a mineral occurrence. The commodity group as given in Table 7.1 determines the colours of the mineral occurrence symbols on the map. The commodity groupings are based on those published by the Mining Journal Ltd (1997), and are modified as shown in Table 7.2 to suit the range of minerals and end-uses for Western Australian mineral output.

Mineralization style

There are a number of detailed schemes for dividing mineral occurrences into groups representing the style of mineralization. The most widely used scheme is probably that of Cox and Singer (1986). The application of this scheme in Western Australia would necessitate modifications to an already complex scheme, along the lines of those adopted by the Geological Survey of British Columbia (Lefebure and Ray, 1995; Lefebure and Hoy, 1996). Representing the style of mineralization on a map cannot be simply and effectively achieved if the scheme adopted is too complex.

GSWA has adopted the principles of ore-deposit classification from Evans (1987). This scheme works on the premise that 'If a classification is to be of any value it must be capable of including all known ore deposits so that it will provide a framework and a terminology for discussion and so be of use to the mining geologist, the prospector and the exploration geologist'. The system here is based on an environment–rock association classification, with elements of genesis and morphology where they serve to make the system simpler and easier to apply and understand (Table 7.3).

To fully symbolize all the mineralization-style groups would result in a system that is too complex. As the full details of the classification are preserved in the underlying WAMIN database, the chosen symbology has been reduced to nine shapes.

Table 7.4. Minimum intersections for mineral occurrences in drillholes or trenches

Element	*Intersection length (m)*	*Grade*
Hard rock and lateritic deposits		
Gold	> 5	> 1 ppm
Silver	>1 0	> 1 ppm
Platinum	> 0.5	> 1 ppm
Lead	> 5	> 0.5%
Zinc	> 5	> 2%
Copper	> 5	> 0.5%
Nickel	> 5	> 0.5%
Cobalt	> 5	> 0.1%
Chromium	> 0.2	> 5% Cr_2O_3
Tin	> 5	> 0.02%
Iron	> 5	> 40% Fe
Manganese	> 5	> 25%
Uranium	> 5	> 1000 ppm U
Diamonds	na	any diamonds
Tantalum	> 5	> 200 ppm
Tungsten	> 5	> 1000 ppm (0.1%)
Placer deposits		
Gold	na	> 300 mg/m^3 in bulk sample
Diamonds	na	any diamonds
Heavy minerals	> 5	> 2% ilmenite

NOTE: na: not applicable

Mineral occurrence determination limits

The lower cutoff limit for a mineral occurrence is more reliably based on WAMEX exploration company information. Minimum intersections in drillholes or trenches for a number of commodities are in Table 7.4.

Professional judgement is used if shorter intercepts at higher grade (or vice versa) are involved. Any diamonds or gemstones are classified as mineral occurrences, including diamondiferous kimberlites.

References

COX, D. P., and SINGER, D. A., 1986, Mineral deposit models: United States Geological Survey, Bulletin 1693, 379p.

EVANS, A. M., 1987, An introduction to ore geology: Oxford, Blackwell Scientific Publications, 358p.

LEFEBURE, D. V., and RAY, G. E., 1995, Selected British Columbia mineral deposit profiles, Volume 1 — Metallics and coal: British Columbia, Ministry of Employment and Investment, Open File 1995-20, 135p.

LEFEBURE, D. V., and HOY, T., 1996, Selected British Columbia mineral deposit profiles, Volume 2 — Metallic deposits: British Columbia, Ministry of Employment and Investment, Open File 1996-13, 171p.

MINING JOURNAL LTD, 1997, Mining Annual Review, Volume 2 — Metals and minerals: London, Mining Journal Limited, 112p.

TOWNSEND, D. B., GAO, M., and MORGAN, W. R., 2000, Mines and mineral deposits of Western Australia: digital extract from MINEDEX — an explanatory note: Western Australia Geological Survey, Record 2000/13, 28p.

Appendix 8

Description of digital datasets

The following datasets have been used in compiling this Report, Map, and the accompanying CD-ROM.

Regolith–landform geology

Information on regolith–landform geology has been compiled in digital format and is supplied as separate layers or polygon themes:

- regolith–landform geology;
- simplified land systems;
- interpreted onshore bedrock geology.

