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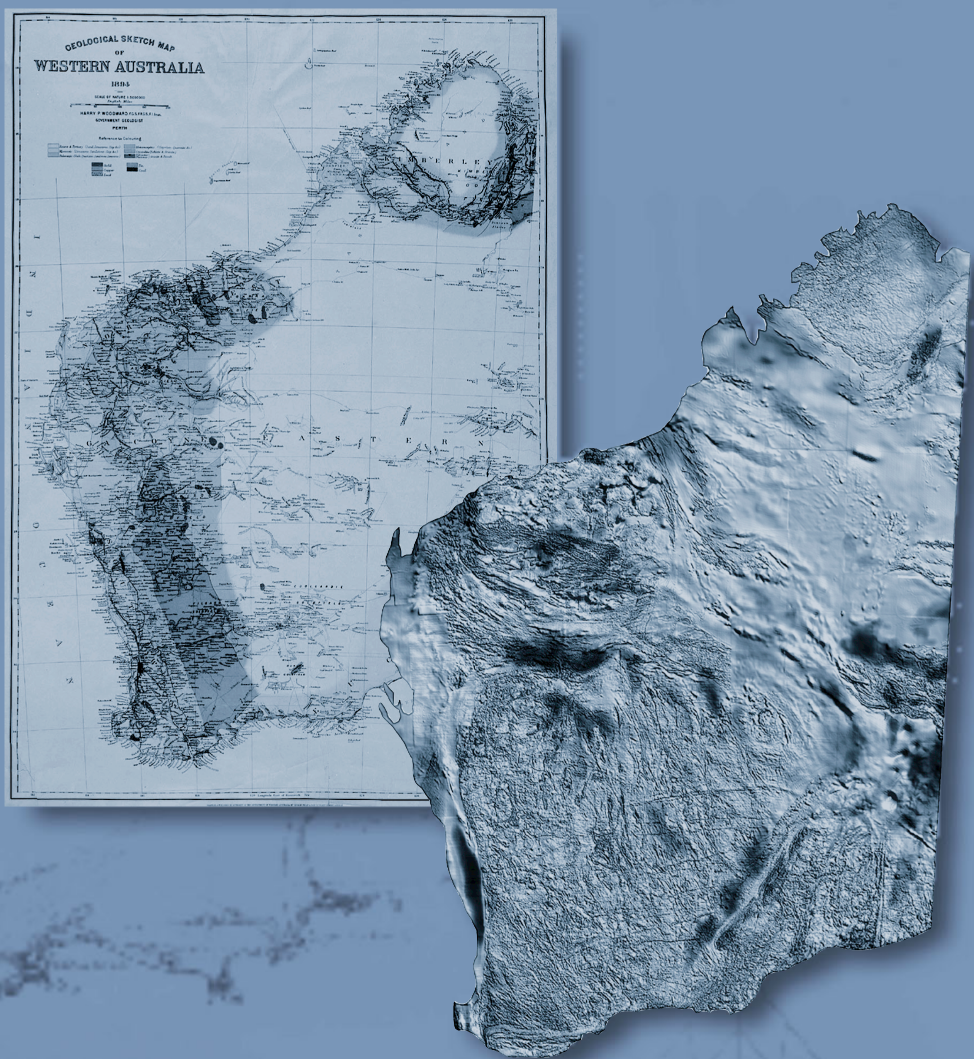
REGOLITH–LANDFORM RESOURCES OF THE KARRIDALE–TOOKER AND LEEUWIN 1:50 000 SHEETS

by G. J. Hall and J. R. Marnham



Geological Survey of Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

Record 2002/10

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by

G. J. Hall and J. R. Marnham

Perth 2002

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Regolith–landform resources of the KARRIDALE–TOOKER 1:50 000 sheet ..... (in pocket)
Regolith–landform resources of the LEEUWIN 1:50 000 sheet ..... (in pocket)

Regolith–landform resources of the Karridale–Tooker and Leeuwin 1:50 000 sheets

by

G. J. Hall and J. R. Marnham

Abstract

Regolith–landform mapping of the KARRIDALE–TOOKER and LEEUWIN 1:50 000-scale map sheets, located about 250 km south of Perth, has defined eight land systems, and provided a subdivision of the seabed materials and morphology. The onshore systems are the Cowaramup, Treeton, Caves Road, Nillup, Scott, Blackwood, Spearwood, and Quindalup Systems. These are defined on the basis of the dominant underlying parent materials that range in age from Proterozoic through 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 from the weathering of Cretaceous strata. The Caves Road System is a level to gently inclined eroded land surface of probable Eocene age made up of residual coastal or fluvial deposits overlying the Leeuwin Complex. The Nillup System is a level to gently undulating shelf composed of residual materials underlain by undivided Cainozoic sediments and rocks of the Cretaceous Leederville Formation. The Scott System is a low-lying, gently undulating plain composed of a mixture of fluvial, eolian, and residual deposits. The Blackwood System consists of a plain, and a tidal estuary with islands and tidal flats associated with the Blackwood River, and overlies both Proterozoic and Cretaceous rocks. 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. 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 composed of Leeuwin Complex and limestone, shoreface, nearshore and offshore sand, and marine channels.

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

Large areas of KARRIDALE–TOOKER and LEEUWIN have landuses that currently 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 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 currently subeconomic to mine.

KEYWORDS: Karridale, Leeuwin, Blackwood, Augusta, Witchcliffe, Cape Leeuwin, geomorphology, mineral resources, basic raw materials, sand, gravel, heavy minerals, coal, regolith–landform, landuse, land systems, natural hazards, viticulture.

Introduction

The KARRIDALE–TOOKER and LEEUWIN* 1:50 000 regolith–landform resources maps 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. These maps 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 maps provide information on the regolith materials (engineering soils) and underlying rocks, on the landforms (landscape), topography and infrastructure, and on the mineral resources of KARRIDALE–TOOKER and LEEUWIN. Land systems are defined as areas with recurring patterns of landform, regolith materials, and vegetation. Within

* Capitalized names refer to standard map sheets.

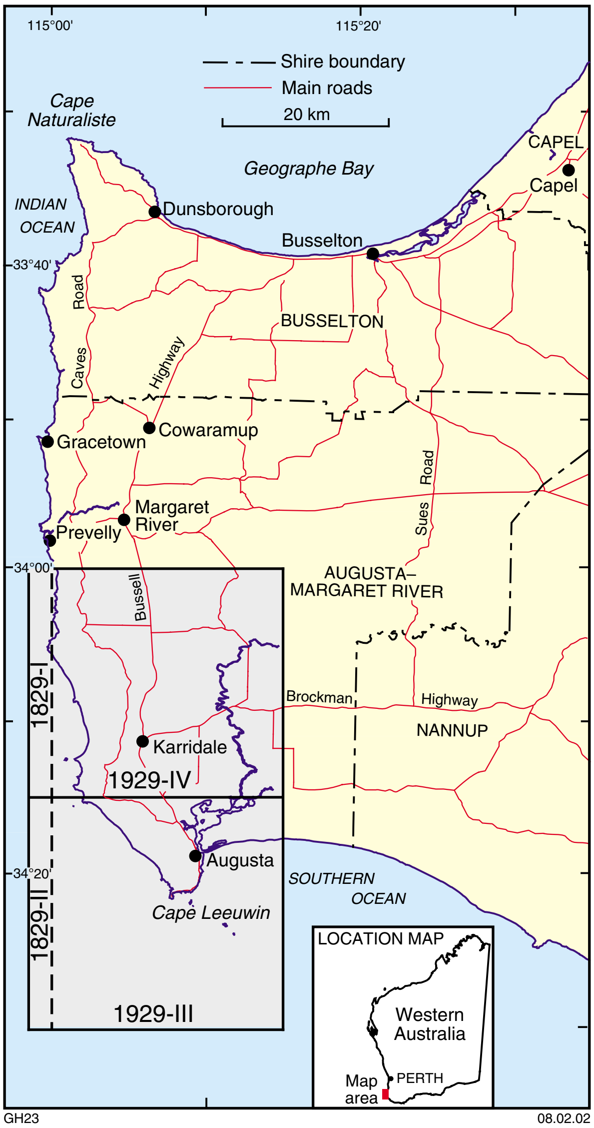

Figure 1. **Location of KARRIDALE–TOOKER and LEEUWIN in Western Australia**

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 potential for basic raw materials and heavy mineral deposits.

The accompanying CD-ROM contains the data used to compile the maps 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. A description of digital datasets is given in Appendix 1.

Location

The KARRIDALE–TOOKER and LEEUWIN 1:50 000-scale maps (1929 IV and part of 1829 I, and 1929 III) lie between latitudes 34°00' and 34°30'S, and longitudes 114°58' and 115°15'E (Fig. 1). The sheets lie in the South West Region of Western Australia, forming part of the Leeuwin–Naturaliste geographic region, a distinctive anvil-shaped promontory 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. KARRIDALE–TOOKER and LEEUWIN lie towards the south of this geographic region, and cover part of the Shire of Augusta–Margaret River.

The land area of KARRIDALE–TOOKER is 605 km^2, and that of LEEUWIN is 157 km^2. The offshore areas for KARRIDALE–TOOKER and LEEUWIN are 249 and 693 km^2 respectively. The population of the main town of Augusta is around 3000, with about another 3000 inhabitants in the surrounding area. A gazetteer of named localities and features is given as Appendix 2. Perth, the capital city of Western Australia, lies about 250 km to the north.

Infrastructure

KARRIDALE–TOOKER and LEEUWIN are 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. Construction of the Busselton bypass was completed in December 2000. The Bussell Highway provides access to the townsites of Witchcliffe and Augusta (Fig. 2). An alternative route to Augusta is via Sues Road, which joins the Brockman Highway east of Nillup, and then on to Karridale where the Bussell Highway is met again. Sues Road was upgraded and sealed for use as an all-weather heavy haulage route by BHP to cater for its Beenup Titanium Minerals mine located immediately east of KARRIDALE–TOOKER. Mining at Beenup ceased in late March 1999 (Broken Hill Proprietary Company Limited, 1999) but the road remains an asset to the infrastructure of the region. There is an extensive network of sealed and unsealed roads serving the local farming community (Fig. 2).

Caves Road runs parallel to the Leeuwin–Naturaliste Ridge, and two sealed roads off Caves Road provide access to Redgate Beach in the north (Redgate Road) and Hamelin Bay (Hamelin Bay Road West) in the south. There is no rail link to the region, with the railway from Perth terminating north of the area at Busselton. A railway once ran from Busselton to Augusta with links extending from a number of timber milling sites around Karridale to the port facilities established at Hamelin Bay for the purpose of timber export (Winfield, 1986). Railway reserves remain through some of the National Park area on KARRIDALE–TOOKER and the route remains as an historic trail. An airfield is situated southwest of Augusta townsite. Currently there are no commercial services operating in the South West, with links to Perth available on a charter flight basis.

For power supply the area forms part of the South West Interconnected System that serves the southwest corner of

Figure 2. Infrastructure and drainage

the State, with a high-voltage transmission line connecting to coal or heavy fuel-oil generating stations at Muja and Bunbury.

Augusta currently has a water supply system based on the Fisher Road borefield supplemented by the Leeuwin Spring near Cape Leeuwin. Previously, water supply was taken solely from the Leeuwin Spring, which emerges at the contact between the Leeuwin Complex and the Tamala Limestone. Later environmental concerns led to the Fisher Road source being investigated (Forrest, 1993) and brought into production. Here, water is extracted from the Leederville Formation. Waterbores typically have low yields west of the Dunsborough Fault, and some water is stored in farm dams, particularly for use in the viticulture industry.

Landuse

The Leeuwin–Naturaliste region was dominated by eucalypt forest when aboriginal people occupied the land. McArthur (1991) summarized the history of settlement in the region. 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 organized development of the area. The dairy industry was almost the sole activity prior to the Second World War. After the war, beef and sheep grazing became more important. The first commercial vineyard was planted in the Margaret River Wine Region on COWARAMUP–MENTELLE in 1967, and by the mid 1970s vineyards had also been planted south of Margaret River on KARRIDALE–TOOKER. Vineyards and orchards have since become significant contributors to the local economy in terms of both wine production and generation of local tourism opportunities.

The dominant land uses in KARRIDALE–TOOKER and LEEUWIN are grazing and dairy farming, forestry, low-density urban development, and recreation reserves. Viticulture is increasingly being developed into areas formerly used for grazing and dairy farming, as the land has attributes similar to COWARAMUP–MENTELLE, where there is currently a higher density of vineyards. The area is a popular tourist destination, with world-renowned surfing beaches, and many accessible caves. Urban development is centred on the townsite of Augusta, with smaller settlements at Witchcliffe, Karridale, Kudardup, and East Augusta. The area between the Leeuwin–Naturaliste Ridge and the Bussell Highway is more intensely developed than coastal or inland areas.

Tille and Lantzke (1990a) provided 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.

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 regolith are summarized in Table 1 (Beard, 1990). The classification of vegetation used during mapping of KARRIDALE–TOOKER and LEEUWIN is given in Appendix 3.

The Menzies Botanical Subdistrict (Southern Jarrah Forest Subregion), which covers the northern portion of KARRIDALE–TOOKER, 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 much of LEEUWIN, 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

Table 1. Relationships between vegetation and regolith

Vegetation type	*Dominant species*	*Height (m)*	*Regolith*
Tall karri forest	*Eucalyptus diversicolor*	≤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 forest	*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
Jarrah low woodland	*E. marginata*	≤10	Poorly drained sands on watersheds

SOURCE: after Beard (1990)

valleys and drainage depressions (Beard, 1990). The coastal vegetation in the Leeuwin–Naturaliste National Park is mostly old growth, whereas most of the State forests are now regrowth.

Climate

The climate across most of KARRIDALE–TOOKER and LEEUWIN is classified as Moderate Mediterranean, characterized by cool wet winters and a short dry season of three to four months (Beard, 1990). Climatic averages for rainfall (Table 2) and temperature (Table 3) are available for stations at Cape Leeuwin, which lies within LEEUWIN, and for Karridale, which lies within KARRIDALE–TOOKER. Rainfall ranges from 1194 mm a year in the north, to 998 mm a year in the south. January and February are the hottest months, with temperatures in the north reaching an average maximum of 24.7°C at Karridale, and 23.3°C to the south at Cape Leeuwin. July is the coldest month, with average maximum temperatures reaching 16.3°C at Cape Leeuwin, and 16.1°C at Karridale. June is the wettest month at Karridale and July is the wettest month at Cape Leeuwin (Bureau of Meteorology website, 2001).

Previous investigations

The majority of geological publications covering KARRIDALE–TOOKER and LEEUWIN 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

Table 2. Mean monthly rainfall (mm) and raindays from the Karridale (1894–1963) and Cape Leeuwin (1897–2001) weather stations

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	***Annual***
Rainfall (mm)													
Karridale	20.1	21.9	35.6	68.9	172.8	227.9	223.3	166.5	110.2	82.4	37.3	27.6	**1 194.6**
Cape Leeuwin	16.5	16.5	29.6	62.0	143.5	184.6	186.6	139.2	92.3	68.1	37.9	21.8	**998.5**
Raindays													
Karridale	3.7	3.8	6.3	10.3	17.2	20.3	22.4	20.1	16.7	13.6	8.6	5.2	**148.2**
Cape Leeuwin	6.1	6.0	8.9	13.3	20.0	22.5	25.0	23.3	20.1	17.1	11.3	8.0	**181.7**

SOURCE: Bureau of Meteorology website

Table 3. Mean maximum and minimum daily temperatures (°C) from the Karridale (1894–1963) and Cape Leeuwin (1897–2001) weather stations

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	***Annual***
Mean max. temp (°C)													
Karridale	24.6	24.7	23.7	22.0	19.1	16.9	16.1	16.4	17.3	18.5	21.3	23.4	**20.3**
Cape Leeuwin	23.0	23.3	22.6	21.2	19.1	17.3	16.3	16.4	17.0	18.2	20.1	21.8	**19.7**
Mean min. temp (°C)													
Karridale	13.6	13.4	12.5	10.8	9.8	8.9	8.1	8.1	8.8	9.4	10.9	12.5	**10.6**
Cape Leeuwin	16.9	17.2	16.6	15.4	13.6	12.1	11.3	11.1	11.7	12.5	14.1	15.7	**14.0**

SOURCE: Bureau of Meteorology website

area mapped and reported by Saint-Smith (1912) includes the northern portion of KARRIDALE–TOOKER, reaching as far south as Crystal Cave. Saint-Smith (1912) noted the widespread blanket of residual material formed by weathering in situ of the underlying rock, the abundant limestone and gneissic granite outcropping along the coast, and recent alluvium forming flats alongside the Blackwood River.

More recently, several regional geological maps have been published that include the KARRIDALE–TOOKER and LEEUWIN sheet areas. 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. 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 most recent account of the geology of the Leeuwin Complex is found in a summary by Wilde and Nelson (2001).

The mineral resource potential of the ALBANY 1:1 000 000-scale sheet was assessed by Townsend (1994), and the subsurface coal resources on the Vasse Shelf were defined by Le Blanc Smith and Kristensen (1998). The Regional Forest Agreement was the impetus for the compilation of mineral occurrence data published in a joint report by Bureau of Resource Sciences and Geological Survey of Western Australia (1998). This was followed by a report, 1:500 000-scale geological map, and digital dataset by Hassan (1998). Crostella and Backhouse (2000) assessed the results of petroleum exploration in the southern Perth Basin, and reviewed the stratigraphy. Baxter (1977) compiled information on heavy mineral sand deposits of the region.

Smith (1951) mapped the soils of the Margaret River – Lower Blackwood River Districts. Bettenay (1983), and Jennings and Mabbutt (1986) defined the broad physiographic framework, and detailed descriptions were given by Playford et al. (1976), and Tille and Lantzke (1990a). Tille and Lantzke (1990a), who used the land systems methodology in their 1:50 000-scale soil and landscape maps, have also documented the land capability and agricultural potential. Beard (1990) provided a regional view of the plant life, including correlations with bedrock, soil, and landform. McArthur (1991) documented representative sites of major soil types in the region.

Geology and geomorphology

Proterozoic

The Leeuwin Complex (Fig. 3), 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).

Estimates of the age of formation and subsequent deformation of the complex ranging from Mesoproterozoic to Cambrian (1090–525 Ma*) are given by Compston and Ariens (1968), Fletcher et al. (1985), McCulloch (1987), Myers (1990a,b), Wilde and Murphy (1990), Fletcher and 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 within the Perth Basin to the east of the Dunsborough Fault was formed and stabilized during an earlier phase of the Pinjarra Orogen than that which formed 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

The oldest known sedimentary rocks in the area are Palaeozoic strata as indicated from drilling and seismic data. They do not outcrop on KARRIDALE–TOOKER and

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

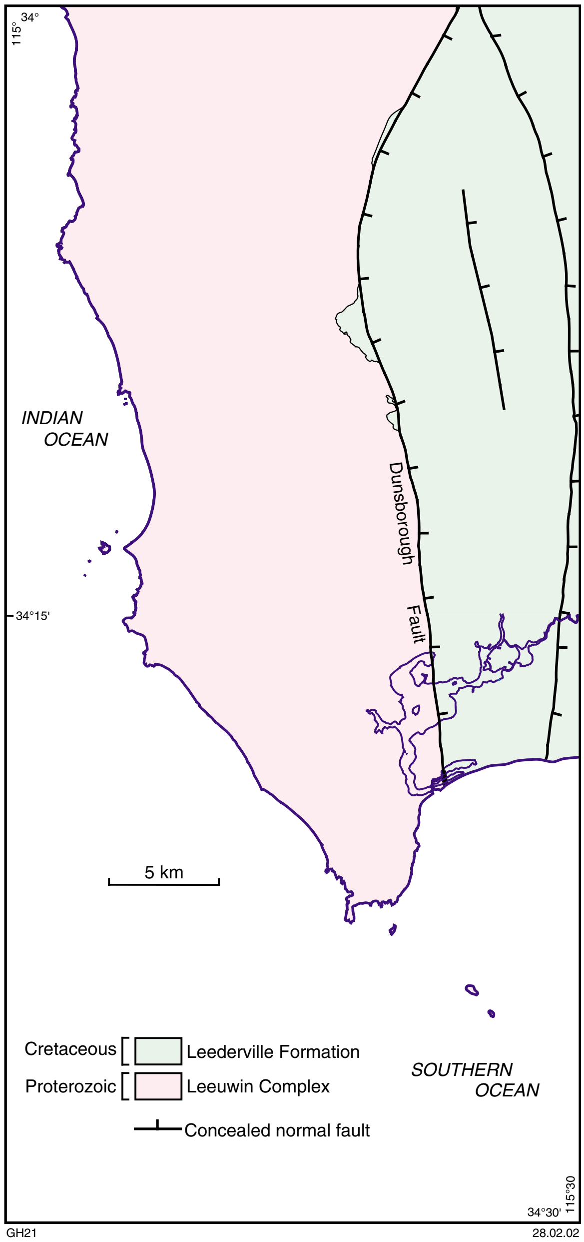

Figure 3. Interpreted onshore bedrock geology

Leeuwin, and are restricted to units within the Permian Stockton and Sue Groups, which subcrop on the Vasse Shelf east of the Dunsborough Fault (Playford et al., 1976; Le Blanc Smith and Kristensen, 1998; Crostella and Backhouse, 2000). The Sue Group conformably overlies the Stockton Group at depth (Le Blanc Smith and Kristensen, 1998), which in turn rests unconformably on Proterozoic basement.

The Palaeozoic strata form part of a non-marine sequence in the Perth Basin that was deposited over the Pinjarra Orogen. Cockbain (1990) recognized three main tectonic phases for the development of the Perth Basin. Rifting began at about 420 Ma in the Silurian and continued intermittently until the Early Cretaceous at about 135 Ma. Early basin development occurred in the northern Perth Basin area, but sediments from this phase are not found in the southern Perth Basin. The Stockton and Sue Groups relate to a second phase of basin development within the southern Perth Basin that went from the Permian through to the Early Cretaceous. Early Permian sedimentation was influenced by the retreating Gondwana ice sheet as the climate became warmer (Le Blanc Smith and Kristensen, 1998). Depositional environments range from fluvial to lacustrine.

Permian

The concealed Permian Stockton and Sue Groups overlie basement rocks of the Perth Basin and lie unconformably below the flat-lying Cretaceous Leederville Formation to the east of the concealed Dunsborough Fault, (Fig. 3; Le Blanc Smith and Kristensen, 1998). Playford et al. (1976) referred to the Sue and Stockton Groups as a single unit, the Sue Coal Measures. Based on the palynostratigraphy of Backhouse (1991, 1992, 1993), the Permian in the southern Perth Basin is now divided into two groups comprising six formations. These are summarized in Le Blanc Smith and Kristensen (1998), and Crostella and Backhouse (2000). The Sue Group contains coal-bearing strata, notably the Vasse River Coalfield located on Cowaramup– Mentelle (Hall et al., 2000) to the north of Karridale–Tooker. The Permian strata on the Treeton Terrace, an uplifted block on the Vasse Shelf bounded to the east by the Wirring Fault, are up to 2 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 Stockton Group is represented by the Mosswood Formation, which is a glacial unit found at the base of the Permian succession. Backhouse (1993) identified the Mosswood Formation in Sue 1, a petroleum exploration borehole on the Vasse Shelf to the east of Karridale–Tooker. Le Blanc Smith and Kristensen (1998) define the type section in two coal exploration holes located on Cowaramup–Mentelle. New isopach maps in Crostella and Backhouse (2000), partially derived from the work of Iasky (1993), show the Mosswood Formation lying at depths between 0.5 and 1.5 km in the area. The thickness of this unit is 35 m in the type section, but this varies over the palaeotopography of the surface that it covers. The upper contact with the Sue Group is conformable and gradational (Crostella and Backhouse, 2000).

The Sue Group (Table 4) contains the Woodynook Sandstone, Rosabrook Coal Measures, Ashbrook Sandstone, Redgate Coal Measures, and Willespie Formation, for which detailed descriptions are given in Le Blanc and Kristensen (1998). As a group, these fluvial and paludal units reach a thickness of up to 1800 m in the Sue 1 borehole. There are few deep boreholes that penetrate the Permian on Karridale–Tooker and Leeuwin. Baddock (1990) reports Sue Group from 200 m to 655 m in KL1A, but drilling in this hole did not extend to basement. Baddock (1995) depicts some areas on the Vasse Shelf where Sue Group lies directly beneath thin Quaternary sediments.