Field information that was collected is held in the GSWA's WAROX database. Selected tables and fields were extracted and this information is supplied as separate layers or point themes:

- field notes;
- rock and regolith descriptions;
- structural information;
- field-sketch sites.

Linear features are presented as separate layers or line themes:

- faults;
- dunecrests.

Full details of each layer or theme are given on the CD-ROM.

Mineral occurrences (WAMIN) and quarry locations

The mineral occurrence dataset, as used in this Report and the Map, is described in Appendix 7. The dataset on the CD-ROM includes textual and numeric information on:

- location of the occurrences (MGA coordinates, latitude and longitude);
- commodities and commodity group;
- mineralization classification and morphology;
- operating status;
- end-use.

Potential construction and industrial mineral resources, and quarry locations, are displayed digitally on separate layers or polygon themes.

Landsat

Landsat 5 TM imagery, using bands 3, 2 and 1 in 8-bit RGB format, has been acquired for COWARAMUP–MENTELLE with the onshore (13/03/1996) and offshore (30/01/1992 and 07/12/1998) regions being enhanced separately and mosaiced together. The raw data are available through the Remote Sensing Services section of the Department of Land Administration. Images are included in the digital package that preserve the original 25 m pixel size, but these cannot be reverse-engineered back to any bands or band ratios of the original 6-band dataset.

Topography, roads, and culture

The following digital data displayed as separate layers or themes come from the Department of Land Administration (DOLA):

- contours;
- topo points;
- spot heights;
- water bodies;
- swamp;
- pipelines;
- roads;
- rail;
- powerlines;
- buildings;
- airport;
- A-class reserves;
- local government areas;
- wharf (jetty).

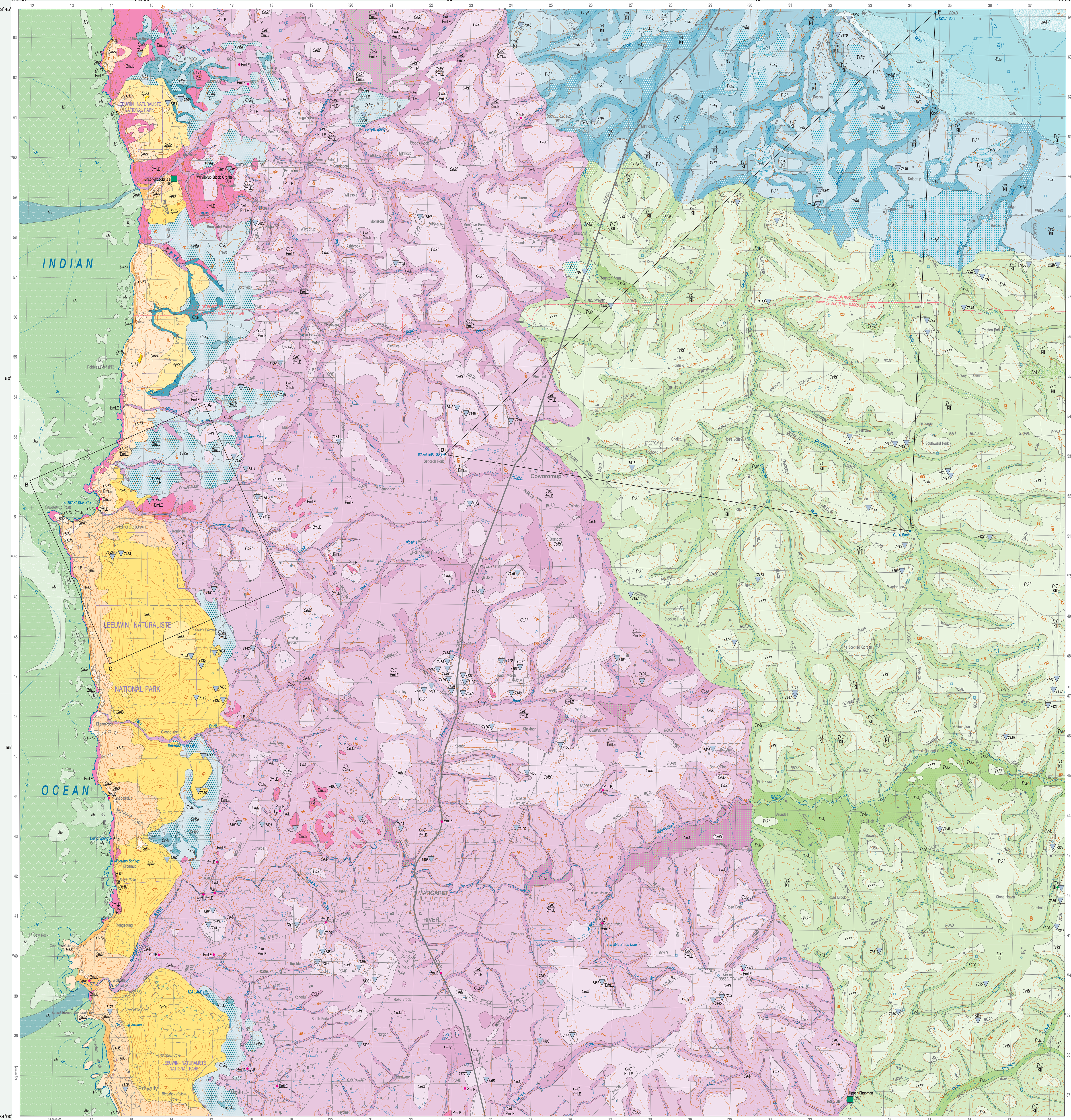
Bathymetric contours are sourced from the Department of Transport. The coastline has been derived from the orthophotographs used for geological mapping.

COWARAMUP — MENTELLE

AUSTRALIA 1:50 000 REGOLITH–LANDFORM RESOURCES SERIES

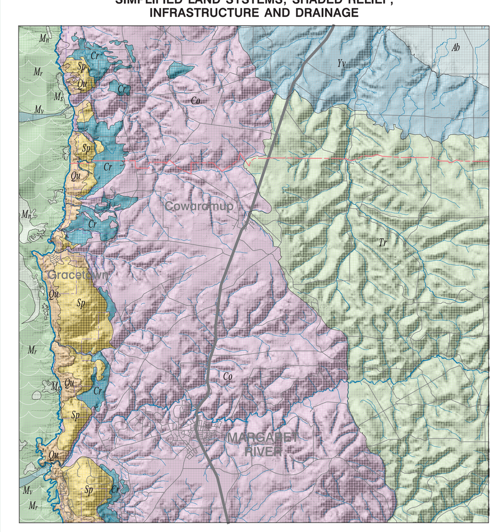
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SHEET 1930-III, AND PART OF 1830-II FIRST EDITION 2000



SYMBOLS

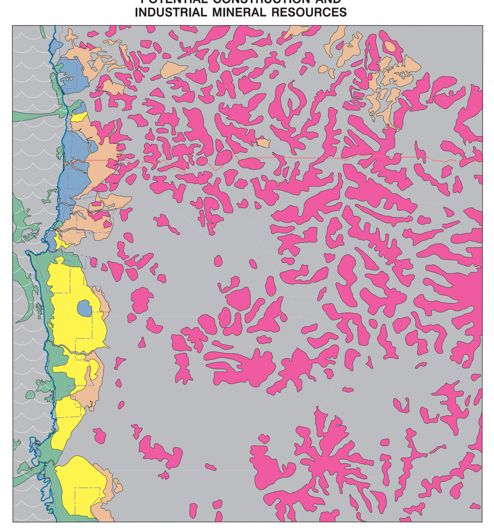
SIMPLIFIED LAND SYSTEMS, SHADED RELIEF, INFRASTRUCTURE AND DRAINAGE



LEGEND

REFERENCE

POTENTIAL CONSTRUCTION AND INDUSTRIAL MINERAL RESOURCES



QuBo, AbAwf, AbAd, AbAa, CrAw, CrAd, CrC/Czs, YvAw, YvRpf, YvAdf, YvC/Kll, YvC/Czs, TrAc, TrAw, TrAd, TrAa, TrAwf, TrAdf, TrC/Kll, CoAw, CoAc, CoAd, CoAt, CoAa, CoC/PmLE, PmLE, Mr

Colluvial sand and gravel, alluvium and associated hardpans, weathered bedrock, and nearshore rocky seabed; limited potential.