Table 4. Permian lithostratigraphy and coal seam names in the Vasse Coalfield

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	

SOURCE: after Le Blanc Smith and Kristensen (1998)

Mesozoic

Mesozoic strata present in the subsurface of the mapping area include the Triassic Sabina Sandstone and Lesueur Sandstone, and the Cretaceous Leederville Formation. The Sabina and Lesueur Sandstones conformably overlie Permian strata at depth, and are seen only in boreholes in the area. Triassic sediments have not been intersected in the northern part of the Vasse Shelf but have been noted in the Sue 1 and Alexandra Bridge 1 boreholes (Iasky, 1993) on the southern Vasse Shelf, just east of the area.

Mesozoic strata on KARRIDALE–TOOKER and LEEUWIN are restricted to the Cretaceous Leederville Formation, which overlies the Leeuwin Complex west of the Dunsborough Fault, and Triassic and Permian strata east of the fault (Fig. 3; 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 around 135 Ma (Cockbain, 1990; Myers, 1995). There were three distinct tectonic phases of this basin's evolution: Silurian to Carboniferous, Permian to Early Cretaceous, and Cretaceous to Holocene. In the southern Perth Basin, the record of deposition began in the Permian with the Sue Group, continued through the Triassic with deposition of the Sabina Sandstone and the Lesueur Sandstone, and then from the Jurassic to the Early Cretaceous with the Yarragadee Formation. Emplacement of the Bunbury Basalt coincided with the final phase of rifting during the separation of Australia and India at the beginning of the Cretaceous. This was followed by the deposition of the Leederville Formation.

Triassic

Triassic sedimentary rocks of the Sabina Sandstone and Lesueur Sandstone lie at depth in the southern Perth Basin on KARRIDALE–TOOKER and LEEUWIN, where they conformably overlie Permian sedimentary rocks. They are dominantly fluvial and lacustrine in origin, and were deposited during a phase of rifting that took place between the Permian and Early Cretaceous (Cockbain, 1990).

The Sabina Sandstone was deposited during the Lower Triassic, and consists of poorly consolidated, coarse clastic materials. The sandstone, which conformably overlies the Willespie Formation of the Sue Group, forms part of the continuous sedimentary sequence deposited throughout the Permian and Triassic. However, there is a palynostratigraphic break close to the boundary (Crostella and Backhouse, 2000). The Sabina Sandstone is conformably overlain by the Lesueur Sandstone.

The thickness of Sabina Sandstone on KARRIDALE–TOOKER and LEEUWIN is known from drillholes KL1A (MGA 332740E 6217850N), SC1A (MGA 335440E 6225850N) and SC3A (MGA 333935E 6203761N) to be 61 m, 23 m and 50 m respectively (Baddock, 1990; 1992; WRC WIN database). The thickest intersection of this unit lies to the east of the mapping area at 120 m depth in KL2A (MGA 342040E 6219150N) (Baddock, 1995).

The Lesueur Sandstone is overlain unconformably by the Leederville Formation. The Lesueur Sandstone has been totally eroded from some areas of the Vasse Shelf during uplift of the shelf (Baddock, 1995). Fluviatile materials range from poorly to moderately sorted, fine to coarse quartz sand and gravel. Palynomorphs from this unit are rare owing to a lack of suitable lithologies and highly oxidizing conditions. The sandstone reaches a thickness of 860 m in KL2A east of the area. On KARRIDALE–TOOKER and LEEUWIN, the thickness of Lesueur Sandstone is measured at 51 m, 105 m, 59 m, and 41 m in the boreholes KL1A, SC3A, SC1A, and SC2A respectively (Baddock, 1990, 1992).

Cretaceous

The Leederville Formation, part of the Warnbro Group, is the only part of the Perth Basin Cretaceous sequence represented on KARRIDALE–TOOKER and LEEUWIN, where it lies unconformably above Proterozoic, Permian, and Triassic rocks. The Warnbro Group was proposed by Cockbain and Playford (1973) and defined by Playford et al. (1976). Fairbridge (1953) introduced the name Leederville Sandstone (now Leederville Formation; Cockbain and Playford, 1973) for the non-marine unit that conformably overlies the Lower Cretaceous South Perth Shale as seen in bores around the Perth metropolitan area in the Perth Basin. The Leederville Formation is barren of foraminifera (Fairbridge, 1953). Later studies (Low, 1958; Backhouse, 1984; Baddock, 1990) have used palynostratigraphy to establish its age and make correlations throughout the Perth Basin. Lowry (1967) noted a Late Jurassic to 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 Jurassic Yarragadee Formation. Playford et al. (1976) also included the basal Warnbro Group in the Yarragadee Formation. Backhouse (1984) later revised the Late Jurassic and Early Cretaceous stratigraphy in the Perth Basin.

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 Triassic Lesueur Sandstone or the Permian Sue Coal Measures. They also noted that stratigraphic relationships are indefinite between the various isolated natural exposures. Lowry's (1967) Quindalup Beds were considered part of the Leederville Formation. Since the work of Playford et al. (1976) there has been no change to the assignation of these strata to the Leederville Formation. More recent hydrogeological (Hirschberg, 1988; Appleyard, 1988; Baddock, 1990, 1992) and petroleum stratigraphic drilling has assigned non-marine sedimentary rocks near the surface in the Southern Perth Basin to the Early Cretaceous 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 up to 300 m thick of sandstone, siltstone, minor conglomerate, and thin seams of lignite of continental origin (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 Leederville Formation also onlaps the Leeuwin Complex to the west of the concealed Dunsborough Fault (Fig. 3). There is limited exposure of the Leederville Formation noted on KARRIDALE–TOOKER. Outcrop is seen in the Blackwood River only where, on the river bed and banks, there are ferruginized sandstones and conglomerates. Elsewhere on KARRIDALE–TOOKER and LEEUWIN the Leederville Formation is highly to completely weathered and lies beneath a blanket of regolith materials.

Cainozoic

The Cainozoic on KARRIDALE–TOOKER and LEEUWIN 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. Their exact age of formation is uncertain, although the process may have started as early as the Middle to Late Eocene (49–34 Ma) (van de Graaff, 1983) when sea level began to rise, reaching a maximum during the Late Eocene (Hocking and Cockbain, 1990). Churchill (1973) suggested that the Eocene transgression at its maximum probably coincides with the present day 300 m contour line on the 'Western Australian Shield', although a 300 m rise in sea level is unlikely as tectonic uplift has probably taken place since then.

The shelves underlying the Caves Road and Nillup 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 subsequently 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 from the Eocene to Oligocene. Based on this, Marnham et al. (2000) proposed that this was also the period when the duricrusts formed on the eroded and partially dissected plateau in 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, and producing the colluvial slopes and present-day drainage system, probably ranges in age from Pliocene to Early Pleistocene. The dissection appears largely to pre-date the deposition of eolian sands of Pleistocene (<1.8 Ma) age that 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 youngest geological units range in age from the Late Tertiary to Holocene, and are concentrated mainly along the Leeuwin–Naturaliste Coast, the Scott Coastal Plain (South Coastal Plain), and alongside the Blackwood River. There are no studies in the mapping area that specifically date the age of their formation, although they can be correlated with similar units that have been dated from more northern areas of the Perth Basin.

A succession of shorelines and associated dune deposits ranging from the Pliocene to Holocene in age (Baxter and Hamilton, 1981; McArthur and Bettenay, 1960; Lowry, 1965) extend along the Scott Coastal Plain from the Hardy Inlet to Point D'Entrecasteaux 90 km to the southeast. They are attributed to the numerous eustatic sea-level changes that occurred mainly during the Pleistocene and which were caused by intermittent expansion and contraction of the polar ice caps. However, the matter may be complicated by tectonism, with uncertainty about how much movement, if any, has occurred along the Darling Fault during the Pleistocene (Playford et al., 1976). Such movements would have influenced shoreline positions. Evidence of warping is seen in the Pliocene Yoganup Formation on the Swan Coastal Plain (Cope, 1975).

The Pleistocene Tamala Limestone is confined to the Leeuwin–Naturaliste Ridge and some offshore reefs, stacks, and islands. Weathering of the formerly uniform calcareous dune sands of the Tamala Limestone has resulted in calcrete-capped calcarenite with an overlying residual quartz sand. Within the Tamala Limestone there is the development of karst features such as caves, dolines, and solution pipes. The maximum thickness of these deflated dunes is 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 Boodjidup and Calgardup Brooks probably relate to a Pleistocene sea-level lowstand of around 40–30 000 years BP. The fluvial deposits adjacent to streams such as the Turner Brook formed after the deposition of the Pleistocene eolian sands, as the river valley that contains these deposits has eroded the Tamala Limestone to form cliffs. Younger fluvial deposits are probably Late Pleistocene to Holocene, as present-day river channels have incised them.

The youngest deposits in the region are eolian dunes and associated coastal deposits of the Safety Bay Sand. Passmore (1967, 1970) defined this unit as Holocene coastal sand dunes and shallow marine to littoral sands. Playford and Low (1972) extended this term to included similar sands throughout the Perth Basin. These are dominantly Holocene parabolic dunes, but they also include weakly lithified dunes that have been subject to coastal erosion to form cliffs, such as those extending along the coast northwest of Skippy Rock on LEEUWIN. Cliffs formed from Holocene calcarenite are less stable than those formed in Pleistocene calcarenite. Beach rock, palaeosols, and basal boulder conglomerates overlying the Leeuwin Complex are also commonly seen in coastal sections. Less common are shallow-marine coral-rich beds of probable Pleistocene age as seen around Cosy Corner on KARRIDALE–TOOKER and LEEUWIN. Dune and beach formation and erosion are both currently active. Coastal rock platforms can be seen in numerous places along the coast on KARRIDALE–TOOKER and LEEUWIN, and are evidence of the most recent Holocene changes in sea level.

Major geological structures

The major geological structure on KARRIDALE–TOOKER and LEEUWIN is the Dunsborough Fault (Fig. 3). This fault lies east of the boundary between the Cowaramup and Treeton Systems, marking the concealed contact between Permian and Triassic strata to the east, and Proterozoic rocks to the west. An unnamed synthetic normal fault (Fig. 3), with a small downthrow to the east, was identified by Iasky (1993) near the eastern edge of KARRIDALE–TOOKER and LEEUWIN. Crostella and Backhouse (2000) have interpreted a number of concealed faults between the Dunsborough Fault and the Busselton Fault, including the unnamed fault referred to above, and the Alexandra Bridge Fault, with a combined downthrow to the east of less than a kilometre. The concealed Busselton Fault, which is located east of KARRIDALE–TOOKER and LEEUWIN, marks the eastern edge of the Vasse Shelf and has a downthrow to the east in excess of 5 km. These faults have been interpreted as rift faults controlling the western part of the southern Perth Basin, and have been intermittently active from the Permian to the Early Cretaceous.

Land systems methodology

Regolith–landform mapping in KARRIDALE–TOOKER and LEEUWIN was completed between late 1998 and late 2000 using a mapping base of 1:10 000-scale, 1 m resolution colour orthophotographs flown in 1996 by Kevron Aerial Surveys, 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.

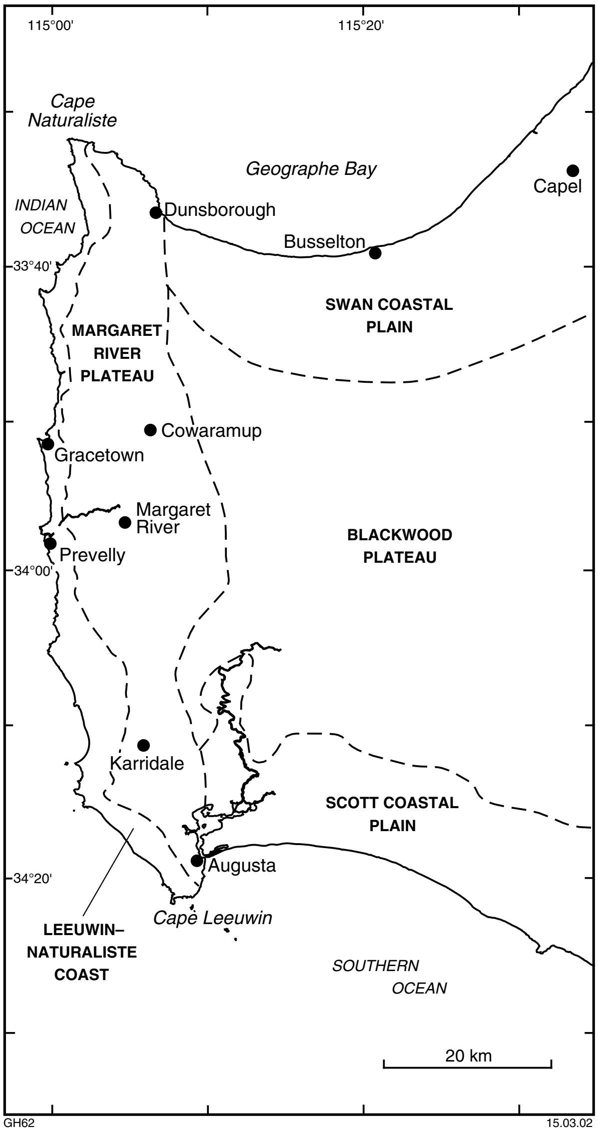

Figure 4. Physiographic regions of the Leeuwin–Naturaliste region (after Tille and Lantzke, 1991)

The nearshore zone has not been bathymetrically surveyed in detail, and few of the contours are continuous. A total of 654 sites were documented in the area, at which 555 photographs and 157 rock samples were taken. From the 399 hand augered soil holes, 62 soil samples were 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 Karridale–Tooker and Leeuwin, and soil catenas are seen as synonymous with the regolith–landform systems described here.

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 systems is based on identifying 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 5.

Previously, land systems have been used in Karridale–Tooker and Leeuwin to define areas with recurring patterns of topography, soil, and vegetation (Christian and Stewart, 1953). The area has been divided in a hierarchical manner into regions, provinces, zones, systems, and subsystems. Karridale–Tooker and Leeuwin

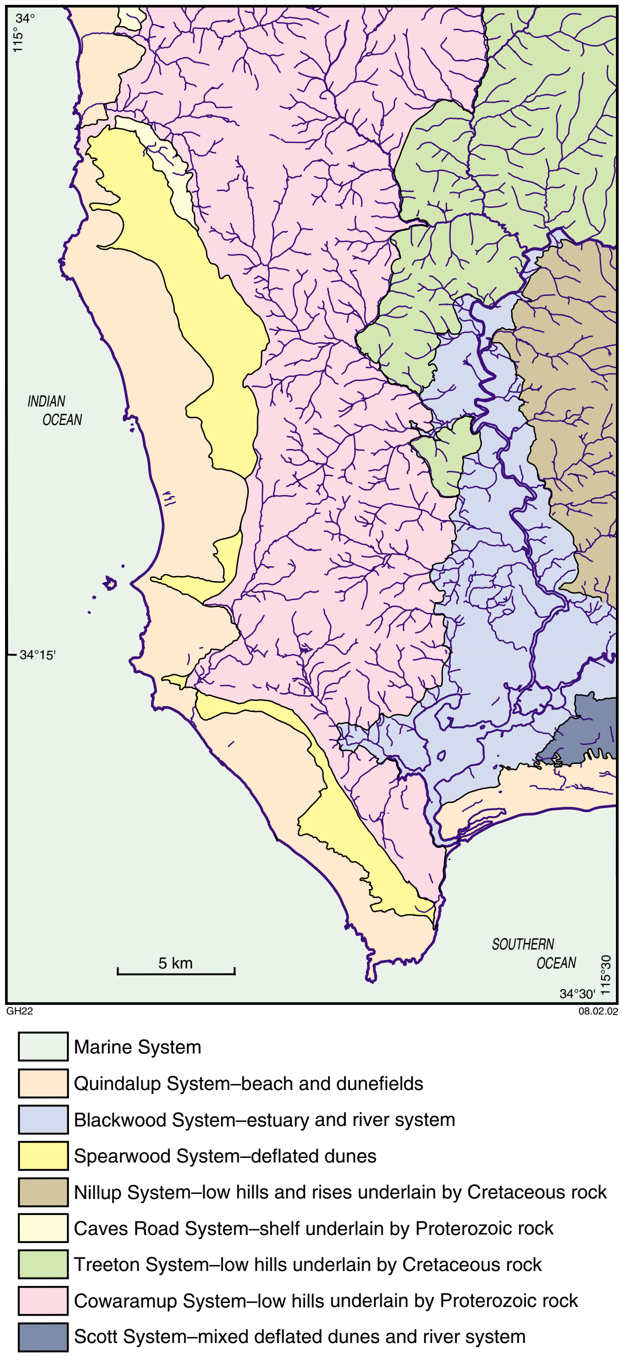

Figure 5. Distribution of land systems

Figure 7. Exposed corestones of moderately weathered felsic granulite of the Leeuwin Complex (*ЄmLE*) on a hillcrest within the Cowaramup System, Glenarty Road (MGA 330730E 6213295N; GSWA Photograph no. 2350)

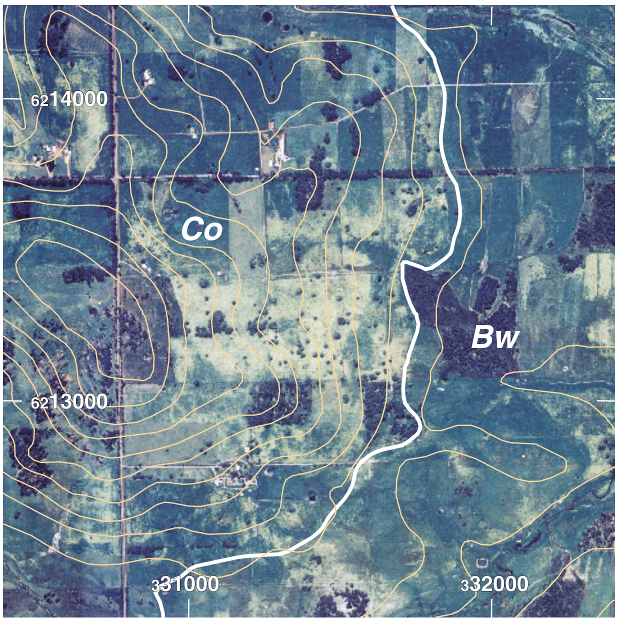

Figure 8. Incision of the Margaret River Plateau forms low hills and rises of the Cowaramup System (*Co*) on Karridale–Tooker; to the east lies the relatively flat Blackwood System (*Bw*); south of Brockman Highway, near Glenarty Road. 1:25 000-scale orthophotograph with contours at 5 m

correlate with where the Cainozoic sediments overlie the Leeuwin Complex. Drill logs of reverse circulation drilling completed by BHP Minerals (Woodget, 1992a) indicate that these sediments vary in lithology from carbonaceous clay beds through to coarse quartz and feldspar gravels; this is reflected in the residual materials seen at the surface.

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. Along the Brockman Highway, road cuttings reveal thin transported gravelly sands and clays overlying weathered granulites. The whole profile of fluvial Cainozoic sediments overlying Proterozoic Leeuwin Complex granites and granulites has been lateritized, creating indistinct unit boundaries. However, on close inspection of a regolith profile, the quartz grains in the residual sand or duricrust commonly do not match the underlying weathered bedrock, indicating that they are not genetically related. The occurrence of these materials over the previously incised Leeuwin Complex, coupled with their sporadic preservation and subsequent weathering, has created a highly variable soil pattern in the region. This may account for the fact that residual sand does not occur on every hillcrest, and complicates simple models of the lateritic profile.

lie in the Western Region, which covers the western half of Western Australia (Bettenay, 1983; Tille and Lantzke, 1990a).

The Leeuwin–Naturaliste region has been divided into five physiographic regions (Tille and Lantzke, 1990a) (Fig. 4). 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. The Southern Coastal Plain is referred to as the Scott Coastal Plain in geological literature (Playford et al., 1976). All these regions except the Swan Coastal Plain are represented on KARRIDALE–TOOKER and LEEUWIN (Tille and Lantzke, 1990a, Fig. 2), and form the basis of the division of the area into regolith–landform systems.

Regolith–landform systems

KARRIDALE–TOOKER has been divided into seven regolith–landform land systems, plus a marine system, and LEEUWIN has been divided into five regolith–landform system 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). Holocene coastal dunes and beach deposits are named the Quindalup System, and are a combination of the Kilcarnup and D'Entrecasteaux Dune Systems of Tille and Lantzke (1990a). The Quindalup System has also been mapped as far north as Geraldton (Langford, 2000, 2001). The Tamala Limestone is the stratigraphic name given to the calcarenite that underlies the Gracetown Ridge System of Tille and Lantzke (1990a). The Tamala Limestone has been renamed the Spearwood System to be more compatible with geomorphic elements adopted by McArthur and Bettenay (1960), the physiographic regions of Playford et al. (1976), and a similar land system mapped around Geraldton (Langford, 2000, 2001). The Cowaramup Upland, Glenarty Hills, and Wilyabrup Valleys Systems of Tille and Lantzke (1990a) are all formed over a profile of materials of similar origin and are here combined into the Cowaramup System. The main features of each of the land systems in the mapping area are shown in Table 5.

Table 5. Classification of land systems

Land system	*Environment of deposition/ process*	*Dominant landforms*	*Minor landforms*	*Mapping/distinguishing features*	*Dominant materials*
Marine	Below low water level; marine and wave-dominated coast	Nearshore and offshore sandplain, marine reef	Shoreface, offshore palaeochannel	Based on phototone and Landsat TM interpretation	Calcareous sand; reef composed of calcarenite and Leeuwin Complex
Quindalup	Modern beach and coastal dunefields; eolian and wave-dominated coast	Beach, parabolic dune, swale	Foredune, beach ridge plain, blowout, drainage depression	Geological unit (Safety Bay Sand); calcareous materials, shell fragments, and quartz sand	Carbonate-rich coastal and eolian; sediment overlying friable calcarenite
Spearwood	Deflated older dunefields; residual after eolian	Deflated dune	Swampy swale, drainage, depression doline, cliff	Geological unit (Tamala Limestone); cave formations and karstic features; weathered dunefield materials over calcarenite	Non-carbonaceous, leached red or yellow quartz sand overlying indurated calcarenite (Tamala Limestone)
Scott	Deflated dunefield and river system; residual after eolian, tide-dominated coast and alluvial	Deflated dune, terrace, swamp	Low rise	Arcuate geomorphology of Scott Coastal Plain; sandy and swampy	Bleached sand and organic-rich sand materials
Caves Road	Shelf underlain by Proterozoic rocks; residual after coastal and alluvial	Swamp, sandplain	Rise	Flat land; swampy; sandy materials	Bleached sand
Nillup	Shelf underlain by Cretaceous rocks; residual after coastal and alluvial	Rise, broad swampy drainage depression	Swamp, low hill	Poorly incised landform; sandy materials over residual materials; topographically distinct from Treeton	Bleached sand; mottled materials poor due to drainage
Blackwood	Estuary and river system; tide-dominated coast and alluvial	Terrace, estuary, intertidal and supratidal flat, river channel, swamp	Drainage depression, rise, channel bench, oxbow, low hill island	Break in slope between flat terrace surface of the Blackwood River and the Blackwood and Margaret River Plateaus; alluvial materials	Yellow quartz sand; quartz- and feldspar-rich sand and gravel; silty sandy estuarine sediment
Treeton	Low hills underlain by Cretaceous rock; residual, colluvial and alluvial	Low hill, deeply incised drainage depression	Stream channel, alluvial plain, terrace, rise	Underlying geology (Leederville Formaton); deeply incised landform	Residual material on hillcrests; colluvium on slopes; alluvium in drainage depressions
Cowaramup	Low hills underlain by Proterozoic rocks; residual, colluvial and alluvial	Low hill, deeply incised drainage depression	Stream channel, swamp, terrace, rise	Underlying geology (Leeuwin Complex); incised landform	Residual materials on hillcrest; colluvium on slopes; alluvium in drainage depressions

Cowaramup System (*Co*)

The Cowaramup System occupies 29 821 ha (22%) of KARRIDALE–TOOKER and LEEUWIN (Fig. 6, Table 6), and is characterized by low hills and rises of residual, colluvial, and fluvial materials overlying weathered metamorphic rocks of the Leeuwin Complex. Hillcrests are commonly capped by residual gravel or duricrust; scattered outcrops of granulites of the Proterozoic Leeuwin Complex can also be seen (Fig. 7). The system is a source of ferruginous gravel, which is used for road construction, and a minor source of quartz sand, which could be used for cement aggregate or landfill. There are numerous pits from which gravel has been removed, but only a few are currently operating on an intermittent basis. Areas of the Cowaramup System have been drilled to estimate potential resources of heavy mineral sands.