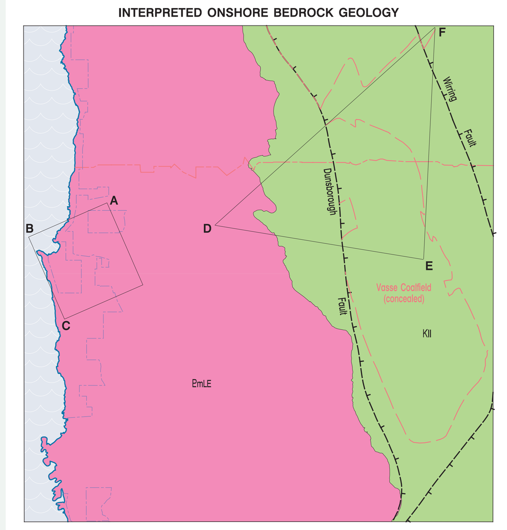
SCALE 1:250 000

0 5 10

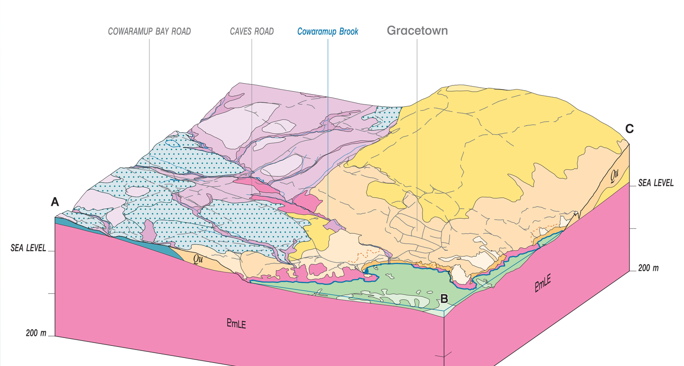
Kilometres

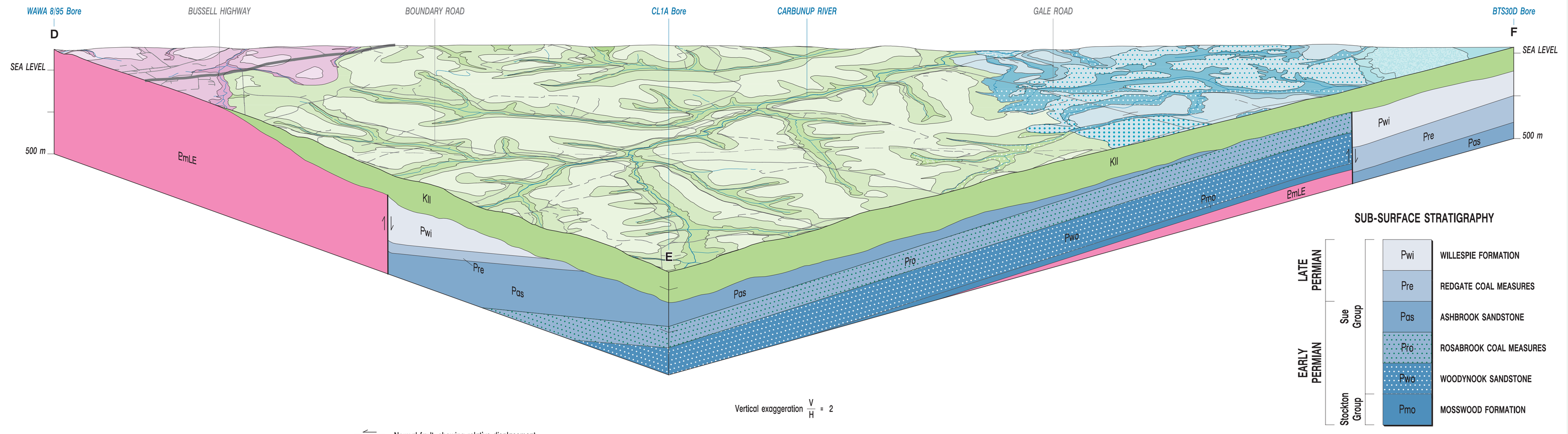
LANDSAT TM IMAGE WITH FIELD SITE LOCATIONS