Landform and distribution

The Cowaramup System exists on the undulating Margaret River Plateau, and is characterized by low hills and rises with broad swampy drainage depressions (Fig. 8). Slopes are gently to moderately inclined, and may become steep to precipitous and locally cliffed near the coast or by waterways. This is the most extensive land system, forming a north–south corridor between the coastal Spearwood and Quindalup Systems to the west, and the Blackwood and Treeton Systems underlain by Cretaceous strata to the east.

In general, the elevation of the land system decreases towards the south. To the east, the plateau is incised around swampy drainage depressions with gently sloping sideslopes (CoA_d) (Fig. 9). However, there are some flat upland areas with very minor incision extending out towards the west, generally west of the Bussell Highway. These flat areas within the system are dotted with a series of swamps and poorly drained depressions (CoA_w)(Fig. 10), rather than distinct open drainage lines. Most of them are seasonally inundated or waterlogged. There are a few deeply incised drainage lines in the north of KARRIDALE–TOOKER, such as the Boodjidup Brook, with small distinctive alluvial channels (CoA_c).

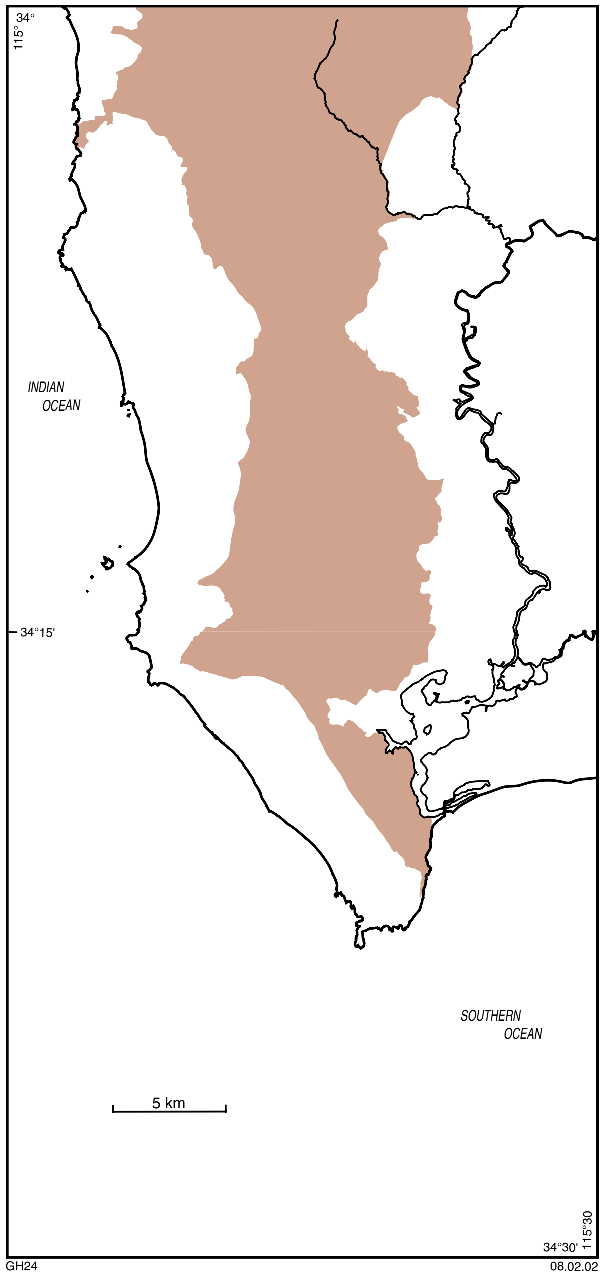

Figure 6. Distribution of the Cowaramup System (*Co*) on KARRIDALE–TOOKER and LEEUWIN

Regolith and rock materials

The weathering and erosion in situ of the underlying Proterozoic Leeuwin Complex formed much of 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 outcrops of mafic granulite and anorthosite, particularly on the coast near Augusta to the north of the Cape Leeuwin Lighthouse. Regolith materials seen throughout the Cowaramup System are also formed from weathering and erosion in situ of undivided Cainozoic alluvial to fluvial sediments (*CoC/A*). These are typically quite thin and overlie the metamorphosed rocks of the Leeuwin Complex. However, one drillhole in the McLeod Creek vicinity (MGA 326975E 6221185N) recorded sediments of up to 78 m thick (BHP Minerals Limited, 1992).

Ferruginous duricrust (*CoRf*) is commonly exposed on hillcrests, and forms the top of the lateritic profile. The duricrust can be up to 2 m thick, with boulders of cemented duricrust sometimes exposed on hillcrests or flat upland areas. Residual bleached quartz sand (*CoRq*), which is thought to be derived from the weathering of the underlying ferruginous duricrust, may also be developed on hillcrests. Stephens (1946) noted that lateritic podzolic soils were common in the southwest of Australia, and attributed the occurrence of bleached sands at the top of the lateritic profile to differences in parent materials rather than to climatic or other influences. The occurrence of residual bleached sands is common on KARRIDALE–TOOKER and LEEUWIN, and does appear to

Table 6. Components of the Cowaramup System

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
Colluvium *CoC* 14431 ha (48%)	Colluvial Undivided slopes of low hills and rises; slopes are level to gently inclined with some moderately inclined slopes; mostly35–80 m AHD Up to 1.5 m (thicker downslope) of gravelly sand[(a)] grading downslope to silty sand over residual soil of mottled gravelly sandy clay (weathered Leeuwin Complex)	West of Bussell Highway; southeast of Poole Road intersection (MGA 327440E 6206625N) Auger hole to 1 m below surface; 0.5 m of colluvium over mottled soil (weathered rock) Colluvium is gravelly, very silty sand; sand mostly coarse; some up to fine gravel; minor (<1%) fine sand opaque minerals; also contains minor ferruginous nodules up to 3 mm Mottled soil is gravelly sandy clay; main constituents apart from clay are coarse to fine subangular quartz gravel; minor ferruginous nodules up to 5 mm with cutans; dark purplish black (hematite rich); nodules contain medium to fine quartz sand; mottled soil derived from weathered granulite
Ferruginous duricrust *CoRf* 5826 ha (20%)	Residual Hillcrests of low hills and rises; level to gently inclined slopes; mostly 30–100 m AHD Ferruginous duricrust overlying mottled soil (weathered Leeuwin Complex); may include small areas of relict leached quartz sand	Harrison/Boulter Road north of Sebbes Road (MGA 325190E 6226600N) 1.5 m roadcut section of residual ferruginous gravel over mottled soil (weathered rock) Yellowish red (5YR 4/6) silty/clayey/sandy gravel; main constituents are ferruginous medium gravel nodules up to 10 cm; grading to cemented duricrust in places at top of profile; nodules have cutans and are moderately strong;they contain fine to medium subrounded to subangular quartz sand; weathered in situ; protolith is Leeuwin Complex granulite
Drainage depression CoA_d 3048 ha (10%)	Alluvial Drainage depressions; well-drained narrow valleys with small stream channels to poorly drained broad swampy valleys; may be seasonally active; dominantly level, with very gently to gently inclined sideslopes, mostly north facing; 0–100 m AHD Formed in weathered bedrock and slope deposits; generally silty clayey sand; alluvium is generally thin	Track off Brooks Road (MGA 330595E 6232085N) Swampy drainage depression with alluvium over mottled alluvium Dark grey, very silty sand over slightly gravelly clayey sand; pale yellow (2.5Y 7/3); mottled strong brown (7.5YR 5/8); contains medium subangular to subrounded quartz sand; a few poorly formed nodules; can be broken between finger nails; also a few cemented nodules up to 12 mm
Quartz sand *CoRq* 2296 ha (8%)	Residual Low hills and rises; level to gently inclined, north- to east-facing slopes; mostly 30–85 m AHD, but of 95–115 m AHD east Witchcliffe Bleached quartz sand over mottled sandy clay	Stevens Road (MGA 320125E 6234085N) Hillcrest area of low hills; residual sand up to 5 m thick overlying weathered boulders of granulite — a mechanical excavator has uncovered boulders Sand bleached white at the surface; below is dark grey (10YR 4/1), slightly silty, slightly clayey, sand; main constituents are rounded quartz and feldspar, mostly around 2 to 3 mm; some up to 5 mm and some fine subangular sand; minor organic matter (dark grey staining); weathered sedimentary deposit
Alluvial terrace CoA_t 1795 ha (6%)	Alluvial Terrace; level to very gently inclined, locally moderately inclined; mostly 20–40 m AHD Gravelly silty sand	Glenarty Road 300 m west of road (MGA 330525E 6212115N) Gravel pit on low alluvial terrace; up to 1 m of gravel over palaeosol 0.9 m of white rounded to subangular quartz and feldspar gravel up to 20 cm; a few cobbles of ?wollastonite (radiating crystal habit); no mafics or

Table 6. (continued)

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
		rock fragments of any other type; 0.9 – 0.95 m black organic gravel; main constituents are organic matter and rounded to subangular quartz gravel up to 3 cm; fluvial organic gravel; 0.95 – 1.1 m; light brown (7.5YR 6/3) clay; fluvial or lacustrine
Colluvium over alluvium *CoC/A* 1354 ha (5%)	Colluvial Undivided slopes of low hills and rises; draining south and east; mostly gently inclined; 30–90 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 Cainozoic sediments)	Mill Road (MGA 326250E 6233945N) Shallow auger hole intersecting a gravel pan at 0.8 m depth; anomalous heavy mineral content; transported materials over mottled soil of sedimentary unit 0.1 – 0.7 m depth; light yellowish brown (2.5Y 6/4) slightly clayey sand; main constituents are medium to coarse subangular to subrounded quartz sand; minor (≤5%) fine heavy mineral sand 0.7 – 0.8 m depth; light yellowish brown (2.5Y 6/4) mottled yellowish red (5YR 5/6) and reddish brown (2.5YR 4/4); slightly gravelly very silty/clayey sand; main constituents are medium to coarse subangular to subrounded quartz sand; clay and silt; minor ferruginous nodules up to 20 mm; some quartz gravel; ≤5% fine heavy mineral sand; mottled soil; sedimentary origin
Swamp *CoA_w* 382 ha (1%)	Alluvial Swamp; several areas, dominantly level, from 10–115 m AHD; largest area around 80 m AHD Very thin organic sediments overlying Leeuwin Complex	Corner of Leeuwin Road and Skippy Rock Road (MGA 329380E 6195570N) Low swampy area with numerous granitoid outcrops West of this location is a flat area covered in reeds; to the east is an area without shrubs, as seen in surrounding areas; numerous gneissic outcrops
Stream channel *CoA_c* 373 ha (1%)	Alluvial Stream channel; includes beds and banks; mostly level, with gently to moderately inclined banks; 20–100 m AHD Sand, gravel, and boulders, with some exposed bedrock; seasonally water filled	0.15 km along Leishman Road from Davis Road (MGA 330770E 6233575N) Alluvium in narrow stream channel in valley Silty, very gravelly, medium sand; subangular; smooth grains; a few coarse quartz grains ≤4 mm; ferruginous nodules ≤45 mm
Proterozoic Leeuwin Complex *ℙmLE* 315 ha (1%)	Bedrock Stream beds, road cuttings, and outcrops; lies beneath 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	Coastal end of Redgate Road; south of car park on rocks (MGA 315315E 6231600N) Rocky coastline with Leeuwin Complex outcropping Felsic granulite; weakly foliated; medium to coarse grained; predominantly granoblastic; contains quartz, feldspar, biotite, opaque minerals, and garnet; some porphyroblastic zones with garnet porphyroblasts in places up to 1 cm; boudins; numerous pegmatite veins ≤5 cm thick; contain quartz feldspar and biotite
Pegmatite *p* <1 ha (<1%)	Bedrock Coastal rocky headlands and rock platforms Very coarse grained (pegmatitic) veins in granulite and granitic gneiss	Coastal end of Redgate Road; south of carpark on rocks (MGA 315315E 6231600N) Numerous pegmatite veins up to 5 cm thick, trending north-northeasterly, variable dip, contain quartz, feldspar and biotite, veins cut through weakly foliated, felsic granulite with garnet porphyroblasts

NOTE: (a) See Appendix 6 for grain-size definitions

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Figure 9. Low hills and swampy drainage depressions are characteristic landforms of the Cowaramup System (*Co*). Residual duricrust and gravel are commonly situated amongst trees on hillcrests. Rocky Road looking south across the valley (MGA 328110E 6229750N; GSWA Photograph no. 2358)

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Figure 10. Flat upland area of the Cowaramup System (*Co*) with cleared swamps and poorly drained depressions, Harrison Road (MGA 330730E 6213295N; GSWA Photograph no. 2121)

Hillslopes are characterized by colluvial deposits of varying thicknesses (*CoC*). Colluvial materials are typically silty or gravelly sand overlying weathered bedrock (Leeuwin Complex or Cainozoic sediments). Near the top of the profile, ferruginous nodular gravel may have eroded cutans, indicating that the clasts have been transported. The thickness of the colluvium generally increases downslope, and the gravel content also decreases downslope. Mottling can occur within the colluvial deposits, which indicates weathering in situ of the materials after deposition. Mottled clay, or completely weathered rock lies below the superficial colluvial materials.

Swamps (CoA_w) are distributed sporadically within the Cowaramup System. These are waterlogged areas containing carbonaceous or peaty silty sand, and they commonly overlie a ferruginous hardpan. In places along waterways such as the McLeod and Glenarty Creeks, degraded alluvial terraces (CoA_t) of silty sands and gravels lie above the river channel and its present floodplain. Materials vary in lithology and are older Cainozoic valley fills. Alluvial channel (CoA_c) and drainage depression (CoA_d) deposits consist of a range of materials from boulders of weathered granulite 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 nodular gravel, soil for 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 gravel is used as aggregate for road construction. In places the gravel is concealed by residual quartz sand which, if thick enough, may be a potential source of sand for landfill or construction purposes. Ferruginous 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 or Vacant Crown Land. A number of gravel pits lie within forested Vacant Crown Land on KARRIDALE–TOOKER, approximately 5 km northeast and east of Witchcliffe townsite between Wickham and Davis Roads (MGA 330760E 6234030N). These pits are operated intermittently to provide local shires and Main Roads WA with gravel for use as roadbase material. A large gravel pit is located on LEEUWIN in a designated gravel reserve operated by the Shire of Augusta–Margaret River (MGA 327565E 6203075N). Most of the gravel has been extracted and scraped down to the mottled soil zone. Traces of the original rock fabric of the Leeuwin Complex can be seen as quartz veins, which retain their general strike and dip directions within a mottled clay matrix. Within this gravel reserve there are also areas of more sandy materials, which have been utilized as fill material.

Heavy minerals were first discovered in the region by Electrolytic Zinc Company of Australasia. BHP followed up with further drilling and defined a resource east of Witchcliffe. The heavy minerals are found in thin fluvial sediments overlying the Leeuwin Complex (BHP Engineering Proprietary Limited, 1995). Remnants of these sediments occur sporadically throughout the Margaret River Plateau and vary in lithology. The source and age of these deposits is uncertain but BHP company reports indicate a Cainozoic age (Dendle, 1989). Alternatively, they could be Leederville Formation or a combination of both Cainozoic sediments overlying Mesozoic strata. Surface expression is poor and the sediments are lateritized. They may correlate with deposits of the Caves Road System defined by Marnham et al. (2000) on COWARAMUP–MENTELLE to the north.

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 and can have marked effects on cleared areas, particularly sandy 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 viticulture, grazing, conservation, recreation, and tourism. Grapevines are often planted on well-drained slopes where the colluvium contains some gravel. Natural vegetation has been cleared from a large portion of the system. However, there are a few remnant pockets, notably State forest between Warner Glen Road and Bullant Drive, National Park including land where the historic Jarrahdene Mill was located north of Vlam Road, and a large block of Vacant Crown Land between Wickham and Davis Roads. The latter contains the headwater of the Boodjidup Brook. Vegetation is commonly retained along watercourses, where water-tolerant plants such as reeds and paperbark trees grow. Within farmland, duricrust-capped hillcrests are commonly covered in natural vegetation of low to medium jarrah and marri forests (Appendix 3).

The main waterways draining the Cowaramup System on KARRIDALE–TOOKER and LEEUWIN are classed as creeks and minor creeks (Pen, 1997), and are subject to little or no flow during some periods of the year. On KARRIDALE–TOOKER they include the Boodjidup, Chapman, and Calgardup Brooks in the north, McLeod and Rushy Creeks in the central region, and Glenarty Creek in the south. On LEEUWIN the main waterways are the Turner Brook and the West Bay Creek. Most watercourses drain from the flat plateau area in the west of the system towards the east into the Blackwood River and its associated estuary. According to Pen (1997) these are part of the Blackwood River drainage basin. Exceptions to this are the Boodjidup, Calgardup, and Turner Brooks, which breach the Pleistocene to Holocene dune systems draining westward to the coast and are included in the Busselton drainage basin of Pen (1997).

Relationships

The Cowaramup System forms part of a dissected plateau that is underlain by residual and colluvial Cainozoic sediments and 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. 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 (1090–525 Ma) rocks of the Leeuwin Complex that were strongly deformed and recrystallized in granulite or 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 residual, colluvial, and alluvial materials of Cainozoic age (65–1.6 Ma), as well as a weathered rock profile of mottled clays. Hocking et al. (1987) suggested that the main period of duricrust development was somewhere between Eocene and Oligocene. The dissection of the plateau forming the Cowaramup System, and producing the colluvial slopes and present-day drainage system, probably took place from Pliocene to Early Pleistocene.

Treeton System (*Tr*)

The Treeton System occupies 11 037 ha (8%) of KARRIDALE–TOOKER and LEEUWIN (Fig. 11, Table 7), and is underlain by residual, colluvial, and alluvial materials that overlie the weathered Cretaceous rocks of the Leederville Formation. The system is characterized by low hills and rises, many of which are capped by cemented nodular duricrust and duricrust gravels, which provides a source of gravel for road construction. 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 northeastern portion of the mapping area, and is found only on KARRIDALE–TOOKER, where it is the second most extensive land system after the Cowaramup System. Low hills and rises are dominant (Fig. 12), and the undulating slopes are generally level to gently inclined. The system is extensively covered by residual materials. The duricrust-dominated hillcrests rise to 120 m AHD, and the colluvial slopes pass downslope into drainage depressions whose elevations range between 20 and 65 m AHD, and locally reach 95 m AHD. The main drainage depressions, the Chapman Brook and Upper Chapman Brook, are typically about 100 m wide, with no floodplain development. They drain southeasterly and southerly into the adjacent Blackwood System. The height of this land system rarely exceeds 120 m AHD, and the

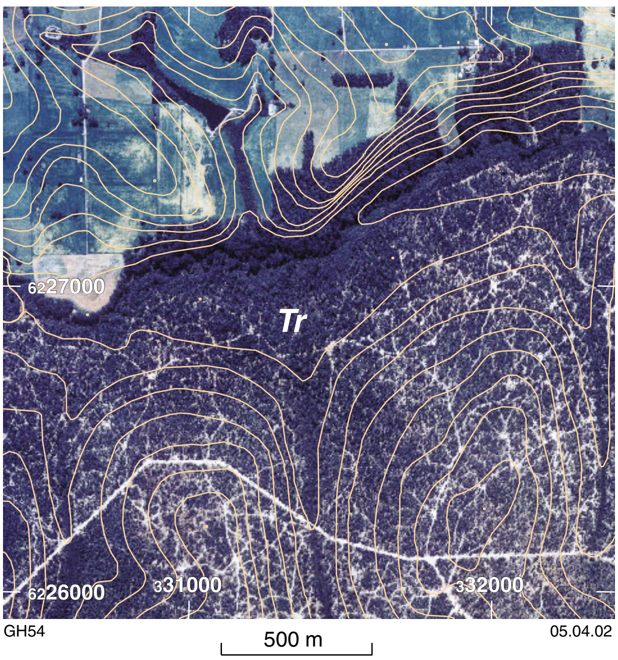

Figure 12. The Treeton System (*Tr*) is incised along the Chapman Brook, and consists of hillcrests capped with ferruginous duricrust, surrounded by colluvial slopes. Some areas have been cleared for grazing, and in some areas the natural bushland has been retained. South of Warner Glen Road. 1:25 000-scale orthophotograph with contours at 5 m

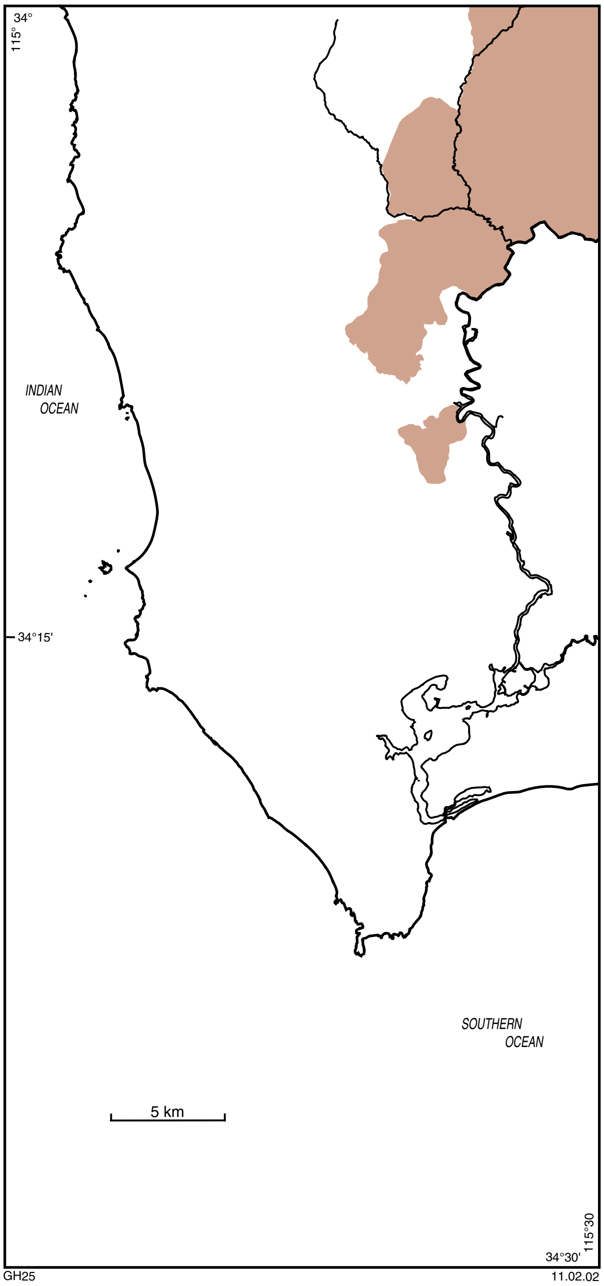

Figure 11. Distribution of Treeton System (*Tr*)

colluvial sideslopes extend down to streams as low as 10 m AHD.

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 (Fig. 13) of cemented nodular 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

Table 7. Components of the Treeton System

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
Colluvial slopes *TrC* 6967 ha (63%)	Colluvial Undivided slopes; dominantly gently inclined slopes; mostly 20–65 m AHD; up to 95 m AHD Silty or gravelly sand overlying mottled sandy clay (weathered Leederville Formation)	0.35 km along Noakes Road from forest edge (MGA 335660 E 6232430 N) 0.5 m of colluvial sand over mottled soil (weathered Leederville Formation); auger hole to 0.8 m Mottled soil is grey, slightly silty clayey sand mottled red (2.5YR 4/8) and brownish yellow (10YR 6/6); main constituent is medium subangular to subrounded quartz sand; minor coarse quartz sand
Ferruginous duricrust *TrRf* 2636 ha (24%)	Residual Hillcrests and upper slopes of low hills and rises; dominantly gently inclined slopes; up to 120 m AHD Ferruginous duricrust and gravel overlying mottled soil (weathered Leederville Formation); may include small areas of relict leached quartz sand	Boathaugh; north of Brockman Highway; (MGA 332755E 6218015N) Gravel pit on private land disused and rehabilitated with a few trees planted; areas of residual quartz gravel near edge of Blackwood River 1–2 m of ferruginous gravel and duricrust scraped down to underlying mottled soil; duricrust is quartz and feldspar rich; clasts are rounded and up to 5 cm and cemented by iron; protolith is Leederville Formation
Stream channel TrA_c 769 ha (7%)	Alluvial Stream channel; includes beds and banks; slopes are mostly level, with gently to moderately inclined banks; up to 90 m AHD Formed in weathered bedrock and slope deposits; silty sandy clay	Noakes Road at edge of forest in creek bed (MGA 335335E 6232570N) Swampy valley with alluvial channel; 1 m auger into mottled alluvium Greyish brown (10YR 5/2) gravelly sandy clay (alluvium); mottled yellowish red (5YR 5/6); yellowish brown ferruginous nodules ≤20 mm, contain medium quartz sand, no cutans, weakly formed and easy to break.
Terrace TrA_t 295 ha (3%)	Alluvial Alluvial terrace; level to gently inclined; 10–20 m AHD Gravelly silty sand	Adjacent to the northern banks of McLeod Creek (MGA 328990E 6220245N) Narrow alluvial terrace between alluvial channel and colluvial slopes
Drainage depression TrA_d 265 ha (2%)	Alluvial Drainage depression; level to gently inclined, dominantly north-facing slopes; mostly 10–40 m AHD Formed in weathered bedrock and slope deposits; silty sandy mottled yellowish red (5YR 5/6); medium quartz sand; clay	Noakes Road (MGA 335335E 6232570N) At edge of forest in a creek bed; auger jammed at 1.0 m Gravelly sandy mottled clay; greyish brown (10YR 5/2) grains are equidimensional; ferruginous nodules ≤20 mm contain quartz; cutans poorly retained; some soft, poorly formed nodules
Bleached quartz sand *TrRq* 105 ha (1%)	Residual Low hills and rises; dominantly gently inclined; 40–70 m AHD Bleached quartz sand overlying ferruginous duricrust	Hinton Road (MGA 329835E 6222140N) Hillcrest; augered to 0.5 m then hit duricrust Thin layer of sand over duricrust; light brownish grey (2.5Y 6/2); poorly sorted; medium quartz sand to fine quartz gravel; angular grains; a few ferruginous fragments

Table 7. (continued)

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
Cretaceous Leederville Formation *KWl* (lies at shallow depth beneath *TrC*)	Bedrock Predominantly subsurface bedrock beneath colluvium, minor outcrop on river banks Weathered, interbedded sandstones, siltstones, claystones, shales, and conglomerates; quartz rich	Blackwood River stream bank, downstream from Chapman Brook (MGA 336150E 6226965N) Very steep river bank 7 to 9 m high, extending down to river channel, formed in ferruginized sandstone, many exposures of sandstone on this bank, massive in places Highly ferruginized sandstone, grain size variation throughout the outcrop, pebbly at waterlevel, no pebbles from approximately 1 m above waterlevel to about 4 to 5 m above water level then more pebbles, rounded to subrounded, pebbles are reworked vein quartz, sand grains of matrix are angular to subangular

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 nodular duricrust is commonly exposed on the hillcrests, although it is in places 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 also 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

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Figure 13. Low hills capped by ferruginous duricrust (*TrRf*) amongst the trees are common in the Treeton System (*Tr*). Colluvial slopes are used for viticulture or grazing; here, land in foreground is being used for hay making (MGA 328100E 6229750N; GSWA Photograph no. 2362)

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Figure 14. Ferruginous duricrust and gravel are common on hillcrests, and are a source of gravel for roadbase. Gravel is removed down to the level of weathered rock, and sites are then revegetated (MGA 332755E 6218015N; GSWA Photograph no. 2334)

gravelly silty sand. Mottling is almost invariably present in the colluvium, indicating weathering in situ after deposition. This makes 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 bedrock has mostly weathered to a residual soil composed of mottled sandy clay, and only very rarely is the silty sandstone parent rock (*KW1*) identifiable.

Mineral resource potential

The Treeton System has the potential to provide gravel, sand, clay for rammed earth, coal, and heavy mineral sands. Gravel is the only resource being extracted at present, with several pits located within the system (Fig. 14), of which some are operating and some are abandoned. Gravel is used as roadbase for the construction of roads. Sand is commonly used as building pads beneath houses or as clean fill.

Coal deposits 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). Drilling in the area has shown occurrences of both heavy minerals and coal at depth. Coal and heavy mineral sand resources are described in detail in the section on mineral resources.

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 downslope transportation are now all significantly less intensive than during the main Pleistocene and pre-Pleistocene periods of landscape formation. Seasonal rainfall is now the only significant agent driving regolith–landform processes.

Small-scale erosion of soil can take place during heavy rainfall in areas cleared of natural vegetation, and soil 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

Much of the Treeton System is covered with State forest that includes both regrowth and remnant native forest. Some areas on the western edge of the system have been cleared for grazing. The valley floors can become waterlogged, and contain swamp or water-tolerant vegetation. Small parts of the system are a source of either gravel for road construction or sand for building.

In the north, the major drainage depressions are the south-flowing Upper Chapman Brook, and the southeast-flowing Chapman Brook, which flows in from the Cowaramup System. The Chapman and Upper Chapman Brooks join, and then flow into the Blackwood River, on the southeastern boundary of the land system. In the south, McLeod Creek flows to the southeast along the boundary between the Treeton and Cowaramup Systems.

Relationships

The Treeton System forms part of a dissected plateau that includes the adjacent Cowaramup System. The system lies in the northeastern section of the mapping area, to the east of the Cowaramup System, and the north of the Blackwood and Nillup Systems. The colluvial deposits of the Treeton System onlap the materials of the Cowaramup System in places. The Cretaceous strata underlying this system rest on top of the older Proterozoic metamorphic rocks that characterize the Cowaramup 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. The Cretaceous sediments are now overlain by colluvial and alluvial materials of Cainozoic age (65–1.6 Ma), and a weathered rock profile of mottled clays. The mottling of these deposits indicates that they have been weathered in situ, and this is a process that is probably currently active.

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).

Caves Road System (*Cr*)

The Caves Road System accounts for the smallest proportion of KARRIDALE–TOOKER and LEEUWIN, occupying 559 ha (<1%) (Fig. 15, Table 8). The system represents an eroded land surface made up of weathered and reworked eolian, coastal or fluvial deposits over the Leeuwin Complex. The thick podzolized sands of the system are composed almost entirely of quartz. They are locally gravelly, and are a possible source of sand and aggregate for roadbase and landfill.

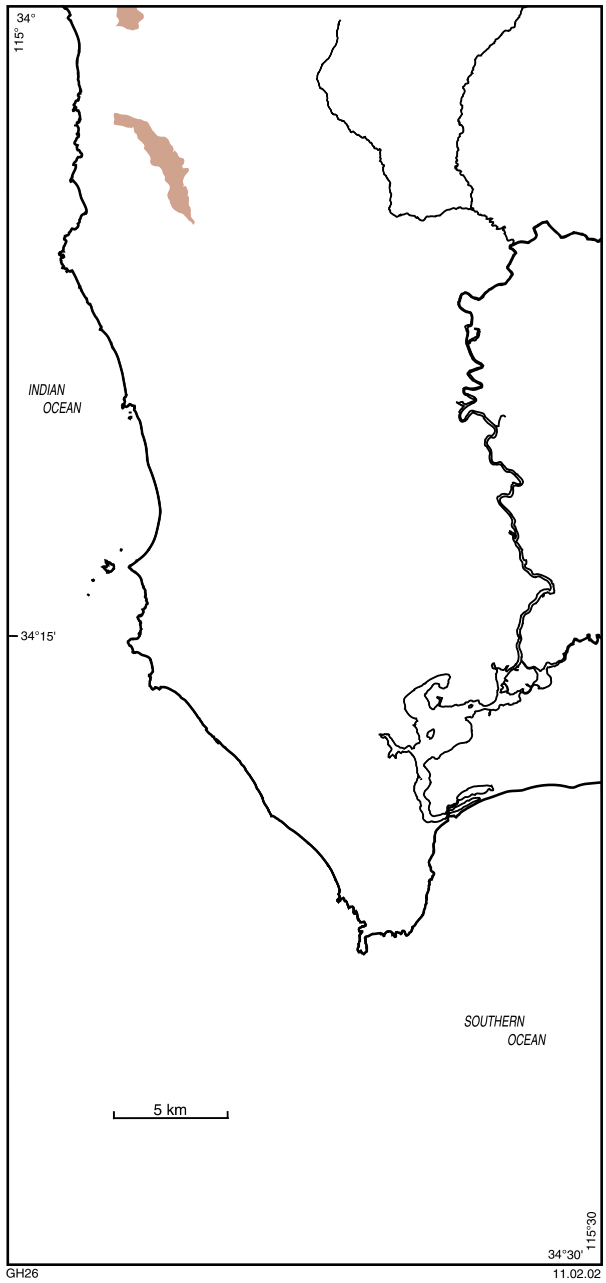

Figure 15. Distribution of the Caves Road System (*Cr*)

Landform and distribution

The Caves Road System is a level to gently inclined shelf ranging in height between 50 m and 80 m AHD. The system can be found sporadically along the Leeuwin–Naturaliste Coast, generally west of Caves Road and east of the Spearwood System. The system lies in the northwestern quadrant of KARRIDALE–TOOKER, east of the Spearwood System. Similar sandy materials are seen in a similar position in the landscape on LEEUWIN, but they are thin and sporadic and do not form the distinctive land system pattern as seen farther north on KARRIDALE–TOOKER and COWARAMUP–MENTELLE (Hall et al., 2000). These materials have been included within the Cowaramup System.

The surface of the system is gently undulating, with shallow hollows and low rises. Swamps (*CrA*$_w$) and poorly drained depressions are also characteristic of the system.

Regolith and rock materials

The dominant regolith material in the Caves Road System is residual leached quartz sand derived from Eocene sedimentary deposits (*CrRq*) (Fig. 16). Grain size varies from fine gravel through to fine sand, with the most common fraction being from medium to coarse sand. Grains are predominantly subrounded to rounded, 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 fluvial, alluvial or coastal origin.

The podzolized sand is probably over 5 m thick, although the base has not been seen in the study area. Farther north on COWARAMUP–MENTELLE, a ferruginous duricrust or hardpan underlie this sand. This 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.

Mineral resource potential

The Caves Road System provides a source of sand, and has a potential for gravel and heavy mineral sand extraction. Heavy mineral anomalies were detected to the north on COWARAMUP–MENTELLE, so it is possible that there may be some on KARRIDALE–TOOKER. 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 sand has been extracted from a few small pits in the area (Fig. 16).

Active processes and hazards

Rainfall and wind drive the current regolith–landform processes in the Caves Road System. 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 their comparatively low porosity, will prevent free drainage and

Table 8. Components of the Caves Road System

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
Sand plain *CrRq* 397 ha (71%)	Residual Undulating plain with slight rises and shallow hollows; level to gently inclined slopes; mostly 50–80 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	Blackboy Hollow, Caves Road, Leeuwin–Naturaliste National Park (MGA 317815E 6235085N) Shallow auger hole to 1.2 m; bleached white sand at surface, with 0.9 m of organic matter-rich sand and then clean sand 0.9 – 1.2 m; grey (2.5Y 6/1) sand; main constituents are subrounded to rounded coarse to fine quartz sand;minor fine sand opaque minerals <1% and charcoal; upper 0.9 m of sand stained dark brown by organic matter; residual sand of mixed origin
Swamp *CrAw* 162 ha (29%)	Alluvial Swamp; level slopes; 50–80 m AHD Waterlogged silty quartz sand	Nindup Plain north of Forest Grove Road (MGA 318865E 6229360N) Flat plain with closed swampy depression; surrounding area is low undulating plain of bleached quartz sand; prone to intermittent inundation

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Figure 16. Thick residual sand of the Caves Road System (*Cr*) forms an undulating plain of rises and swampy depressions. Here the sand has been excavated and is over 5 m thick (MGA 317925E 6230850N; GSWA Photograph no. 2059)

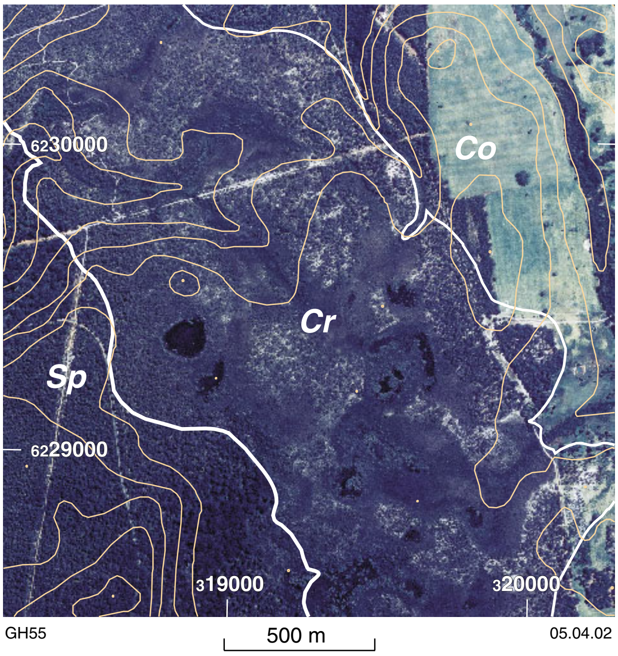

Figure 17. The Caves Road System (*Cr*) near Calgardup Road is characteristically flat, wet, and swampy, with some dry sandy rises. There is no distinctive drainage, and much of the natural vegetation remains intact. The Spearwood System lies to the west and the Cowaramup System lies to the east. 1:25 000-scale orthophotograph with contours at 5 m

seasonal waterlogging will occur. A series of small swamps have formed on flat areas within the Caves Road System, notably in the Nindup Plain area between Calgardup and Forest Grove Roads (Fig. 17).

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

Landuse, vegetation, and drainage

Most of the Caves Road System remains naturally vegetated (Fig. 18), as the leached sands have poor nutrient properties as well as poor drainage characteristics, making them unsuitable for agriculture or viticulture. Landuses include conservation and sand extraction.

The are no major watercourses in the Caves Road System. The system is particularly subject to flooding in the winter months, and includes numerous swamps and poorly drained depressions. Although the dominant material is sand, the thickness of this sand can affect the drainage characteristics of the soil. 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 have developed in this way.

Figure 18. Typical landform and vegetation of the Caves Road System (*Cr*), Widderson Place (MGA 317895E 6235560N; GSWA Photograph no. 2130)

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 (1090–525 Ma) Leeuwin Complex. Materials underlying the system were part of a coastal sequence deposited when sea levels were higher, and may include eolian and fluvial deposits. The shelf of the Cave Road System ranges from 80 to 100 m AHD, pre-dates 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. More recent modification includes eolian redistribution and fluvial reworking.

Nillup System (*Ni*)

The Nillup System occupies 5191 ha (4%) of KARRIDALE–TOOKER and LEEUWIN (Fig. 19, Table 9), and is underlain by residual materials over thin sediments of probable Cainozoic age (possibly Eocene) 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 Nillup System comprises fluvial and coastal materials deposited on an incised shelf, formed in weathered Leederville Formation, and has had a formation similar to that of the Yelverton System in the north on COWARAMUP–MENTELLE (Marnham et al., 2000). However, the topographic feature is not as clearly defined in comparison to the Yelverton System. The Nillup System occupies a small area in the southeast of KARRIDALE–TOOKER east of the Blackwood River (Fig. 19), and extends out towards the east beyond the area. The elevation of the system decreases southerly towards the coast from about 60 m AHD to 30 m AHD. The shelf and its overlying materials have been weakly incised to form an undulating plain (Fig. 20) with low rises, swampy depressions (Fig. 21), and some low hills.

The northern and southern boundaries of the Nillup System have an indistinct topographic expression. Relative to the Treeton System the Nillup System lies at a lower elevation and is less incised. There is also an increase in the residual sandy materials relative to the Treeton System. The boundary between the Scott Coastal Plain and the Blackwood Plateau outside the area is marked by a well-defined scarp that reaches 80 m AHD in the eastern portion of the plain, but is poorly defined west of Milyeannup Coast Road (Baddock, 1995). Baxter (1977) referred to this feature as the Barlee Scarp, and regarded it as having formed by marine erosion similar to that which formed the Whicher Scarp on COWARAMUP–MENTELLE to the north. The subdued form of the scarp is thought to be due to soil erosion and landslips obscuring the feature. However, it is also probable that the westward migrating Blackwood and Scott Rivers in this area have destroyed parts of this feature. Numerous shorelines exist

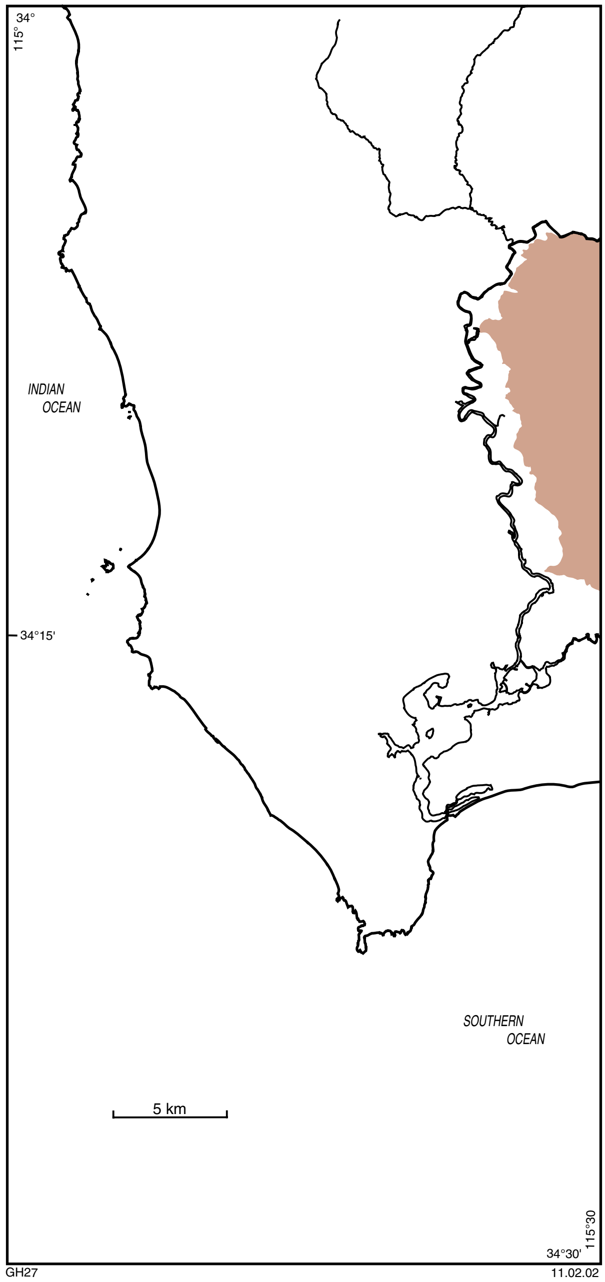

Figure 19. Distribution of the Nillup System (*Ni*)

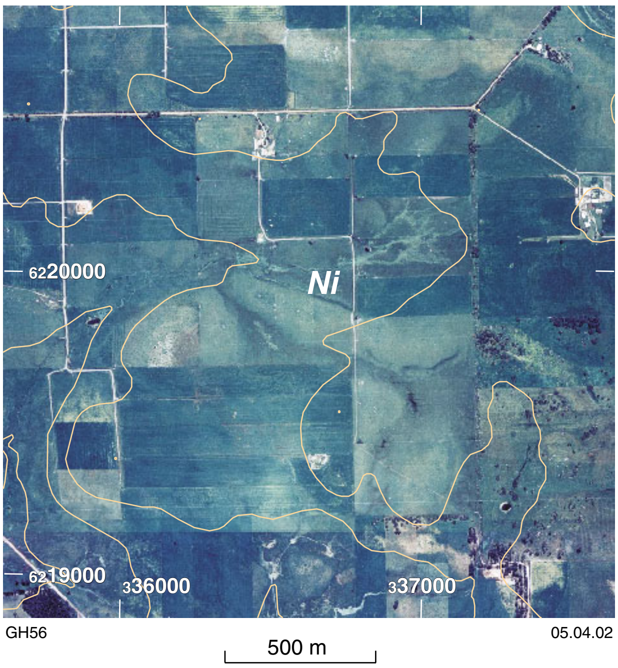

Figure 20. The Nillup System (*Ni*) has been extensively cleared for grazing. The area is generally flat to gently undulating and poorly drained. North of Brockman Highway, with Marsh Road in the north. 1:25 000-scale orthophotograph with contours at 5 m

Table 9. Components of the Nillup System

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
Bleached quartz sand *NiRq* 1832 ha (35%)	Residual Low hills to rises; dominantly level to very gently inclined, rarely moderately inclined, north-facing and west- to southwest-facing slopes; mostly 20–40 m AHD Bleached quartz sand often overlying ferruginous gravel and duricrust at depth. Weathered ?Eocene sediments over Leederville Formation	Wright Road (MGA 336690E 6222265N) Shallow auger hole to 1.2 m; 0.3 m of organic topsoil; watertable at 0.8 m; very gentle slope near top of low rise Thick residual sand; light brownish grey; slightly silty/clayey sand; main constituents are subangular coarse quartz sand; minor medium sand opaque minerals; residual sand of sedimentary protolith
Colluvial slopes *NiCq* 1155 ha (22%)	Colluvial Undivided slopes of rises; dominantly very gently inclined, rarely moderately inclined, northwest- to southwest-facing slopes; mostly 15–40 m AHD Colluvium and slopewash deposits overlying weathered Leederville Formation at depth	Marsh Road (MGA 337465E 6221160N) Shallow auger hole to 1.2 m; poorly drained with mottling; colluvial slope of low rise Colluvial and sheetwash sand; light orangish grey, mottled orangish brown; slightly silty/clayey/ gravelly sand; main constituents are subangular coarse quartz sand; some fine gravel; minor medium sand, opaque minerals <5%; poorly drained colluvial sand
Colluvial slopes *NiC* 963 ha (19%)	Colluvial Undivided slopes of low hills; very gently to gently inclined, locally moderately inclined, northwest- to southwest-facing slopes; mostly 15–40 m AHD Mottled colluvium overlying weathered Leederville Formation (mottled soil)	Campbell Road (MGA 334735E 6220970N) Shallow auger hole to 1.2 m; midway down colluvial slope of low hill hillcrest lies 100 m east and is covered by trees Mottled colluvial sand; light brownish grey, mottled reddish and yellowish brown, slightly silty/gravelly sand; main constituents are subangular medium quartz sand; minor weakly developed nodules at 0.3 m up to 5 mm; nodules slightly ferruginous and break easily with fingers; no cutans; composed of medium to coarse quartz sand (same as matrix); mottled soil beneath
Drainage depression *NiA_d* 657 ha (13%)	Alluvial Drainage depression; dominantly level, rarely moderately inclined, north-facing slopes; mostly 10–40 m AHD Formed in weathered bedrock and slope deposits; silty to gravelly sand and clay; sometimes organic; alluvium is generally thin	0.8 km along Miles Road from where stream crosses track (MGA 337830E 6225410N) Shallow auger hole into alluvial sand; could only auger through the gravelly alluvium to 0.4 m; the slopes of the drainage depression are mostly sandy with minor gravel Slightly silty, slightly gravelly sand; medium to fine gravel; angular to subangular; nodules 5–65 mm; poorly sorted; large range in clast sphericity
Ferruginous duricrust *NiRf* 529 ha (10%)	Residual Hillcrests of low hills to rises; level to very gently inclined, rarely moderately inclined, dominantly west-facing slopes; mostly 20–40 m AHD Ferruginous duricrust overlying mottled soil (weathered Leederville Formation); may include small areas of relict leached quartz sand	Farm off Marsh Road; 650 m west of Wright Road (MGA 337980E 6220880N) Ferruginous duricrust at surface Ferruginous duricrust; contains abundant subangular fine quartz gravel ≤5 mm; quartz is more coarse and abundant near gravel pit area 150 m east and is finer farther east near property boundary fence
Swamp *NiA_w* 54 ha (1%)	Alluvial Swamps and closed depressions; level to very gently inclined, north- or south-facing slopes; dominantly 25–40 m AHD	Marsh Road Farm; 600 m west of Warner Glen Road (MGA 338065E 6221170N) Shallow auger hole to 1.2 m; watertable at 0.5 m; area quite swampy with patches of sedges; 0– 0.4 m

Table 9. (continued)

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
	Poorly drained organic silty sand	of topsoil with high organic matter content; peaty soil near waterway Organic-rich alluvium; brownish grey; slightly silty sand; main constituents are subangular coarse to medium quartz sand; minor medium sand, opaque minerals; organic sand
Cretaceous Leederville Formation *KWl* (lies at shallow depth Beneath *NiC*)	Bedrock Predominantly subsurface bedrock beneath colluvium, minor outcrop on river banks Weathered, interbedded sandstones, siltstones, claystones, shales, and conglomerates; quartz rich	Blackwood River stream bank (MGA 337910E 6226215N) Exposed rock, gently inclined, stream bank extending down to river channel, formed in ferruginized sandstone Highly ferruginized sandstone, less pebbly than other sites, some faint cross bedding, coarse grained, general direction of cross-beds is south to southwest

along the southern Scott Coastal Plain area to the south, and four shorelines are shown in Playford et al. (1976). The highest and oldest shown by Playford et al. (1976) is the Donnelly Shoreline, which is thought to correlate with the Yoganup Shoreline on the Swan Coastal Plain, and is situated near the southern margin of the Nillup System with the Scott System.