INTERPRETED ONSHORE BEDROCK GEOLOGY



BLOCK DIAGRAMS





COWARAMUP — MENTELLE MINERAL OCCURRENCES

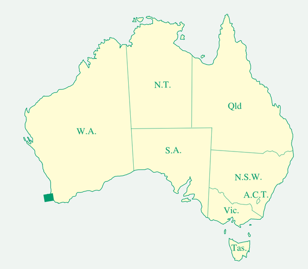
NUMBER*	COMMODITY	EASTING	NORTHING
SPECIALITY METAL—HMS			
Sedimentary—alluvial to beach placers			
69	HMS	315650	6259550
2042	HMS	333000	6236800
CONSTRUCTION MATERIAL—Gvl, Lsd, Lst, Sv, Bsdi			
Undivided			
6144	Gvl	326015	6238285
6145	Sv	329530	6239220
6622	Gvl	317060	6259820
6624	Gvl	318385	6254990
6625	Gvl	317690	6258480
7130	Gvl	336700	6245985
7133	Lst	314265	6250005
7134	Gvl	323200	6251555
7135	Gvl	317870	6251615
7136	Sv	318295	6254210
7137	Gvl	317255	6252620
7138	Gvl	323110	6247245
7139	Gvl	323155	6247085
7140	Gvl	322725	6247380
7142	Gvl	317825	6247825
7143	Lsd	316285	6247605
7144	Gvl	322105	6246870
7145	Gvl	323060	6253815
7147	Gvl	331440	6246900
7148	Gvl	337985	6247435
7149	Sv	316435	6246565
7153	Lst	314480	6250145
7154	Gvl	322820	6247685
7155	Gvl	322705	6247575
7156	Gvl	325585	6245545
7157	Gvl	337920	6247190
7159	Gvl	334055	6250060
7160	Gvl	332685	6253405
7163	Gvl	330760	6258775
7165	Gvl	330580	6256745
7167	Gvl	329765	6259215
7168	Sv	320355	6261240
7169	Gvl	334595	6256040
7170	Gvl	332200	6263455
7172	Gvl	333190	6251625
7173	Gvl	330450	6249775
7174	Sv	329890	6248195
7175	Gvl	331435	6246960
7176	Gvl	338195	6242195
7177	Gvl	323430	6237285
7178	Lsd	314415	6238655
7179	Lsd	314835	6236720
7180	Sv	316630	6245100
7181	Gvl	316825	6249285
7182	Gvl	315170	6251480
7183	Gvl	317410	6254360
7184	Gvl	319885	6253040
7185	Gvl	324190	6253630
7186	Gvl	324425	6249840
7187	Gvl	327275	6249340
7188	Gvl	324530	6247475
7189	Gvl	324330	6246815
7190	Gvl	324520	6243450
7197	Sv	325965	6257405
7198	Gvl	326130	6261220
7294	Sv	332475	6263870
7327	Gvl	335930	6257465
7332	Gvl	335785	6257585
7334	Bsdi	317090	6259730
7342	Sv	331810	6259560
7343	Sv	331780	6259210
7344	Gvl	335485	6256685
7345	Gvl	333775	6260150
7346	Gvl	324255	6263560
7347	Gvl	326640	6256565
7348	Gvl	321810	6258705
7349	Gvl	321230	6257535
7350	Sv	315780	6261545
7351	Lst	315445	6261440
7352	Lst	314720	6262645
7353	Gvl	336170	6238845
7355	Gvl	336350	6239765
7356	Gvl	334165	6239020
7357	Gvl	338100	6241225
7358	Gvl	337960	6243220
7359	Gvl	338180	6241885
7360	Gvl	335120	6243600
7361	Sv	333665	6240540
7362	Gvl	329745	6239305
7371	Gvl	330275	6240055
7383	Gvl	320600	6243615
7384	Sv	319715	6240260
7386	Sv	316530	6244245
7387	Sv	315775	6242490
7388	Gvl	326730	6239630
7389	Gvl	325205	6239585
7390	Gvl	325205	6238130
7391	Gvl	323875	6237135
7392	Gvl	320690	6237960
7393	Gvl	321040	6239590
7394	Gvl	320635	6239880
7395	Gvl	319670	6240735
7396	Sv	319595	6240000
7397	Gvl	319055	6240925
7398	Gvl	316840	6240875
7399	Gvl	316950	6241240
7400	Gvl	317565	6243435
7401	Sv	318140	6243420
7402	Gvl	318975	6243335
7403	Gvl	320025	6244425
7404	Gvl	321615	6243380
7405	Gvl	322395	6242625
7406	Gvl	324755	6244840
7407	Gvl	329405	6245525
7409	Gvl	326955	6247750
7410	Gvl	324060	6247615
7411	Gvl	317565	6252325
7412	Sv	317960	6251160
7413	Gvl	322840	6253940
7414	Gvl	323540	6249355
7415	Sv	327245	6252525
7417	Gvl	333825	6253240
7418	Gvl	334110	6253270
7419	Gvl	334115	6250705
7420	Gvl	335165	6252580
7421	Gvl	335240	6252470
7422	Sv	336245	6250945
7423	Gvl	337780	6246770
7425	Sv	327595	6247180
7426	Sv	323850	6245975
7427	Gvl	323110	6246800
7428	Gvl	322825	6246845
7429	Gvl	322745	6247140
7430	Gvl	322475	6247385
7431	Gvl	322320	6246970
7432	Sv	317105	6246520
7433	Sv	316920	6246790
7434	Sv	316870	6247690
7435	Sv	316545	6247365
7436	Gvl	337095	6257800
7439	Gvl	337815	6257810
7721	Gvl	334565	6256350