Drainage areas in the Nillup System are generally broad, swampy depressions with shallow incision of the shelf. Thus adjacent landforms are mainly low rises with broad flat crests and may be described as an undulating plain. Incision increases towards the Blackwood River, forming minor low hills. Compared with hillcrests in the Treeton System to the north, those in the Nillup System

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Figure 21. Landform and vegetation of a swampy drainage depression (*NiA*$_d$) between low rises of bleached sand (*NiRq*) within the Nillup System (*Ni*), Marsh Road (MGA 338040E 6221005N; GSWA Photograph no. 2345)

are less prominent because of the draping effect produced by the overlying leached sands.

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, climate changes, and migration of the fluvial systems.

Ferruginous duricrust and nodular gravel are often buried at shallow depths by bleached sand (*NiRq*) beneath the hillcrests of low hills or rises (Fig. 22), or they may be exposed on a few hillcrests (*NiRf*) but this is not common. These materials may be extracted as a source of gravel once overlying sand is removed. The sand is the weathered residue of younger deposits of probable Eocene age that may have been coastal or fluvial in origin, and which overlie the Leederville Formation. There may be weak nodule formation at depth in the sand, grading into weakly mottled clayey sand. Sideslope colluvium on rises (*NiCq*) is composed of thick bleached sand and, on more prominent low hills, is more clayey and mottled (*NiC*). The colluvium overlies weathered Leederville Formation at depth (mottled soil), and grades downslope from colluvial gravelly sand to sand or silty sand.

Materials found in drainage depressions (NiA_d) and swamps (NiA_w) are silty to gravelly sand. Swampy areas contain high organic matter, and at shallow depths may be mottled and gleyed due to poor drainage.

Mineral resource potential

The Nillup System is a potential source of sand and ferruginous nodular gravel. There is also potential for heavy mineral sand extraction, as demonstrated by the abandoned operation at Beenup to the east. Like the Treeton System to the north, the Nillup System is also underlain at depth by Permian coal-bearing strata.

Very few gravel and sand extraction pits exist in the Nillup System, probably because the gravel is commonly covered by thick sand. There are a few small pits for private use that are possibly abandoned or intermittently active. Gravel up to 1 m thick is generally extracted to the underlying mottled clay, and is used as aggregate.

This system potentially may contain heavy mineral sand deposits. The Nillup System has been explored by Amax Mining Australia (Connelly, 1969) and Minsaco Resources (Minsaco Resources Proprietary Limited, 1987) who reported minor heavy mineral anomalies. There has been no further development of these deposits.

Coal is known to exist on the Vasse Shelf to the north on COWARAMUP–MENTELLE. The economic potential of the Vasse River Coalfield was assessed by Le Blanc Smith and Kristensen (1998). There, the Permian coal-bearing strata lie at depths between 100 and 250 m within an upthrown block called the Treeton Terrace. Similar strata on KARRIDALE–TOOKER and LEEUWIN lie at greater depths and therefore are less likely to be economic. Esso Australia

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Figure 22. Soil auger hole samples taken north of Marsh Road on the crest of a low rise. Materials encountered were half a metre of residual sand (*NiRq*), with a well-developed organic A horizon at the top, over ferruginous gravel (*NiRf*) (MGA 336745E 6220720N; GSWA Photograph no. 716)

(1984) drilled two holes in the north of the Nillup System and intersected coal seams within the Leederville Formation and the Sue Group.

Active processes and hazards

The weathering in situ and subsequent erosion of the underlying rock (Eocene sediments and Leederville Formation) formed the materials and landforms of the Nillup System. The current processes of weathering, duricrust formation, and transport of materials downslope are much weaker than those that 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. Strong southerly winds may also cause soil erosion on cleared sandy areas. Inundation of the flat-lying areas occurs during winter months.

Landuse, vegetation, and drainage

The Nillup System is largely cleared of natural vegetation and is used intensively for grazing cattle and sheep. Tille and Lantzke (1990a) suggested that the area is suitable for timber production, although there are only a few areas of plantation timber.

Relationships

The Nillup System is identified on KARRIDALE–TOOKER and lies between the Treeton System to the north and the Scott System to the south on LEEUWIN. To the west, the Nillup System gives way to the Blackwood System. The Nillup System overlies residual materials of Cainozoic age formed from thin Cainozoic sediments, which overlie the Cretaceous rocks of the Leederville Formation.

Geological history

The Nillup 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 of possible Eocene age. Coastal and fluvial sediments consisting of undivided sand and sandy clay were deposited 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 weakly incised, and forms rises and some low hills, with swampy drainage depressions and poorly drained flats.

The shelf of the Nillup System pre-dates the Pleistocene eolian deposits of the Spearwood System. The highest and oldest shoreline, the Donnelly Shoreline, is thought to correlate with the Yoganup Shoreline on the Swan Coastal Plain (Playford et al., 1976; Baxter, 1977) and is situated near the southern margin of the Nillup System with the Scott System. Based on relative height of this shoreline, the shelf also pre-dates the Pliocene Yoganup Formation. The erosional surface ranges from 30 to 60 m AHD, and may therefore relate to an Eocene sea-level high. Modification of the shelf on KARRIDALE–TOOKER has taken place after this time, with the migration of the Blackwood and Scott Rivers depositing Quaternary fluvial sediments over the Leederville Formation and Eocene sediments and downcutting into their present positions in the landscape.

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.

Scott System (*Sc*)

The Scott System occupies 649 ha (0.5%) of KARRIDALE–TOOKER and LEEUWIN (Fig. 23, Table 10). This is one of the two smallest land systems in the area. The system is characterized by a low-lying, level to very gently undulating plain underlain by a mixture of deflated fluvial and coastal deposits. The system may be prospective for sand, gravel, and heavy minerals.

Landform and distribution

The Scott System is a small wedge on the eastern edge of LEEUWIN. The system lies between the fluvial deposits of the Blackwood System and the coastal dune deposits of the Quindalup System. The Scott System contains attributes of both of these systems, with a deflated series of low rises of mixed fluvial and coastal origin. Swampy depressions are common in the Scott System, as drainage is poor on the low-lying alluvial terrace (ScA_t), which was formed at times of higher sea levels when the Blackwood River and its estuary were larger (Larson, 1972). Elevations range between 10 and 15 m AHD, and slopes are level to very gently inclined. At its widest, the system spans about 3 km. Water drains northwest into the Blackwood System and south into the Quindalup System. Sandy rises (Fig. 24) support taller vegetation and remain dry throughout the wet season, whereas the surrounding low-lying areas are subject to seasonal inundation, and support scrub heath.

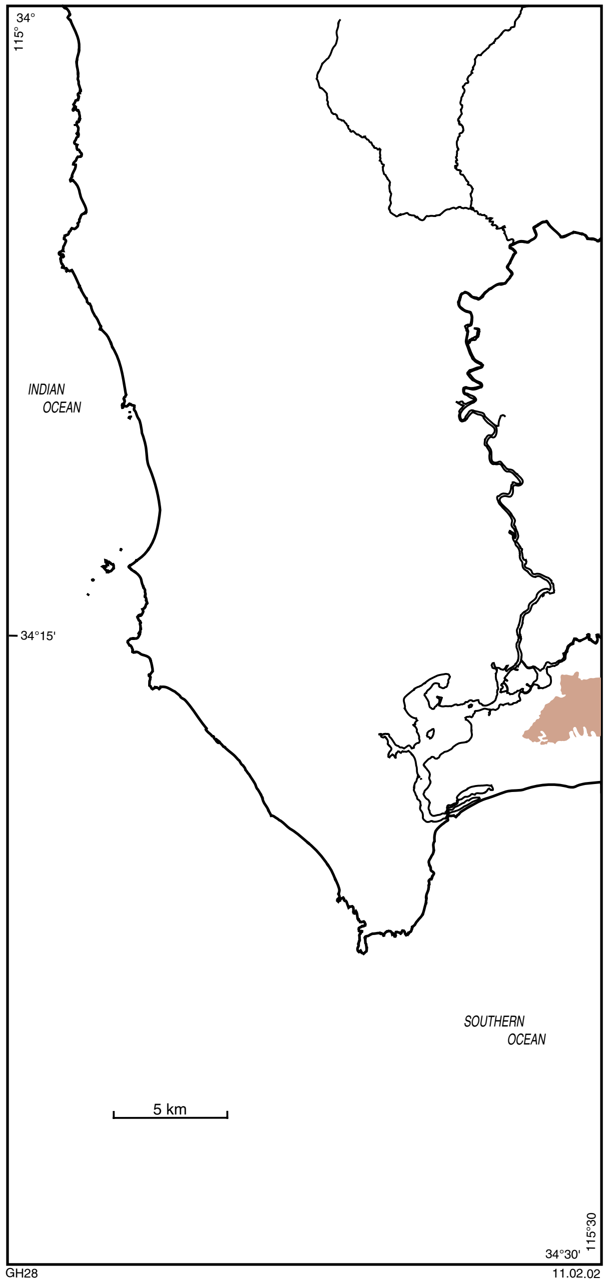

Figure 23. Distribution of the Scott System (*Sc*)

Regolith and rock materials

The Scott System has been formed by fluvial and coastal deposition of sands and silty sands, and has been modified over time by erosion and leaching. To the south, closer to the coast, the Scott System is underlain by unconsolidated and poorly consolidated Mesozoic and Cainozoic sediments. The Cainozoic sediments consist of Recent to Pleistocene dune and beach sands, made up of broken shell fragments and rounded eolian quartz grains (Woodget, 1992b). Local ferruginization is evident as thin, impersistent duricrust. The Mesozoic sediments are of Cretaceous age and consist of a variety of gravels, sands, clays, and micaceous siltstone (Woodget, 1992b).

Farther to the north, closer to the Blackwood and Scott Rivers, and the Hardy Inlet, the sediments of the Scott System are dominantly of fluvial origin, deposited during times of higher sea level when the estuary was much larger (Larson, 1972). Sands are composed of quartz grains of a more angular nature, and in places sands are more yellow.

Hillslopes and crests (ScE_q) of the Scott System are characterized by coarse quartz sand and silty sand, of both coastal and fluvial origin. The lower lying swamps (ScA_w) surrounding the rises consist of waterlogged, organic-rich silty quartz sand (Fig. 25).

Mineral resource potential

The sandy rises along the northeastern border of the system are a potential source of sand for building and construction. The alluvial terrace may provide a source of sand and gravel. Heavy mineral sands may potentially be found within the system, closer to the coast. Drilling by BHP Minerals (Woodget, 1992c), the Project Mining Corporation and Norwest Development Corporation joint venture, and the Project Mining Corporation and Samedan of Australia joint venture (Larson, 1972) has identified occurrences of heavy minerals both within and adjacent to the Scott System, although this has mostly been to the east of the area. Heavy minerals are present either as strand lines in Cainozoic sediments or as disseminations throughout the Cainozoic and Cretaceous lithologies. Ilmenite dominates the heavy mineral suite, with minor zircon and leucoxene. Rutile is rare, and pyrite and garnet

Table 10. Components of the Scott System

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
Terrace ScA_t 438 ha (68%)	Alluvial Alluvial terrace; generally level; north- or northwest-facing slopes; 10–15 m AHD Silty sand	300 north of Scott River Road (MGA 336690E 6204960N) Low-lying land, not as prone to waterlogging as the adjacent swampy areas
Bleached quartz sand *ScEq* 111 ha (17%)	Residual Mainly hillcrests of low rises and low hills; mostly level to very gently inclined; mostly northwest-facing slopes; 10–15 m AHD Quartz sand	20 m south of Scott River Road (MGA 337075E 6204810N) Crest of a small sandy low rise; augered to 1.2 m depth Coarse quartz sand; brown (7.5YR 5/2) with equidimensional, subangular frosted grains; soil became darker and wet at depth
Swamp ScA_w 100 ha (15%)	Alluvial Poorly drained depression; level slopes; 10–15 m AHD Waterlogged, organic-rich silty sand	200 m south of Scott River Road (MGA 336620E 6204390N) Waterlogged low-lying closed depression; supports water-tolerant plant species; adjacent to the alluvial terrace Organic-rich alluvial deposits; silty sand

are common, especially in older sediments (Woodget, 1992c). The Permian Sue Group, which lies at depth below the Cretaceous Leederville Formation, is a potential source of coal. Coal and heavy mineral sand resources are described in the section on mineral resources.

Active processes and hazards

The fluvial and coastal processes that originally formed the Scott System are no longer significant. Sea level is now about 45 m lower, and the fluvial processes that formed the inland portions of the system are now greatly reduced due to the northward migration of the Blackwood River. Rainfall is now the most significant agent controlling the current regolith–landform processes, and the most obvious effects are erosion, deposition, and flooding. Over time, the sandy rises have been leached by rainfall and groundwater movements. In the Scott System, the low-lying areas often become waterlogged during the wet season and can be a hazard to any vehicles using the tracks in the area.

Landuse, vegetation, and drainage

The major landuses of the Scott System are conservation and recreation. The system is covered by the Scott National Park, which incorporates dense areas of scrub heath on the low-lying areas, and low woodland on the drier sandy rises (Fig. 26). The system is poorly drained and consists of numerous swampy depressions. In the neighbouring Quindalup and Blackwood Systems, drains have been dug to alleviate the problem of waterlogging and allow the land to be cleared and used for grazing. Water movement within the Scott System is north into the Blackwood System and south into Long Swamp in the Quindalup System.

Relationships

The Scott System is bounded to the north by the Blackwood System, and to the south by the Quindalup System. The system has been deposited over the Cretaceous sedimentary rocks of the Leederville Formation, and extends off the eastern edge of the area, following the coastline in an arcuate form.

Geological history

The Scott System consists of a mixture of fluvial and coastal deposits overlying unconsolidated to poorly consolidated Mesozoic and Cainozoic sediments (Woodget, 1992b). These sediments lie on the Vasse Shelf, between the Dunsborough Fault and the Busselton Fault, which is the boundary between the Vasse Shelf and the Bunbury Trough (Playford et al., 1976).

Dunes were deposited farther inland when sea levels were higher than at present. These dunes have since been eroded and leached, and are now deflated. Farther inland, closer to the Hardy Inlet, the sediments are fluvial,

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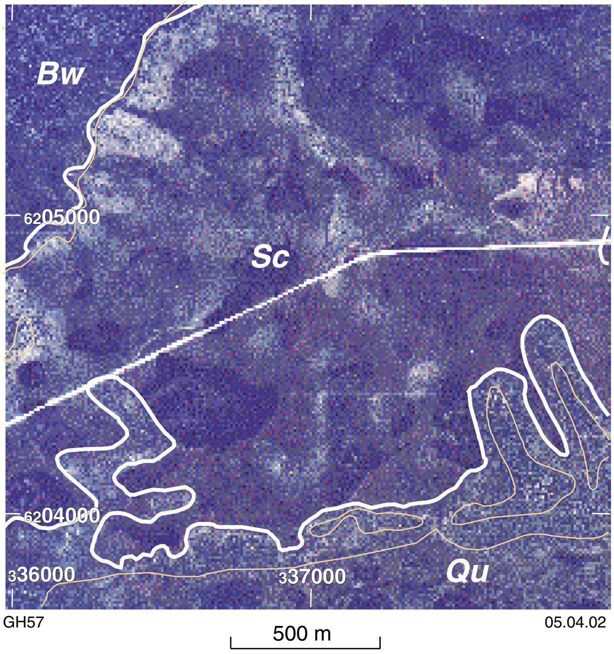

Figure 26. The Scott System (*Sc*) is low-lying and generally very swampy, with no distinctive drainage channels. Dry sandy rises occur throughout the system, and are host to taller vegetation than on the surrounding areas that are prone to waterlogging. Dunes of the Quindalup System (*Qu*) lie to the south, and alluvial terrace of the Blackwood System (*Bw*) to the north. Scott River Road runs through the centre of the land system. 1:25 000-scale orthophotograph with contours at 5 m

Top left:
Figure 24. Sandy rises are generally less prone to waterlogging than the surrounding swampy areas, and are vegetated with low forest and woodland. Leached quartz sands are common. Photograph from Tille and Lantzke (1990a)

Bottom left:
Figure 25. The Scott System (*Sc*) is a low-lying area with a mixture of fluvial and eolian deposits. Waterlogged soils commonly have accumulations of organic material

having been deposited when the estuary was larger (Larson, 1972). The entire land system has been subjected to erosion and leaching, leading to a very deflated topography where it is difficult to distinguish between the fluvial and coastal landforms.

Spearwood System (*Sp*)

The Spearwood System occupies 5799 ha (4%) of Karridale–Tooker and Leeuwin (Fig. 27, Table 11) 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 underlain by materials that are the equivalent of the Pleistocene Tamala Limestone, and these are a source of limestone and building sand, with a number of limestone quarries providing roadbase aggregate and materials for agricultural use.

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, form a northerly trending ridge along the Leeuwin–Naturaliste Coast. To the west are eolian sands underlying the Quindalup System, and to the east are the older sediments that underlie 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 (Fig. 28) that overhang in places. The limestone ridge of the Spearwood System is characterized by large-scale eolian cross-bedding, and contains many caves (Fig. 29) and areas of karst topography (Tille and Lantzke, 1990b). Most of the caves lie within the Leeuwin–Naturaliste National Park.

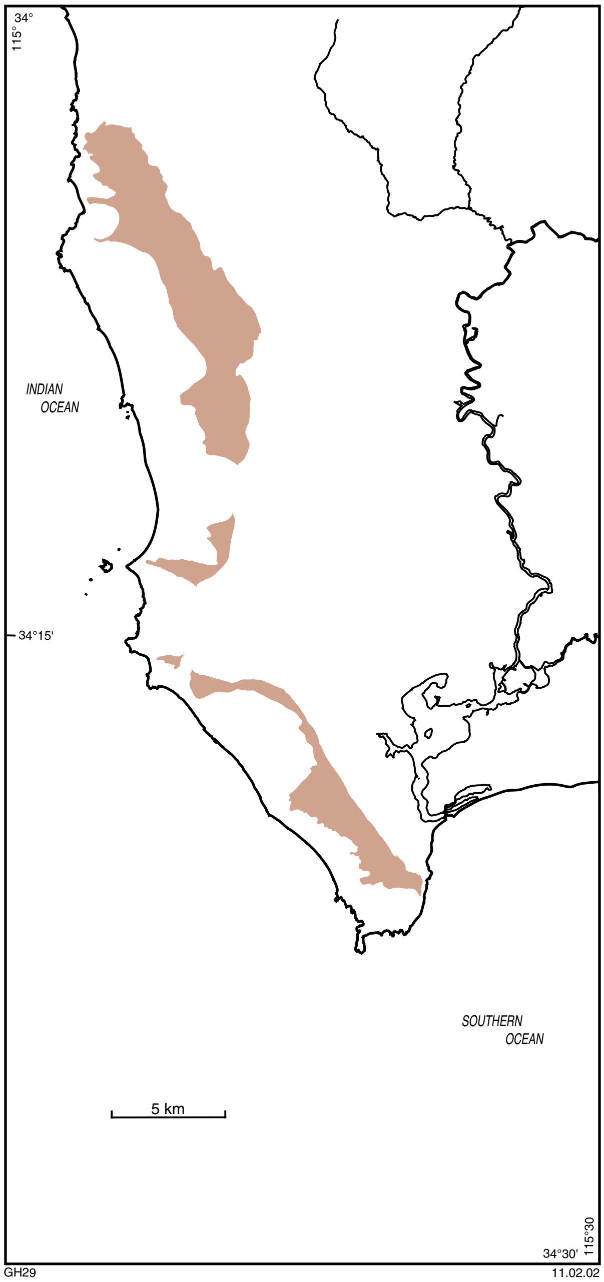

Figure 27. Distribution of the Spearwood System (*Sp*)

Regolith and rock materials

The dunes of the Spearwood System (*SpE$_d$*) were formed by dominantly eolian processes, and have been modified over time by groundwater. The dunes now consist of 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 carbonate at depth in the profile. The limestone includes many rhizomorphs and solution pipes, which formed around tree roots at a time when forest was widespread over the system. The limestones underlying the Spearwood System are more strongly cemented than those beneath the younger Quindalup System, and karstic weathering has created features such as caves, dolines (*SpR$_d$*), and drainage depressions In places, limestone outcrops through the overlying residual sand. 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 red quartz 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 commonly covered in remnant vegetation. There are a number of quarries in the system that contain limestone with varying degrees of lithification, ranging from friable to strongly lithified. These materials are used as roadbase aggregate and applied to agricultural land. Red residual quartz sand with a slightly silty content is widespread throughout the system, and is used for construction purposes, principally pads for buildings and landscaping.

Table 11. Components of the Spearwood System

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
Deflated parabolic dunefield SpE_d 5633 ha (97%)	Eolian Low hills and deflated parabolic dunes; gently to moderately inclined north- to east-facing slopes; mostly 60–110 m AHD; up to 220 m AHD Red to brown residual quartz sand over calcarenite	Coleman Road (MGA 321660E 6223490N) Limestone protrudes through the red Spearwood sand in karri forest; limestone occurs 100 m north on track from site GJH229 Strong brown (7.5YR 4/6), slightly silty, gravelly sand; main constituent is subangular to rounded medium quartz sand; minor (<1%) fine opaques and moderately strong ferruginous nodules with cutans; up to 4 mm across overlies pale yellow (2.5Y 8/2) limestone; strong rock composed of $CaCO_3$ cement; faintly recognizable shell fragments; minor subrounded medium quartz sand; and traces of fine sand opaque minerals; small dissolution cavities forming
Calcareous eolianite *SpEk* 94 ha (2%)	Eolian Exposed limestone; dominantly moderately inclined, locally steep to cliffed, west- to southwest- and north- to northeast-facing slopes; 10–110 m AHD Well-indurated calcarenite and carbonate cement	Turner Brook, Deepdene (MGA 320925E 6206395N) Cliffs of exposed limestone with cave formations; limestone rests on Leeuwin Complex rocks; high percentage of calcium carbonate cement, visible shell fragments rare
Doline SpR_d 49 ha (1%)	Residual Exposed limestone and underground caves; closed depressions and underground drainage systems; dominantly gently inclined slopes; rare steep slopes, locally cliffed; mostly 20–95 m AHD Calcarenite and calcium carbonate cement	Mammoth Cave, Caves Road (MGA 318200E 6229550N) Dolines, caves, sinkholes, and drainage depressions formed from solution of Pleistocene calcarenite
Drainage depression SpA_d 12 ha (<1%)	Alluvial Drainage depression; level to very gently inclined, north- to southeast- facing slopes; around 25 m AHD Red quartz sand	North of Skippy Rock Road (MGA 330695E 6197920N) Swampy drainage depression draining to the east off the slopes of the dune ridge; reworked red silty sand
Swamp SpE_w 10 ha (<1%)	Eolian Swamps and closed depressions; dominantly level slopes; small areas around 5 and 25 m AHD Waterlogged organic soil over red residual quartz sand	North of Skippy Rock Road (MGA 330280E 6198005N) Swampy drainage depression on the edge of the system Organic silty sand

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Figure 28. Cliff section in the Spearwood System (*Sp*) showing exposed cave formations. Tamala Limestone sits on top of the Leeuwin Complex. Turner Brook gorge (MGA 320925E 6206520N; GSWA Photograph no. 991)

Dunes west of Augusta were explored for heavy mineral sands in the late 1960s. Alferink and Alferink (1969) found that the older, yellow sands (Spearwood System) contained some heavy minerals, but the younger, lime-bearing sands (Quindalup System) were barren of heavy minerals.

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 obstacles for agricultural 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 within this system may be prone to collapse. If westerly slopes are cleared of vegetation, blowouts may be formed and migrating sand may become a minor hazard. The dense coverage of vegetation makes these areas a high risk for bush fires.

Landuse, vegetation, and drainage

Most of the Spearwood System lies 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. With the introduction of the Leeuwin–Naturaliste Ridge Statement of Planning Policy (Ministry for Planning, 1998), a few small areas bordering the National Park areas now fall within Principal Ridge Protection Areas or Ridge Landscape Amenity Areas thus affording protection from substantial future developments.

The western slopes of the ridge are exposed to strong, salt-laden coastal winds, which restrict the vegetation to heath and 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 the well-drained loamy soils of the system (Beard, 1990), and can be seen in regrowth forests along Caves Road (Fig. 30).