* KEY TO OPERATING STATUS

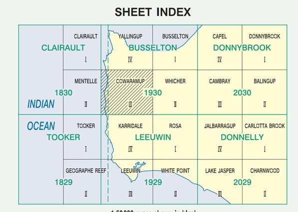
Bold numbers (i.e. 6592) — Operating quarry
Bold and italic numbers (i.e. 6609) — Abandoned quarry
Plain numbers (i.e. 1609) — Mineral deposit
Italic numbers (i.e. 7334) — Mineral occurrence or prospect

Numbers refer to GSWA WAMIN mineral occurrence database

True north, grid north and magnetic north are shown diagrammatically for the centre of the map. Magnetic north is correct for 2000 and moves easterly by about 0.1° in 2 years.



SHEET INDEX



Geology by G. Hall, J. Marnham, and R. L. Langford 1998–99

Edited by D. Ferdinando and G. Loan

Cartography by S. Collopy, J. Kirk, and B. Williams

Topography from the Department of Land Administration Sheet SI 50-5, 1930 and part of 1830, with modifications from geological field survey

Landsat Imagery was supplied by the Remote Sensing Services, Department of Land Administration

Bathymetric data supplied by the Department of Transport. This map is not intended for marine navigation

Bore and well data supplied by the Water and Rivers Commission

Published by the Geological Survey of Western Australia. Copies available from the Information Centre, Department of Minerals and Energy, 100 Plain Street, East Perth, WA, 6004. Phone (08) 9222 3459, Fax (08) 9222 3444

This map is also available in digital form

Plotted by the Geological Survey of Western Australia

The recommended reference for this map is:
HALL, G., MARNHAM, J., and LANGFORD, R.L., 2000, Cowaramup—Mentelle, W.A. Sheet 1930 III, and part of 1830 II: Western Australia Geological Survey, 1:50 000 Regolith–Landform Resources Series

DEPARTMENT OF MINERALS AND ENERGY
L. C. RANFORD, DIRECTOR GENERAL

GOVERNMENT OF WESTERN AUSTRALIA
HON. NORMAN MOORE, M.L.C.
MINISTER FOR MINES

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
DAVID BLIGHT, DIRECTOR

SCALE 1:50 000

1000 500 0 1 2 3 4 5

Metres Kilometres

UNIVERSAL TRANSVERSE MERCATOR PROJECTION
HORIZONTAL DATUM: GEOCENTRIC DATUM OF AUSTRALIA 1994
VERTICAL DATUM: AUSTRALIAN HEIGHT DATUM
BATHYMETRIC DATUM: LOWEST LOW SEA LEVEL

Grid lines indicate 1000 metre interval of the Map Grid Australia Zone 50

The Map Grid Australia (MGA) is based on the Geocentric Datum of Australia 1994 (GDA94). GDA94 positions are compatible within one metre of the datum WGS84 positions.

AUSTRALIA 1:50 000 REGOLITH–LANDFORM RESOURCES SERIES

COWARAMUP — MENTELLE

SHEET 1930-III, AND PART OF 1830-II FIRST EDITION 2000

COLOUR PLOT 4, REVISED APPROVAL PLOT — 6 SEPTEMBER 2000