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 Turner Brook where the cemented dunes lie directly on top of rocks of the Leeuwin Complex.

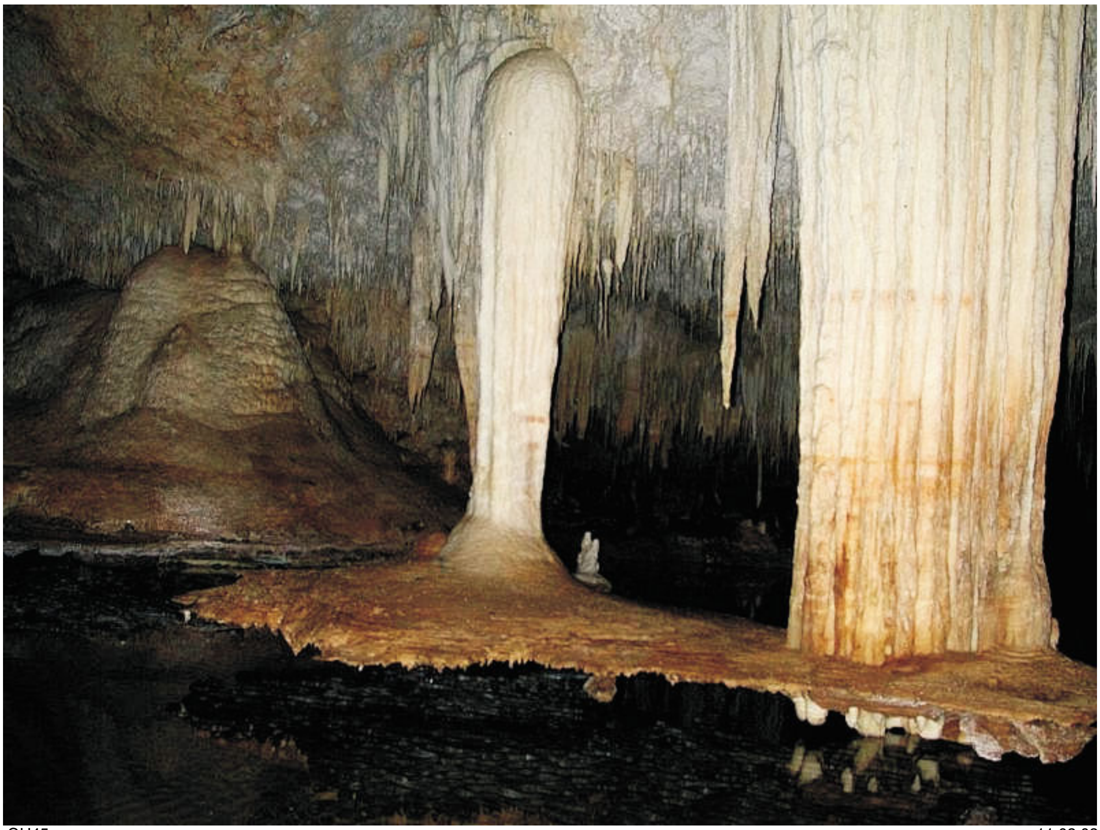

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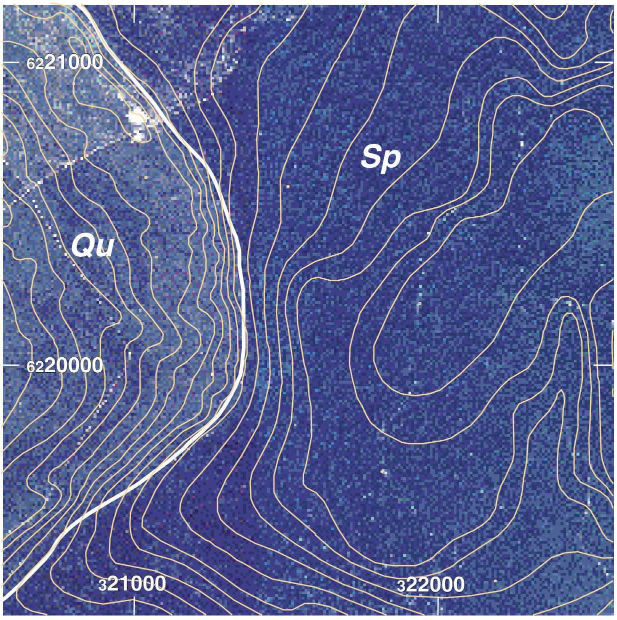
Figure 29. Lake Cave, east of Caves Road (MGA 318240E 6227305N)



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500 m

Figure 30. Vegetation on the Spearwood System (*Sp*) consists of tall trees, compared with the low scrubland of the Quindalup System (*Qu*) to the west. The Spearwood System (*Sp*) shows a more subdued topography than the adjacent Quindalup System (*Qu*). Dingo, Crystal, and Nannup Caves are found within the karri forest near Boranup Hill. 1:25 000-scale orthophotograph with contours at 5 m

Dunes that are underlain by limestone commonly contain subsurface waterways that formed during more pluvial periods. These are now largely relict features and waterlevels are much lower than they were previously. 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 that were formed as sea levels fluctuated during the Late Pleistocene. The dunes have a weathering profile of leached quartz sand over a hard, indurated calcrete caprock. 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, some of 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 calcrete, which is in turn weathered to expose limestone in the cores of the dunes (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).

Blackwood System (*Bw*)

The Blackwood System occupies 11 092 ha (8%) of KARRIDALE–TOOKER and LEEUWIN (Fig. 31, Table 12) and is underlain by alluvial deposits, estuarine and tidal deposits, and residual and colluvial materials. The Blackwood System is the fourth largest system in the area. The system may be a source of sand, gravel, and combined deposits of sand and gravel on the extensive alluvial terrace. There may also be a potential for heavy mineral sand mining.

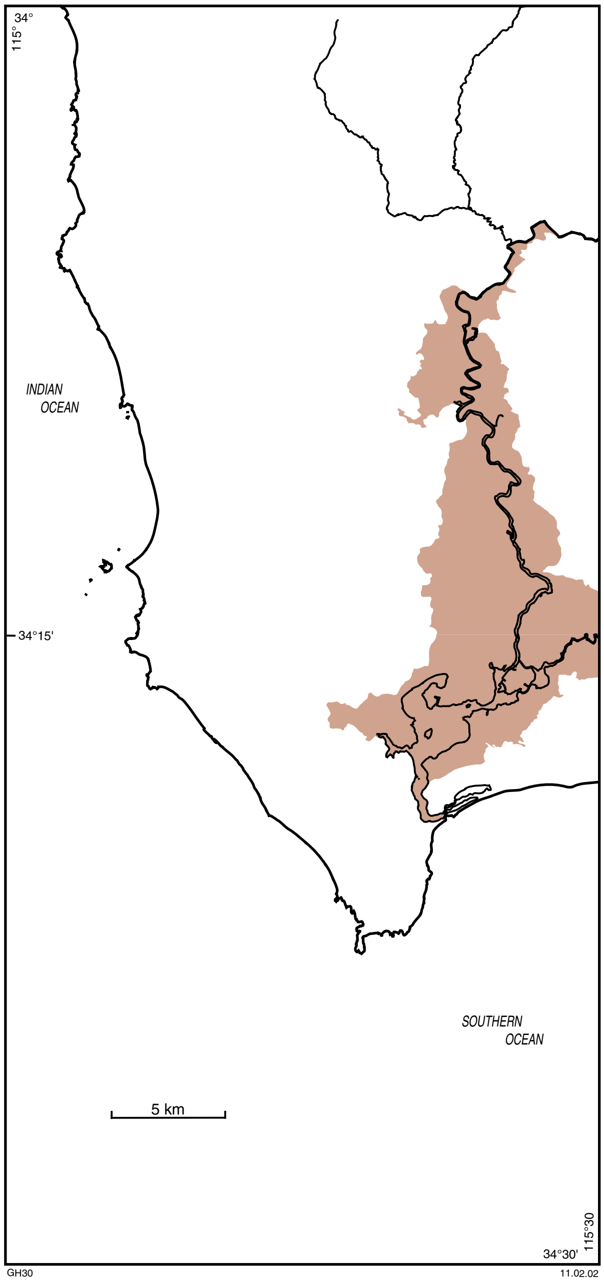

Figure 31. Distribution of the Blackwood System (*Bw*)

Landform and distribution

The extent of the Blackwood System roughly follows the course of the Blackwood River to its mouth near Augusta, and includes the Hardy Inlet. The Blackwood System comprises fluvial and estuarine materials deposited on Leeuwin Complex granulites to the west of the Dunsborough Fault, and Leederville Formation sandstones east of the Dunsborough Fault. The elevation of the system ranges from below waterlevel in the estuary to 30 m AHD on the hilltops. The system consists predominantly of a high alluvial terrace flanking the modern incised Blackwood River. The alluvial terrace has been dissected by tributaries of the Blackwood River. The fluvial materials of the migrating Blackwood River were deposited around residual low hills and rises that now protrude through the terrace in places (Fig. 32). Slopes are level to very gently inclined, with rare moderately inclined slopes. The Blackwood System lies towards the eastern side of the mapped area, and is up to 8 km wide. The elevation of the system decreases in a southerly direction to the coast.

The Hardy Inlet covers approximately 9 km^2, and includes backwaters, tidal flats, a number of islands, both permanent and intermittently inundated, and peripheral wetlands (Pen, 1997). Molloy Island is the largest of these islands, and supports a number of residential properties. The Deadwater and Swan Lake lagoons within the dunes are remnant entrance channels to the estuary formed by past meandering of the river (Pen, 1997). The Blackwood River discharged about 10 km east of its current location when sea levels were higher, or into a much larger estuary (Larson, 1972). Progressive accretion of the bars, beach lines, and dunes has moved the Blackwood channel to its present position, at the westernmost possible position against the Leeuwin Complex (Larson, 1972).

Regolith and rock materials

Ferruginous duricrust and pisolitic gravel are common on hillcrests, and may be extracted as a source of gravel. In the north and east of the Blackwood System, hillslope colluvium (*BwC*) overlies weathered Leederville Formation (mottled soil), and grades downslope from colluvial gravelly sand to sand or silty sand. Alluvial terrace (BwA_t) is extensive throughout the system, and consists of yellow sands that are locally gravelly. Within drainage depressions and the estuary, silty sands have been deposited either over granulites of the Leeuwin Complex near the coast, or sandstone of the Leederville Formation in the north.

Leached quartz sand (*BwRq*) also lies over the hillcrest duricrust. 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 can be completely eroded, leaving a low hillcrest capped by duricrust (*BwRf*) developed over Leederville Formation.

Mineral resource potential

The Blackwood System is a potential source of ferruginous pisolithic gravel and sand and, like the Treeton System to the south, is also underlain at depth by Permian coal-

Table 12. Components of the Blackwood System

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
Terrace BwA_t 7115 ha (64%)	Alluvial Terrace; dominantly level, rarely moderately inclined slopes; mostly 5–15 m AHD Gravelly silty sand	Scott National Park; Wall Road (MGA 336860E 6212460N) Residual alluvial terrace; close to river bank; augered to 1.2 m depth Yellowish brown slightly silty sand; main constituents are subrounded medium quartz sand; minor (<5%) fine sand opaques; Blackwood alluvials
Swamp BwA_w 877 ha (8%)	Alluvial Swamp; mostly level slopes; dominantly 5–15 m AHD Waterlogged, poorly drained depressions	800 m east of Blackwood River (MGA 333645E 6221385N) Series of low-relief ridges with intermittent flat swampy swales; auger jammed at 0.3 m on hardpan Brownish grey, slightly silty medium sand
Estuary BwT_e 847 ha (8%)	Tidal Tidal estuary; level slopes; dominantly below waterlevel to 5 m AHD Silty sand	About 2 km north of Augusta townsite (MGA 331170E 6203600N) Hardy Inlet covers approximately 9 km^2; past river meandering formed backwaters, islands, mudflats, and peripheral wetlands (Pen, 1997) Silty sand
Ferruginous duricrust *BwRf* 766 ha (7%)	Residual Hillcrests of low hills and rises; level, rarely moderately inclined slopes; mostly 10–20 m AHD, up to 30 m AHD Ferruginous duricrust overlying mottled soil (weathered Leederville Formation); may include small areas of relict leached quartz sand	300 m south along Coffey Road (MGA 334205E 6220760N) Gravel pit 10 m east of road; gravel has been scraped away leaving mottled soil zone exposed in places Cemented ferruginous duricrust and gravel; contains approximately 30% coarse quartz sand to fine gravel; angular to subangular; minor coarse sand opaques; about 1 m of gravel over mottled soil grading into weathered parent rock
Drainage depression BwA_d 579 ha (5%)	Alluvial Drainage depressions; may be seasonally active; level to very gently inclined, rarely moderately inclined, dominantly north-facing slopes; mostly 5–15 m AHD Formed in weathered bedrock and slope deposits; generally silty clayey sand; alluvium is generally thin	350 m east of Twinems Bend (MGA 337080E 6210655N) Next to a small culvert Coarse slightly silty sand; equidimensional, subangular to subrounded, smooth and glassy grains; fine sand opaques; nodules up to 6 mm at base of shallow auger hole; nodules are ferruginous with fine quartz grains; hard at base of hole; watertable at 1.1 m
Stream channel BwA_c 361 ha (3%)	Alluvial Stream channel; includes bed and banks; level, locally moderately inclined slopes; dominantly 5–10 m AHD Formed in weathered bedrock and slope deposits; generally silty clayey sand; alluvium is generally thin	Right bank of the Blackwood River, north of Alexandra Bridge (MGA 333165E 6218490N) Blackwood River next to private jetty; 2 m section with weathered gravel and sand on top Poorly cross-bedded ferruginized sandstone; sets 20–40 cm; abundant subrounded to subangular quartz gravel up to 3 cm; dip direction north

Table 12. (continued)

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
Plain BwA_a 222 ha (2%)	Alluvial Alluvial plain; dominantly level to very gently inclined, north- or south-facing slopes; 0–10 m AHD Thin alluvium (silty sandy clay); in places over weathered Leeuwin Complex (ⱣmLE) at shallow depth	50 m east of Blackwood River at Twinems Bend (MGA 336715E 6210530N) 1.2 m shallow auger hole; sand at surface bleached white Orangish brown; slightly silty medium quartz sand; equidimensional; subangular to subrounded; smooth and glassy grains; medium to fine sand opaque minerals <5%
Intertidal flat BwT_i 157 ha (1%)	Tidal Intertidal flat; level slopes; dominantly LAT up to 2 m AHD Silty sand	500 m northeast of Thomas Island (MGA 331855E 6204710N) Large flat between high and low tide surrounding Thomas Island
Supratidal flat BwT_u 62 ha (1%)	Tidal Supratidal flat; level slopes; dominantly 2–5 m AHD Silty sand	Just below the eastern bank of North Bay (MGA 331625E 6206400N) Zone marginal to the intertidal zone, above mean high tide
Colluvial slopes *BwC* 48 ha (<1%)	Colluvial Undivided slopes of low hills and rises; very gently to gently inclined, west- to south-facing slopes; mostly 5–15 m AHD Silty gravelly sand over mottled sandy clay over weathered Cretaceous Leederville Formation	400 m along Coffey Road from Campbell Road (MGA 334245E 6220610N) Southeast aspect, midslope of a rise; major break in slope 20 m east; augered to 1.2 m Coarse, slightly clayey, slightly gravelly sand; angular to subangular grains; minor opaque minerals; minor ferruginous nodules up to 1.5 cm, easily broken
Oxbow lake BwA_x 35 ha (<1%)	Alluvial Oxbow lake; dominantly level to very gently inclined, locally gently inclined slopes; 5–20 m AHD Gravelly silty organic sand	West of Blackwood River, 500 m south of Alexandra Bridge (MGA 333480E 6217285N) Closed depression with water dependent vegetation of low shrubs; seasonal standing water; formed by past meanders of the river channel; organic gravelly deposits
Bleached quartz sand *BwRq* 24 ha (<1%)	Residual Low hills and rises; level to moderately inclined slopes; dominantly 5–10 m AHD Bleached quartz sand	Bend in Scott River Road (MGA 334830E 620410N) Strong brown (10YR 6/6) with light greyish white mottles; fluvial; poorly sorted slightly silty coarse quartz sand to fine quartz gravel; equidimensional, subangular, glassy grains
Cretaceous Leederville Formation *KWl* <1 ha (<1%)	Bedrock Predominantly subsurface, rare, small, weathered outcrops on river banks and in channel Weathered, interbedded sandstones, siltstones, claystones, shales, and conglomerates; quartz rich	Left bank of the Blackwood River, north of Alexandra Bridge (MGA 333080E 6218895N) 2 m section of Leederville Formation incised by the Blackwood River forming the bank down to about a metre below water surface, alluvium on opposite right bank Reddish brown ferruginized sandstone, poorly sorted,composed of medium sand- to fine gravel-sized, subrounded to subangular quartz, faint trace of cross bedding, cm-scale beds with a low angle dip to the south, cosets are 30 to 50 cm, at base of exposed section are beds of subrounded vein quartz gravel up to 1.5 cm

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Figure 32. Fluvial materials of the migrating palaeo-Blackwood River form a flat terrace and were deposited around already formed residual low hills, seen here as a ridge topped with duricrust on the horizon. The flat terrace in the foreground has been weakly incised by modern drainage, forming shallow drainage depressions. Vegetation has been removed from the terraces to allow for grazing in places, but closer to the river the natural vegetation has been retained (MGA 333645E 6221385N; GSWA Photograph no. 729)

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Figure 33. The Blackwood River is about 100 m wide near Alexandra Bridge, and the banks are thickly vegetated with eucalypt forest (MGA 333165E 6218490N; GSWA Photograph no. 1467)

bearing strata. The Blackwood System is also a potential source of sand and gravel from within the alluvial terrace. There is some potential for heavy mineral sand deposits within the system. Dredging claims were held over the Hardy Inlet and parts of the Blackwood and Scott Rivers in the early 1970s by a joint venture between Project Mining Corporation and Norwest Development Corporation. The estuary opposite and to the north of Augusta showed concentrations of heavy minerals, as did the upper reaches of the Blackwood River (Project Mining Corporation Limited – Norwest Development Corporation Limited, 1971). Drilling within the Blackwood System continued into the 1990s, but no significant economic deposits of heavy minerals have been found to date.

There are three gravel pits on KARRIDALE–TOOKER. Two of the pits are adjacent to the Brockman Highway (MGA 333080 6217980 and MGA 334265 6218055), and the third is adjacent to Warner Glen Road (MGA 334205 6220760). Gravel up to 1.5 m thick is generally extracted to the underlying mottled clay, and is used as aggregate for road construction. Some of the gravel is concealed by residual quartz sand (*BwRq*) that, if thick enough, could potentially be a source of sand for landfill or construction purposes. Ferruginous pisolithic gravel (*BwRf*) is exposed on many hillcrests, where it commonly forms a resistant feature above a slight break in slope. There are two sand extraction sites on LEEUWIN, both adjacent to Fisher Road near the Blackwood River (MGA 334800 6207980 and MGA 334375 6208070).

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

Active processes and hazards

The current processes of weathering, duricrust formation, and the downslope transportation of materials are much weaker than during 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. During periods of high rainfall, streamflow may be increased and cause erosion of stream channels and banks. Closer to the coast, tidal processes become important, creating tidal flats that are alternately exposed and inundated with water. Hazards within the Blackwood System include flooding along the Blackwood River, waterlogging in the low-lying areas, and erosion by rainfall in areas cleared of vegetation.

Landuse, vegetation, and drainage

Along the Blackwood River much of the natural vegetation has been retained and the main landuse is recreation and conservation (Fig. 33). The Scott National Park extends north from the Scott System and continues into the Blackwood System. Farther from the river, much of the vegetation has been cleared to allow for grazing cattle and tree plantations (Fig. 34). Other uses include sand and gravel extraction, and forestry. There is minor urban development on Molloy Island and around East Augusta. Vegetation along the Blackwood River is commonly dense. Jarrah forest is common on duricrust topped hillcrests. Jarrah and marri forest flourishes on leached sands.

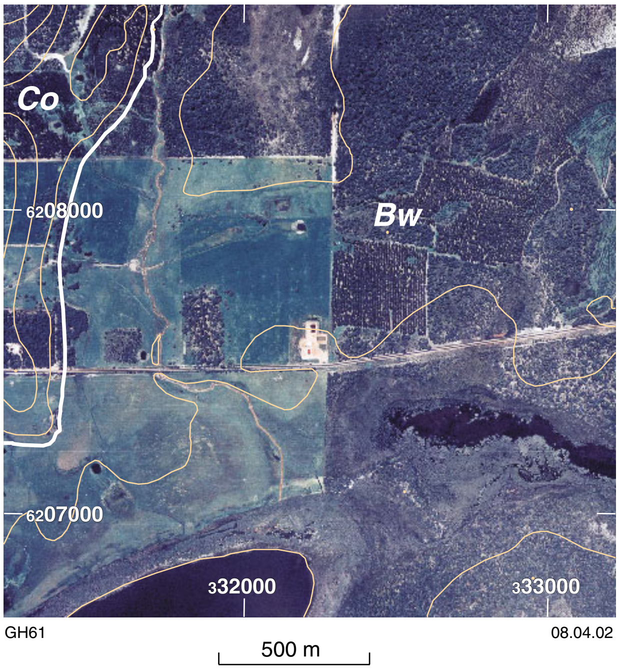

Figure 34. Around North Bay and the Hardy Inlet, the Blackwood System (*Bw*) is low-lying and flat, and swampy areas are common. Slopes become more steep in the Cowaramup System (*Co*) to the west. Land has been cleared for grazing, and tree plantations also form part of the land system. Turnwood Creek flows south across the alluvial terrace into North Bay. 1:25 000-scale orthophotograph with contours at 5 m

The Blackwood River is the main drainage feature within the system, and is more deeply incised than its tributary streams. The Blackwood River is often meandering in form, with oxbow lakes formed in places as the river changed its course over time. Salt water reaches 30 km up the Blackwood River from the Hardy Inlet (Pen, 1997). In the north, the combined Upper Chapman and Chapman Brooks flow southeast from the Treeton System into the Blackwood System. The southeast-flowing McLeod Creek and the northeast-flowing Rushy Creek enter the Blackwood System from the Cowaramup System to the west, where they join on the boundary between the two systems and then flow into the Blackwood River. Glenarty Creek drains east into the Blackwood River, and Turnwood Creek drains south into North Bay, part of the estuary of the Blackwood River. The Scott River flows southwest and enters the Blackwood River at the Scott River Basin near Molloy Island. Salt water reaches 8 km up the Scott River (Pen, 1997). The extensive flat alluvial terrace south of the estuary is subject to waterlogging during winter months, and numerous drains have been excavated to help improve drainage.

Relationships

On KARRIDALE–TOOKER the Blackwood System is bounded to the east by the Nillup System and to the west by the Cowaramup System. Along a small portion of its boundary to the north, the Blackwood System is bounded by the Treeton System. On LEEUWIN the Blackwood System is bounded to the east by the Scott System, to the south by the Quindalup System and to the west by the Cowaramup System. The Blackwood System overlies the Cretaceous rocks of the Leederville Formation to the north and east, and the Proterozoic rocks of the Leeuwin Complex closer to the coast. The Blackwood River has cut into the underlying rocks, creating alluvial and terrace deposits.

Geological history

The Blackwood System is underlain by a combination of fluvial sediments and weathering products. The Blackwood River has dissected and incised the Blackwood Plateau, forming low hills and rises, with broad swampy drainage depressions.

The Blackwood System is underlain at depth by both Permian and Proterozoic rocks, which are divided by the Dunsborough Fault. To the east of the Dunsborough Fault, undivided sand, clayey sand and fluvial sediments were deposited on top of the Leederville Formation, which had been extensively eroded, lateritized, and leached to produce ferruginous duricrust overlain locally by quartz sand. The Blackwood System is underlain in places by mottled soils, which are derived from weathered Cretaceous Leederville Formation.

To the west of the Dunsborough Fault, closer to the coast, the sediments of the Blackwood System overlie the granites and granulites of the Proterozoic Leeuwin Complex, which outcrop along the western edge of the Hardy Inlet near Augusta.

Quindalup System (*Qu*)

The Quindalup System occupies 12 053 ha (9%) of KARRIDALE–TOOKER and LEEUWIN (Fig. 35, Table 13), and consists of parabolic dunes, deflated dunes, swales, and blowouts. Materials are dominantly calcareous sand and weakly lithified calcarenite, with organic sandy soils in swales. The system is a source of limestone for roadbase, and a potential source of limesand for agricultural purposes, sand for construction, and heavy mineral sands.

Distribution and landform

The Quindalup System is the westernmost land system on KARRIDALE–TOOKER and LEEUWIN, and also the southernmost land system on LEEUWIN. The system occupies a belt up to about 4 km wide along the Leeuwin–Naturaliste Coast, and is underlain by eolian and coastal deposits that rest on the older Tamala Limestone or rocks of the Leeuwin Complex. The western margin of the Quindalup System is a beach, backed by a foredune (Fig. 36). In places the beach is backed by cliffs of calcarenite or bluffs of granulite. The dunes of the Quindalup System are often parabolic, with swampy swales filled with organic sandy soils where the 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. 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. Beaches to the east of Cape Leeuwin face south and southeast. The beaches have low relief and are generally gently to moderately sloping. Dune slopes are mostly gently to moderately 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 225 m AHD, with heights generally increasing towards the east.

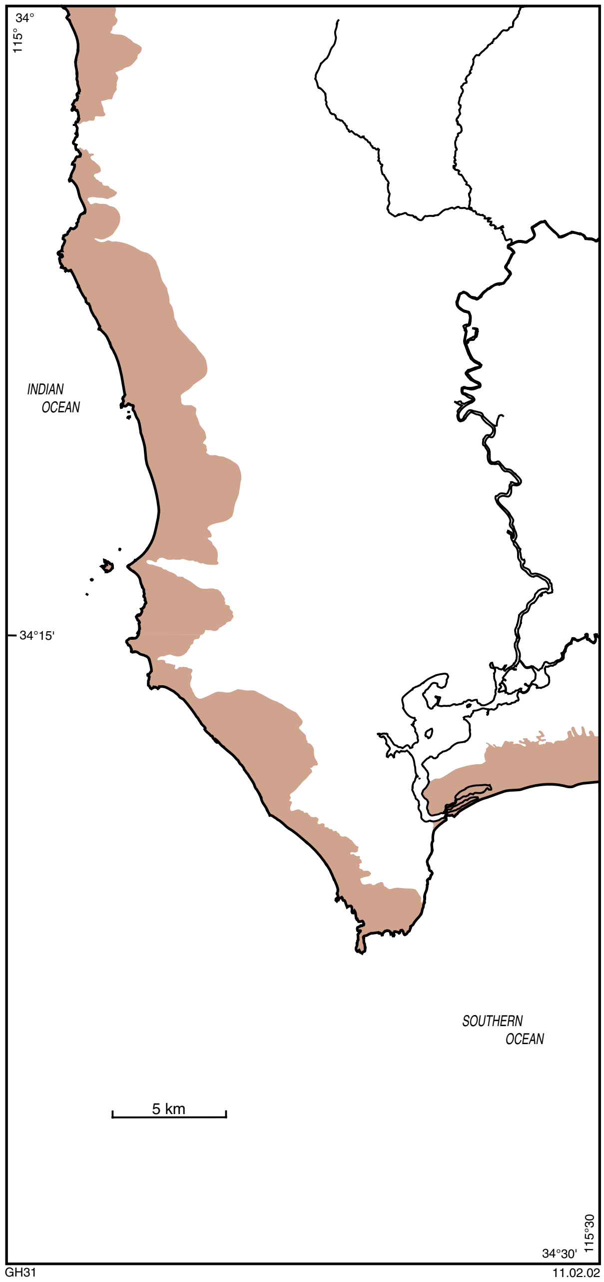

Figure 35. Distribution of the Quindalup System (*Qu*)

Regolith and rock materials

The dominant material in the Quindalup System is calcareous eolian sand composed of shell fragments and quartz, with 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 predominantly eolian environment of the 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 (Fig. 37) are exposed at both current sea level and old sea level stands, and may be unconformably overlain by lithified dune sand. Outcrops of Proterozoic granulite are also common along the coast.

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

The dunes have varying degrees of lithification at depth, depending on their relative age. The younger parabolic dunes (QuE_a) can have very weak* calcarenite cores, whereas the older, deflated dunes (QuE_d) are composed of calcareous soils over moderately weak limestone.

* See Appendix 7 for rock material strength

Table 13. Components of the Quindalup System

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
Parabolic dunefield QuE_a 7093 ha (59%)	Eolian Dunes; gently to moderately inclined, locally very steep, mostly west- to southwest-facing slopes; 0–220 m AHD Shell and quartz sand	East of Boranup Beach on Grace Road (MGA 320845E 6216485N) On a westerly facing duneslope Calcareous sand with minor subangular quartz and very fine mafic minerals; pale yellow (2.5Y 8/3); grains are equidimensional and elongate, subangular to subrounded
Dunefield QuE_d 3859 ha (32%)	Eolian Undivided dunes; gently to moderately inclined, locally precipitous slopes, mostly south to southwest facing; 0–225 m AHD Shell and quartz sand	Trig Road, 600 m from intersection with Davies Road (MGA 320795E 6220585N) Easterly facing duneslope Ferruginous quartz sand over limestone; yellowish red (5YR 4/6); hit limestone at 0.8 m depth; medium quartz sand with equidimensional, subangular to subrounded, smooth grains; minor very fine mafic minerals
Swamp QuE_w 309 ha (3%)	Eolian Swamp; level, north- or south-facing slopes; 0–15 m AHD Waterlogged organic soil over shell and quartz sand	Long Swamp, south of Scott River Road (MGA 336977E 6203630N) Area of water-tolerant vegetation, poorly drained, over 2.5 km long by 500 m wide
Beach QuB_b 271 ha (2%)	Coastal Beach and foredune; gently to moderately inclined, dominantly west- to southwest-facing slopes; south facing east of the Hardy Inlet; mostly 0–15 m AHD Marine shell and quartz sand; eolian in part	Boranup Beach near North Point (MGA 318130E 6218290N) Sandy beach backed by limestone cliffs; limestone platforms on the beach and just below waterlevel Calcareous sand; very pale brown (10YR 8/4); abundant shell fragments; equidimensional and elongate; minor quartz
Blowout QuE_b 250 ha (2%)	Eolian Dunefield; gently to moderately inclined, locally precipitous slopes, mostly south to southwest facing; 0–175 m AHD Actively eroding shell and quartz sand	Boranup Sand Patch, just off Caves Road (MGA 322790E 6215540N) Limesand quarry, with numerous blowouts nearby Weakly lithified calcarenite
Proterozoic Leeuwin Complex *ⱣmLE* 136 ha (1%)	Bedrock Stream beds and coastline; exposed at beach level and as cliffs along the coast; mostly gentle to moderate slopes; very steep in places Fresh to weathered, undivided felsic granulite and granite; minor mafic granulite and anorthosite	Foul Bay (MGA 318815E 6210110N) Granitoid outcrops on the beach in Foul Bay Numerous pegmatites; the granitoid is lineated and folded in places; lineations trend 030° to 040°; some remnants of limestone over the granitoid, which varies from medium to coarse grained
Foredune QuB_d 57 ha (1%)	Coastal Foredune; gently to moderately inclined, dominantly west-facing slopes; south facing east of the Hardy Inlet; dominantly 5–10 m AHD Eolian shell and quartz sand	Near Leeuwin Road, east of Cape Leeuwin (MGA 329190E 6195440N) Narrow foredune behind the beach Calcareous coarse sand; subrounded to rounded shell fragments

Table 13. (continued)

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
Drainage depression QuA_d 40 ha (<1%)	Alluvial Drainage depression; includes seasonally active channels; level to moderately inclined; mostly 0–15 m AHD; up to 35 m AHD Formed between dunecrests in eolian deposits and weathered bedrock; silty sand	Mouth of Turner Brook (MGA 320680E 6205540N) Precipitous river-bank cutting Fluvially emplaced sand eroded by meandering stream; medium to fine silty sand with rounded and elongate shell fragments and sponge spicules; minor quartz; opaques rare or confined to separate small laminae within beds
Lithified dunefield *QuEk* 18 ha (<1%)	Eolian Dunes; mostly level to moderately inclined slopes, locally precipitous and cliffed; dominantly north facing; 0–30 m AHD Calcareous eolianite; weakly lithified shell and quartz sand; includes coastal rock platform	South of Cosy Corner (MGA 319020E 6207295N) Undercut low cliffed ledge about 3 m high; wave-cut platform; cross bedded with small sets; beach or shallow marine unit; unconformably overlies a similar unit lacking cross-bedding Coarse-grained, well sorted, clast supported, moderately indurated to weak with case hardening; approximately 90% rounded shell particles; 10% quartz and opaques
Beach ridge QuB_r 14 ha (<1%)	Coastal Beach ridge; level, locally gently inclined; mostly north-facing slopes; 0–5 m AHD Shell and quartz sand	At the mouth of the Blackwood River (MGA 331915E 6200315N) Currents in Flinders Bay have created a beach ridge partially blocking the mouth of the river
Parabolic dunes over Leeuwin Complex QuE_a 6 ha (<1%)	Eolian Dunes; dominantly moderately inclined; mostly east- to south-facing slopes; 5–40 m AHD Shell and quartz sand over bedrock	East of Cape Leeuwin (MGA 330555E 6195640N) Thin layer of dune deposits over bedrock; numerous outcrops of granulite on the duneslope
Pegmatite <1 ha (<1%)	Bedrock Coastal rocky headlands and rock platforms Very coarse grained (pegmatitic) veins in granulite and granitic gneiss	Skippy Rock (MGA 327760E 6196880N) Basement rock outcrop on coast, level rock platform Minor cross-cutting pegmatite veins within coarse-grained granite gneiss; vein trends southwest, steeply dipping, host rock is grossly banded with felsic/mafic zones, weakly to moderately foliated, mafic zones are more foliated and are preferentially weathered due to high proportion of ferromagnesian minerals, particularly amphibole, highly deformed, folding in mafic bands, boudinage in more felsic bands

Figure 36. Steeply sloping foredunes and gently sloping sandy beaches are characteristic landforms of the Quindalup System (*Qu*), northwest of skippy Rock, (MGA 326165E 6199360N; GSWA Photograph no. 960)

Figure 37. Blowouts are common in the dunes of the Quindalup System (*Qu*). In places, limestone platforms exist at the wave base, and heavy minerals can accumulate near coastal outcrops of Leeuwin Complex granulites (Hamelin Bay, MGA 318315E 6211475N; GSWA Photograph no. 1737)

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. Several small quarries provide limesand as well as lithified calcarenite from the cores of the dunes for use as roadbase. A tenement exists over a portion of the Boranup Sand Patch on KARRIDALE–TOOKER, and some material has been removed in the past for agricultural application. Most of this series of blowouts on the Leeuwin–Naturaliste Ridge lie within the National Park.

There is some mineral resource potential for heavy mineral sands within the beach and dune sands of the system, an example being near Skippy Rock on LEEUWIN. Exploration was carried out to the east of Augusta (Project Mining Corporation Limited – Norwest Development Corporation Limited, 1971), where three principal shorelines and dune complexes were identified from aerial photographs. Heavy mineral concentrations were found at two levels within the parallel dunes. The concentrations are mainly eolian, and may represent two stages of dune development. The deeper zone of concentration may represent older beach and bar deposits blanketed by younger eolian deposits (Project Mining Corporation Limited – Norwest Development Corporation Limited, 1971). The upper zone of concentration was found to be subeconomic as the heavy minerals rest mainly above the watertable.

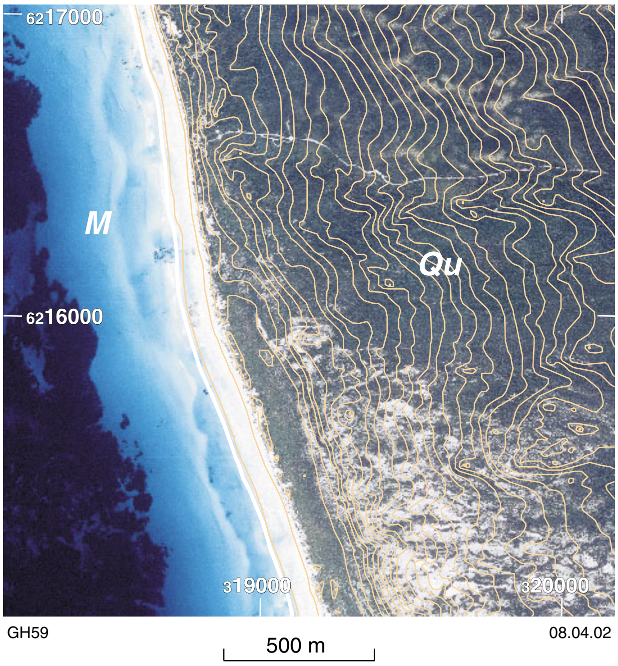

Figure 38. Parabolic dunes and blowouts are characteristic features of the Quindalup System (*Qu*). The steep slopes of the dunes and foredunes meet the gently sloping sandy beaches that border the Marine System to the west. Leeuwin–Naturaliste National Park north of Boranup Sand Patch. 1:25 000-scale orthophotograph with contours at 5 m

Active processes and hazards

Eolian processes dominate on the dunes, and both eolian and coastal processes are dominant on the beaches and foredunes. 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 (Fig. 38) 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 a natural, usually seasonal, process.

Collapse or subsidence of material, particularly overhanging cliffs, is a significant hazard along the coast. 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 taken place around Augusta. Grazing is a minor landuse in the Quindalup System.

The vegetation along the coast 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. Scrub heath can be found on stable dunes, with larger shrubs such as peppermint (*Agonis flexuosa*), banksia (*Banksia grandis*), and some eucalypts (*Eucalyptus 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, which are generally granulites, can be very steep, but farther inland the stream banks are more gently sloping. There are no channels on the dune slopes, as the sands of the dunes are well drained. A few drains have been dug along swampy depressions within the deflated dunes east of the mouth of the Blackwood River in an attempt to alleviate waterlogging problems.

Relationships

The Quindalup System trends in a northerly direction along the Leeuwin–Naturaliste Coast, and in an easterly direction east of the Blackwood River. Eolian sands of the system overlie the Proterozoic rocks of the Leeuwin

Complex, which are exposed in places along the coastline. East of the Dunsborough Fault the sands of the Quindalup System overlie the Cretaceous rocks of the Leederville Formation. To the west the 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 Safety Bay Sand, which was deposited during the Holocene (<40 000 years BP). The Safety Bay Sand is defined as coastal sand dunes and littoral sands (Passmore, 1967, 1970). The older deflated 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 underlying the Quindalup System continues today, together with their erosion by the prevailing winds and rain.

Marine System (*M*)

The Marine System occupies 60 257 ha (44%) of KARRIDALE–TOOKER and LEEUWIN (Fig. 39, Table 14), and includes the nearshore rock ridges and flats, nearshore and offshore sandplains, marine channels, reef or rock flats, and shoreface seabed. The shallow waters have the potential to be a source of limestone, sand, and limesand. Reef and rock flats occupy a significant proportion (43%) of the Marine System.

Morphology and distribution

The Marine System consists of a level to gently inclined nearshore and offshore seabed, and level to very gently inclined shoreface. The system includes all seabed materials and morphological features up to Chart Datum (CD), which is the level of the lowest astronomical tide (LAT), and a few features of the littoral zone that are more closely related to the marine environment. A major component of the Marine System on KARRIDALE–TOOKER is nearshore reefs and rock flats. The reefs and rock flats can be exposed in the littoral zone between high and low tide, or form inshore or nearshore rock platforms. On LEEUWIN the major component of the Marine System is offshore sandplain, as the mapping area extends farther offshore than on KARRIDALE–TOOKER. Erosional channels offshore from Boodjidup Beach and Redgate Beach are relicts of fluvial palaeochannels associated with the Boodjidup and Calgardup Brooks that formed during lower sea levels. Small islands of limestone (Fig. 40) are found just offshore in many places along the coast.

Seabed materials

The seabed is dominantly covered by either sand of the offshore sandplain (M_p) or by rocky platforms and reefs composed mostly of Leeuwin Complex granulite and granite, with some calcarenite of eolian or beach origin (M_r). The calcarenite is mostly Tamala Limestone of eolian origin. Some rocky platforms and reefs are partially emergent in the shoreface region (Fig. 41). Around Cape Leeuwin, granulites outcrop on the seabed, with folding and faulting structures visible on aerial photographs through the clear waters (Fig. 42).

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 that have brought materials from weathered rocks farther inland. The sand is also made up of grains from the weathering of marine reefs and rocks, as well as from biogenic activity. Narrow terrestrial palaeochannels (M_v), which were incised during lower sea levels, are now infilled with sand from the currently active drainage systems. This sand has been reworked in the nearshore marine environment.

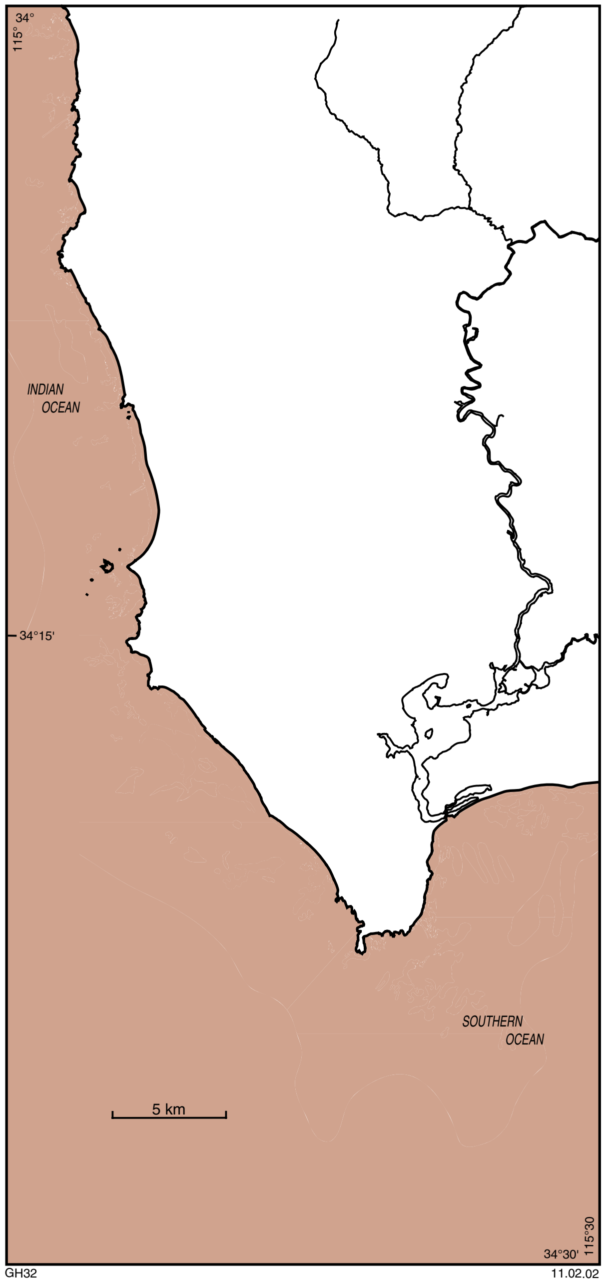

Figure 39. Distribution of the Marine System (*M*)

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 KARRIDALE–TOOKER and LEEUWIN is covered by water in excess of 10 m depth, and the sea conditions are often rough, 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 KARRIDALE–TOOKER and LEEUWIN, with constantly active

Table 14. Components of the Marine System

Unit name, map symbol and area	*Process, landform, and material*	*Typical occurrence*
Offshore sand plain M_p 27 133 ha (45%)	Marine Offshore sand plain; mostly level to very gently sloping; –20 to –50 m LAT Shell and quartz sand	About 3.5 km west of Hamelin Island (MGA 313445E 6211440N) Sand, fine sand, and some shell and coral in grab samples noted on Chart AUS756 (R.A.N. Hydrographic Office, 1985)
Reef and rock flats M_r 25 828 ha (43%)	Marine Minor sandy areas; can be exposed at low tide; –5 to –40 m LAT Undivided Leeuwin Complex and eolian calcarenite	Hamelin Bay (MGA 317780E 6213675N) Exposures of granulite and calcarenite extend offshore into rock flats on the seabed
Nearshore sand plain and sandy hollows M_n 6694 ha (11%)	Marine Nearshore sand plain and sandy hollows; mostly level to gently sloping; –5 to –20 m LAT Shell and quartz sand; minor rock ridges and flats	About 1.7 km south of North Point near Boranup Beach (MGA 318295E 6216890N) Sharp change in aerial phototone from the nearshore rock flats to the adjacent sand plain
Shoreface M_s 546 ha (1%)	Marine Shoreface; mostly gentle slopes; down to –5 m LAT Shell and quartz sand; minor rock ridges and flats	About 2.8 km south of Cape Freycinet (MGA 315950E 6222675N) Sharp change in phototone from pale sand on the shoreface to the adjacent nearshore rock flats
Proterozoic Leeuwin Complex *PmLE* 31 ha (<1%)	Bedrock Islands of Leeuwin Complex granulite and granite; both close to the shore and farther offshore Granulite and granite	Seal Island (MGA 330570E 6194215N) Large granitoid island south of Cape Leeuwin; approximately 400 m long by 150 m wide
Palaeochannel M_v 24 ha (<1%)	Marine Sand-filled palaeochannel in shoreface and nearshore sediments; level to gently inclined; –5 to –50 m LAT Shell and quartz sand	West of the mouth of Calgardup Brook (MGA 314550E 6230725N) Sand-filled channel feeding from the mouth of the brook, extending offshore in a southwesterly direction as a narrow erosional channel

GH50 12.02.02

Figure 40. Small limestone islands are a common feature of the Marine System (*M*) close to the coastline. In the foreground, beachrock has formed within the intertidal zone of the Quindalup System, Cosy Corner, (MGA 318420E 6207615N; GSWA Photograph no. 998)

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Figure 41. Granulites of the Leeuwin Complex outcrop extensively along the coast, are exposed on the seabed, and form islands offshore, Redgate Road, (MGA 315315E 6231600N; GSWA Photograph no. 2128)

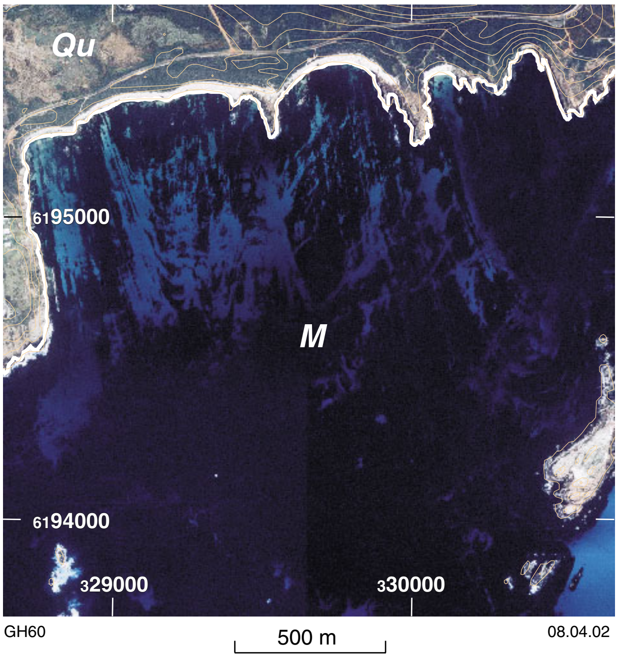

Figure 42. Folding and faulting structures in the granulites of the Leeuwin Complex are common in the Marine System (*M*) around Cape Leeuwin. Numerous offshore islands occur in the area. 1:25 000-scale orthophotograph with onshore contours at 5 m

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.

Rapid deposition and erosion of coastal deposits can take place during storms, and coastal cliff collapse can be induced by a combination of heavy rainfall and storm action. Rough coastal waters combined with submerged reefs pose a hazard for boats. Longshore drift from south to north is constantly modifying the inshore shoreface, as well as the adjacent beach in the Quindalup System. Regeneration of the shoreface and adjacent beach is a natural, seasonal process.

Seabed use

The seabed has limited potential for use of its materials because of the depth and roughness of the waters, and the presence of numerous rocky reefs that pose a hazard to boats. Other potential uses of the Marine System include fishing, recreation, surfing, and whale watching.

Relationships

The materials of the Marine System overlie the granulites and granites of the Leeuwin Complex that protrude through the marine sediments in places. Closer to the coast, the calcareous sands of the Marine System overlie the older beach and dune deposits of the Quindalup System.

Geological history

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 KARRIDALE–TOOKER and LEEUWIN is limited to a small range of construction and industrial minerals (Fig. 43). The area is also known to contain coal occurrences and heavy mineral sands, and there are some early reports of gold occurrences. At present there seems to be a good regional supply of basic raw materials such as sand, limestone, limesand, gravel, rammed earth materials, and aggregate. However, demand will continue to increase as population rises, and future urban, industrial and infrastructure development of the region will rely on a good supply of local materials at competitive costs. The presence of National Parks will contribute to restrictions on the supply of some commodities such as limestone and limesand. Knowledge of the distribution and supply of these resources will help avoid future landuse conflicts, and thus provide benefits to the whole community.

The mineral occurrences on the map are grouped into mineral commodity and mineralization style as described in Appendix 8.

Gravel

The ferruginous duricrust and transported gravels that cover many of the hillcrests in the Cowaramup and Treeton Systems, and some hillcrests in the Blackwood and Nillup Systems (Fig. 42), range from strongly cemented to loose, and overlie mottled residual soil. This underlying 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 maintaining unsealed shire roads and tracks.

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

Thick deposits of yellow and red sand underlying the Spearwood System have formed by the weathering of calcareous sand (Fig. 42). 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 (Tamala Limestone).

Residual bleached sand has formed in places above the ferruginous duricrust. This clean white sand sometimes contains gravel-sized quartz grains, and is commonly used for landfill, or as a base beneath roads and footpaths. The sand is probably derived from the weathering of the underlying ferruginous duricrust, or is possibly the leached

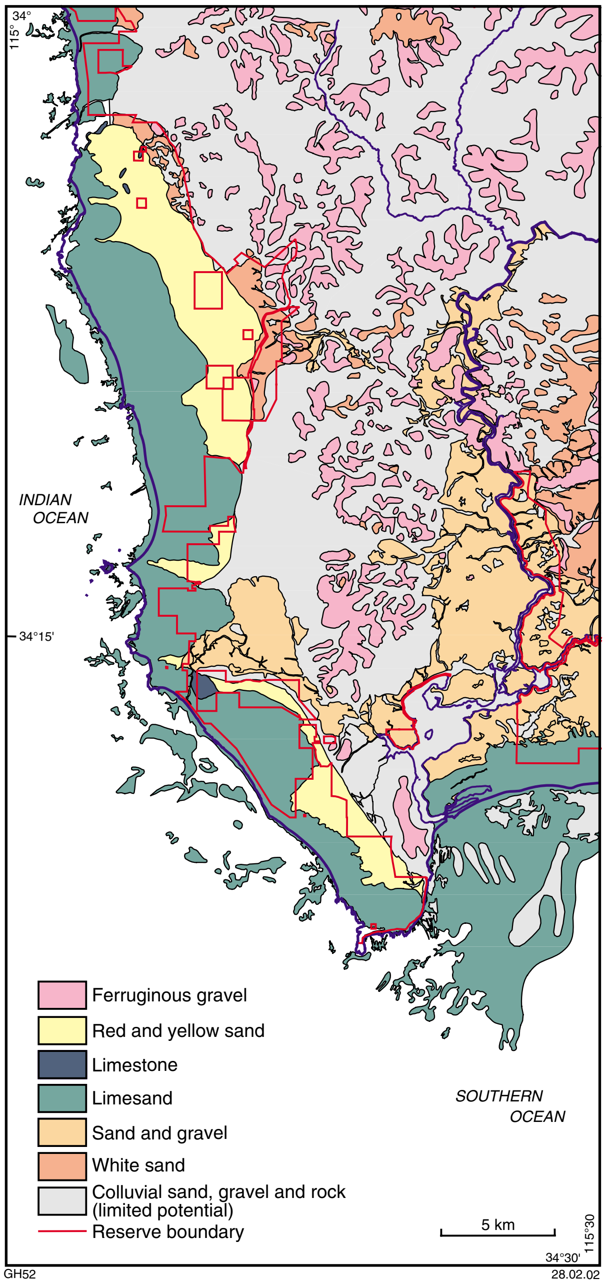

Figure 43. Construction and industrial mineral resource potential of KARRIDALE–TOOKER and LEEUWIN

residuum of permeable sandy deposits. The occurrence of residual bleached sands seems to correlate with the outcrop of Cainozoic sediments overlying the Leeuwin Complex or Cretaceous strata.

The alluvial terraces of the Blackwood and Scott Systems are also a source of sand and gravel. The Blackwood System includes areas of yellow sand, and the Scott System is underlain in places by clean white sand.

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 soil 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, underlying the Spearwood System, comprises calcrete over calcarenite. The younger Safety Bay Sand, underlying the Quindalup System, includes weak calcarenite. Calcarenites in these two geological units are generally referred to as limestone (Fig. 43). Abeysinghe (1998) reviewed the limestone resources of the Cape Leeuwin–Cape Naturaliste region. In KARRIDALE–TOOKER and LEEUWIN the major use of limestone is as an aggregate for roadbase and concrete. More friable limestone may be used for agricultural purposes.

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 the term ‘lime’ is used incorrectly to describe calcareous products such as agricultural limesand.

Limesand on KARRIDALE–TOOKER and LEEUWIN is predominantly an eolian deposit 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 underlie 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. 42). There is a small limesand pit on LEEUWIN, on private land east of Augusta (MGA 333570E 6202255N). Limesand has also been removed from Boranup Sand Patch on KARRIDALE–TOOKER (MGA 322795E 6215560N). Redgate Lime is a privately operating limesand quarry on Redgate Road (MGA 316960E 6232465N). The calcarenite of the Quindalup System here is very weak and friable, which allows for easy crushing to form limesand. A few other abandoned pits in the vicinity are intermittently operated by the Shire of Augusta–Margaret River.

Aggregate and dimension stone

The Leeuwin Complex, which is composed of fresh granulite and granite at shallow depths, is a potential source of both crushed rock aggregate and dimension stone. These potential resources have not yet been investigated or exploited within the area.

Heavy minerals

The eolian and coastal sands in the Swan Coastal Plain contain minor amounts of heavy minerals, with the most important economic deposits in the region located to the northeast of KARRIDALE–TOOKER and LEEUWIN 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 Cainozoic valley-fill deposits on the plateau adjacent to the Leeuwin–Naturaliste Ridge.

A significant occurrence has been noted in KARRIDALE–TOOKER in the area lying east of Witchcliffe. Heavy mineral anomalies were first noted by the Electrolytic Zinc Company of Australasia Limited (1971). Since then BHP Minerals has carried out reverse-circulation drilling programs over much of the area, targeting heavy minerals within the Cainozoic sediments overlying the Leeuwin Complex. Resource estimates for the Witchcliffe Deposit ranged from 47.9 million tonnes (Mt) of 3.43% ilmenite to 958.2 Mt of 2.74% ilmenite (BHP Engineering Proprietary Limited, 1995).

BHP also produced a resource model for the Glenarty Creek area underlying the Blackwood System. Resource estimates were 701 Mt of 2.6% ilmenite at a 2% cutoff. From feasibility studies, including mine planning and financial analysis, Shackleton (1999) concluded that the deposit lacked development potential.

The deposits on LEEUWIN at Blackwood (deposno 10644–10650) and Location E (deposno 10651–10654) are probably southwestern extensions of the major Beenup mineralization that lies to the northeast.

Gold

Saint-Smith (1912) reported two gold occurrences on KARRIDALE–TOOKER. One is approximately 14 km southeast of the Margaret River Post Office near a branch of the Chapman Brook where small quantities of gold were obtained from a quartz reef within the Leeuwin Complex. Some gold was obtained at the surface, and two shallow costeens were dug, the longest 12 feet (3.7 m), but not enough gold to continue work. The other occurrence is

8.3 km south-southeast of the Margaret River Post Office on the Boodjidup Brook. Attempts to locate these occurrences during the present survey were unsuccessful.

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 noted 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 Department of Mines drilled a line of waterbores (Probert, 1968; Wharton, 1981; Kristensen and Wilson, 1986; Townsend, 1994).

The Vasse River Coalfield, assessed by Le Blanc Smith and Kristensen (1998), lies to the north of the map area on COWARAMUP–MENTELLE (Hall et al., 2000) on the uplifted Treeton Terrace of the Vasse Shelf. Owing to faulting, Permian strata beneath KARRIDALE–TOOKER and LEEUWIN lie on the Vasse Shelf at greater depths, and are therefore less likely to contain deposits which are economic. Some rotary and diamond drilling completed by Esso Australia Limited (1984) and CRA Exploration Proprietary Limited (Ellis, 1985) indicated that coal seams underlie the Treeton, Nillup, Blackwood, Scott and Quindalup Systems of the Blackwood Plateau and Scott Coastal Plain at depth within the Permian strata. While drilling for heavy mineral sands, Westralian Sands (Gifford, 1991, 1992) also noted thin coal seams within the Leederville Formation. Esso Australia (1984) analysed coal from the Leederville Formation but it was considered to be of inferior quality compared with Permian coals.

Hydrogeology

Six groundwater regions (Swan Coastal Plain, Blackwood Plateau, Margaret River Plateau, Leeuwin–Naturaliste Coast, Scott River Plain, and Blackwood River Alluvials) 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). These groundwater regions closely correlate to physiographic regions, and five of them (summarized below) can be found within KARRIDALE–TOOKER and LEEUWIN. Moore (1990) summarized the total availability of renewable groundwater resources underlying the study area.

Beneath the Blackwood Plateau, which can be equated with the Treeton and Nillup Systems, 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, but the iron content is typically high.

The Blackwood River Alluvials, which can be equated with the Blackwood System, consists of alluvial sediments of unknown thickness overlying older formations of the southern Perth Basin. The alluvium contains unconfined groundwater, generally at shallow depth. Little is known about the quality and quantity of this groundwater. However, it is expected that the salinity of the Blackwood River would not have a large effect on the groundwater salinity in this area (Hirschberg, K., pers. comm. *in* Tille and Lantzke, 1990b). Large groundwater supplies are generally available from sandy sections within the Leederville Formation. Yields are commonly only small to moderate because of the clayey nature of the sediments. The salinity of the confined groundwater is normally less than 500 mg/L total dissolved solids (TDS), with a slight increase towards the coast, and the iron content is commonly high.

The Scott River Plain, equivalent to the Scott System, is covered by a veneer of superficial formations of predominantly clayey regolith some 3 to 30 m thick, or thicker in the coastal dunes, overlying the older formations of the southern Perth Basin. The superficial formations contain unconfined groundwater, but nothing is known about yields. The watertable is expected to be shallow (Hirschberg, K., pers. comm. *in* Tille and Lantzke, 1990b). The groundwater from the superficial formations is fresh, ranging between 200 and 530 mg/L TDS from GSWA bores, and between 340 and 690 mg/L from sampled springs (Baddock, 1995). Groundwater salinity tends to be higher near wetlands, where there is a greater rate of evapotranspiration (Baddock, 1995). The direction of groundwater flow is predominantly southward towards the coast (Baddock, 1995). In some areas the groundwater within the superficial formations is confined or semi-confined by a layer of ferruginous cemented sand developed within the Guildford Formation. The supplies and quality of confined groundwater from the sandy intervals within the older formations will be similar to those from underneath the coastal plain and the Blackwood Plateau, with a high iron content. The Yarragadee Formation and parts of the Lesueur Sandstone and Cockleshell Gully Formation contain fresh groundwater and form a major confined aquifer with a single, hydraulically connected flow system referred to as the Yarragadee aquifer (Baddock, 1994). Smaller, but important fresh groundwater resources are present within the Warnbro Group, and the Sue Group contains brackish to saline groundwater (Baddock, 1995).

The Margaret River Plateau, which can be equated to the Cowaramup System, 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 Leeuwin–Naturaliste Coast, equivalent to the Quindalup and Spearwood Systems, 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 rarely developed. Groundwater supplies from the sand and limestone are restricted to a few favourable locations, including town supplies for Augusta.

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Appendix 1

Description of digital datasets

The following datasets have been used in compiling this Record, 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 Geological Survey of Western Australia's (GSWA) 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 locations.

Linear features are presented as separate layers or line themes:
- faults;
- dunecrests;
- cliffs or scarps.

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 Record and the Map, is described in Appendix 8. 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 KARRIDALE–TOOKER and LEEUWIN 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 (DOLA). 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 DOLA:
- contours
- topographic points
- spot heights
- water bodies
- swamps
- pipelines
- roads
- rail
- powerlines
- buildings
- airports
- 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, and the bathymetry.

Appendix 2

Gazetteer of localities

Locality	MGA coordinates Easting	MGA coordinates Northing
Adelphi Memorial Monument	332800	6218500
Alexandra Bridge	333500	6218300
Allan Dale Homestead	331500	6211000
Amber Springs Homestead	329400	6210300
Arakoonah Homestead	326100	6221700
Arumvale	323200	6216900
Arumvale Cave	322400	6218600
Augusta	330600	6201700
Augusta Primary School	330500	6201100
Augusta River Mouth surfing spot	331800	6200400
Barrack Point	331700	6198000
Beenup	338100	6210200
Bellview Homestead	324300	6234700
Black Rock	316200	6210100
Black Stump Homestead	330300	6205000
Blackwood River	333600	6218300
Blue Rock Caves	323000	6221900
Boathaugh Homestead	332200	6218200
Bobs Hollow	315500	6229500
Boodjidup Beach surfing spot	315600	6234700
Boodjidup Brook	315400	6234000
Boodjidup Brook Homestead	317900	6234700
Boodjidup Homestead	318100	6234500
Boranup	323000	6220900
Boranup Beach	318200	6218200
Boranup Beach surfing spot	317700	6218400
Boranup Community Homestead	321900	6224800
Boranup Downs Homestead	325600	6221000
Boranup Hill	319500	6220200
Boranup Sand Patch	321100	6214200
Braebrook Homestead	326800	6233200
Breakneck Gully	323000	6218200
Brennan Reef	330800	6202600
Bride Cave	319100	6226500
Cadeby Downs Homestead	322000	6211300
Calgardup Brook	318000	6231600
Calgardup Cave	317700	6230500
Candowie Homestead	325100	6215400
Cape Freycinet	314700	6225100
Cape Hamelin	319000	6206200
Cape Leeuwin	328600	6194500
Cape Leeuwin Lighthouse	328600	6194700
Chapman Brook	334600	6225900
Chapman Pool	334500	6226100
Charandor Homestead	325000	6206700
Chitterbin Homestead	317900	6232600
Civic Park	330200	6201400
Cliff Spackman Reserve	323600	6206200
Cloverdene Homestead	326200	6213200
Cloverlea Homestead	327600	6230500
Cole Rock	332200	6197600
Connelly Cave	315500	6229000
Conto Spring	315800	6226900
Cosy Corner	318400	6207700
Courtenay	337000	6215900
Crustacea Cave	318800	6226900
Crystal Cave	322400	6219700
Crystal Springs Homestead	326200	6222400
Cumberland Rock	321700	6199100
Dead Finish Anchorage	330800	6195700
Deepdene	320900	6207000
Deepdene Cave	321200	6206700
Deepdene Homestead	320900	6207000
Deepdene surfing spot	320500	6205300
Deere Reef	331800	6199600
Devil Pool	317000	6234900
Dianella	323100	6215700
Dick Island	333100	6205500
Dingo Cave	321700	6219800
Duke Head	331600	6200400
East Augusta	332200	6201900
East Hill	319300	6212200
East Witchcliffe	326300	6234200
Easter Cave	325000	6205800
Edith Rock	315600	6213700
Ellterra Homestead	327700	6219100
Elwood Park Homestead	325800	6229500
Flinders Bay	333100	6200200
Flinders Island	335200	6190500
Forest Grove	324500	6228300
Foul Bay	318100	6209700
Gas Bay	314900	6235700
Geographe Reef	314700	6202200
Georgiana Park	331300	6200300
Giants Cave	319600	6226100
Gillespie Homestead	329500	6233100
Glen Karri Homestead	324700	6226700
Glen View Homestead	331100	6212800
Glenarty Creek	330800	6212200
Glenleigh Homestead	329500	6207800
Glenroa Homestead	326000	6236200
Gnarabup	315300	6235800
Golgotha Cave	320200	6225400
Grace Bussell Memorial Monument	315300	6231800
Grace Rock	317000	6216100
Granny Pool	331600	6198000
Green Hill	326600	6200700
Green Valley Farm	325000	6226200
Green Valley Homestead	328300	6216200
Groper Bay	330400	6195500
Grunters surfing spot	314400	6236000
Haere Mai Homestead	326200	6234000
Halcyon Homestead	331700	6234000
Hamelin Bay	318100	6215100
Hamelin Island	317200	6211300
Hamelin Island Nature Reserve	317200	6211300
Hardy Inlet	331600	6204700
Hazel Wood Homestead	331600	6233700
Hill View Homestead	330100	6227800
Hillier Park	330300	6201900
Hillocks, The Homestead	325800	6230800
Holmwood Homestead	323900	6234900
Honeycomb Rocks	318100	6206900
Horseshoe Reef	317300	6211700
Hukochini Homestead	329400	6204300
Inchyra Homestead	329600	6213300
Indian Ocean	317100	6204200
Inside Rocks	318400	6212300
Isaacs Rock	315200	6231500
Island Point	332900	6205000
Jack Ledge	322600	6199500
Jerusalem Hollow	318200	6227400
Jewel Cave	324900	6205800
JR's Homestead	330200	6228500
Karridale	325000	6213900
Karridale Estate Homestead	324100	6216200
Keoringle Homestead	333900	6232400
Knobby Head	318000	6208100
Kudardup	327300	6207000
Labyrinth Cave	325000	6205800
Lake Cave	318200	6227300
Lake Davies	318900	6211600

Appendix 2 (continued)

Locality	MGA coordinates Easting	Northing	Locality	MGA coordinates Easting	Northing
Lavinjane Homestead	323900	6234900	Rosa Pool Homestead	332200	6231200
Ledge Point	337600	6202100	Rosslyn Homestead	332400	6234000
Leeuwin	328600	6198000	Rushy Creek	329800	6217600
Leeuwin Estate Farm	321400	6234700	Saint Alouarn Island Nature Reserve	334200	6191500
Leeuwin-Naturaliste National Park	327100	6200200	Sam Griffiths Park	331500	6198900
Lion Islands	331000	6202300	Santhoven Homestead	325300	6227000
Lions Park	331600	6200200	Sarge Bay	329700	6195500
Lisle Channel	316100	6212900	Schroeder	336300	6230200
Long Swamp	337600	6203700	Scotsman Rock	318200	6206800
Lostbiscca Homestead	325900	6222900	Scott National Park	337100	6206200
Lupine Park Homestead	329100	6211100	Scott River	334400	6205700
Mammoth Cave	318200	6229700	Seal Island	330500	6194200
Margaret River	317600	6235800	Seaview Homestead	319000	6232700
Marmaduke Point	314900	6235500	Seine Bay	331200	6200500
Masterman Cove	331800	6205800	Shambayango Homestead	326300	6231100
Matthew Flinders Memorial Monument	330500	6195700	Shervington Park	330300	6202100
Maureens Farm Homestead	324200	6206700	Skippy Rock	327800	6196700
Mcleod Creek	332300	6218900	Skittle Cave	320800	6224900
Middle Rock	318200	6214100	Slabby Bridge	326100	6221800
Milbillo Homestead	334900	6216000	South East Ledge	318300	6213000
Mill Race Farm Homestead	329600	6209000	South East Rocks	335800	6189500
Minns Ledge	318600	6201700	South Rock	317700	6213300
Molloy Channel	336100	6207100	South West Breaker	333400	6187100
Molloy Island	335100	6206600	South West Rock	315200	6209700
Molloy Memorial Monument	331300	6200300	Southern Ocean	336100	6196200
Montoya Homestead	328000	6223800	Spout Rock	332500	6190800
Moondyne Cave	324700	6206000	Square Rock	335500	6189900
Murrumbong Homestead	325000	6207000	Strathblane Homestead	321900	6233000
Museum Cave	318200	6227300	Swan Lake	333100	6201700
Mushroom Reef	318000	6211900	Tallagandra Homestead	329400	6208500
Mushroom Rock	318100	6211800	The Berry Farm Homestead	334500	6235900
Nannup Cave	322400	6220100	The Copse Homestead	329400	6203900
Nillup	338100	6218200	The Deadwater	332600	6200900
Nindup Plain	319100	6228200	The Fishing Place	315000	6229000
North Bay	331600	6206600	The Landing	335200	6207300
North Point	317700	6218600	The Landing Place	331600	6199400
Nuralingup Nursery Homestead	323100	6226122	The Long Blackboy Homestead	336000	6202700
Old Karridale	322700	6212600	The Old Cave	324700	6206100
Old Man Rock	316300	6212200	The Spring	330500	6197700
Peak Island	317600	6216200	The Whaling	331600	6198200
Peninsula Downs Homestead	333300	6223400	Thomas Island	331400	6204300
Peppermint Park Homestead	325900	6223700	Thunder Gulla Homestead	325500	6227000
Pioneer Memorial Monument	331200	6200100	Torr Shamba Homestead	317700	6202400
Point Bussell	332600	6218100	Tunnel Cave	318200	6227400
Point Dalton	334200	6205800	Turner Brook	320700	6205700
Point Ellis	331000	6201100	Turner Brook Farm Homestead	321800	6207500
Point Frederick	331700	6200500	Turner Park	331000	6200300
Point Irwin	331100	6202800	Turnwood Creek	331800	6207500
Point Matthew	330500	6195300	Twinems Bend	336600	6210900
Point Pedder	331500	6205400	Upper Chapman Brook	332900	6227400
Point Trafalgar	330900	6203900	Vardo Homestead	327600	6224000
Praters Homestead	327800	6236000	Wahroonga Homestead	330600	6207600
Quarry Bay	328600	6195800	Warner Glen Bridge	335100	6223200
Quoin Rock	318000	6218200	Warrenella Homestead	325400	6214600
Redgate	315300	6235200	Wellington Farms Homestead	335700	6221000
Redgate Homestead	318600	6235000	West Bay	329800	6203600
Redgate surfing spot	315000	6232700	West Bay Creek	328600	6204700
Redman Brook	330600	6198200	West Bay Stud Homestead	329200	6204900
Ridgefield Homestead	321800	6210400	Whalesback	316400	6210800
Ringbolt Bay	330100	6195500	Whispering Pines Homestead	323500	6234000
Riverbend Homestead	332900	6221800	White Cliff Point	318000	6211300
Rockdale Farm	335400	6220600	Windy Downs Homestead	336700	6222300
Rockville Homestead	328400	6205800	Wirralee Homestead	328900	6204700
Rocky Grove Homestead	330400	6229600	Witchcliffe	324600	6233500
Rosa Glen	333000	6233605	Witchcliffe Cave	316900	6235100
Rosa Glen Pioneer Memorial Monument	333800	6236000	Yulika Homestead	335500	6225400

Appendix 3

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 grass	
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 4

Abbreviations

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

Appendix 5

Slope classification system

Slope (°)	*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

SOURCE: McDonald et al. (1984)

Appendix 6

Grain-size ranges for field classification and particle-size determinations of regolith

Size range	*Sieve size (mm)*	*Range (mm)*
boulders	–	>200
cobbles	–	200 – 60
coarse gravel	>2.36	60 – 20
medium gravel	–	20 – 6
fine gravel	–	6 – 2
coarse sand	0.6 – 2.36	2 – 0.6
medium sand	0.212 – 0.6	0.6 – 0.2
fine sand	0.075 – 0.212	0.2 – 0.06
silt	<0.075	0.06 – 0.002
clay	–	<0.002

SOURCES: Geotechnical Control Office, 1988; Standards Australia, 1993

Appendix 7

Classification of rock material strength

Strength	Test method				
	Hand	*Thumbnail*	*Pocket knife*	*Geological pick*	*Hand specimen*
Extremely weak	easily crumbled	indented steeply	–	–	–
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	difficulty 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

SOURCES: Geotechnical Control Office, 1988; Standards Australia, 1993

Appendix 8

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 Record 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 KARRIDALE–TOOKER and LEEUWIN 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) mines 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

Table 8.1. WAMIN authority table for commodity groups

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

Table 8.2. Modifications made to the Mining Journal Limited (1997) commodity classification

Commodity group (Mining Journal Limited, 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 8.3. 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 8.1

which there is no recorded production (italic, serif numbers, e.g. *3175*);
- 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.

Table 8.4. 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

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 8.1 determines the colours of the mineral occurrence symbols on the map. The commodity groupings are based on those published by the Mining Journal Limited (1997), and are modified as shown in Table 8.2 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 8.3).

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.

Mineral occurrence determination limits

The lower cutoff limit for a mineral occurrence is more reliably based on exploration company information from the Western Australian mineral exporation database (WAMEX). Minimum intersections in drillholes or trenches for a number of commodities are in Table 8.4.

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.

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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.

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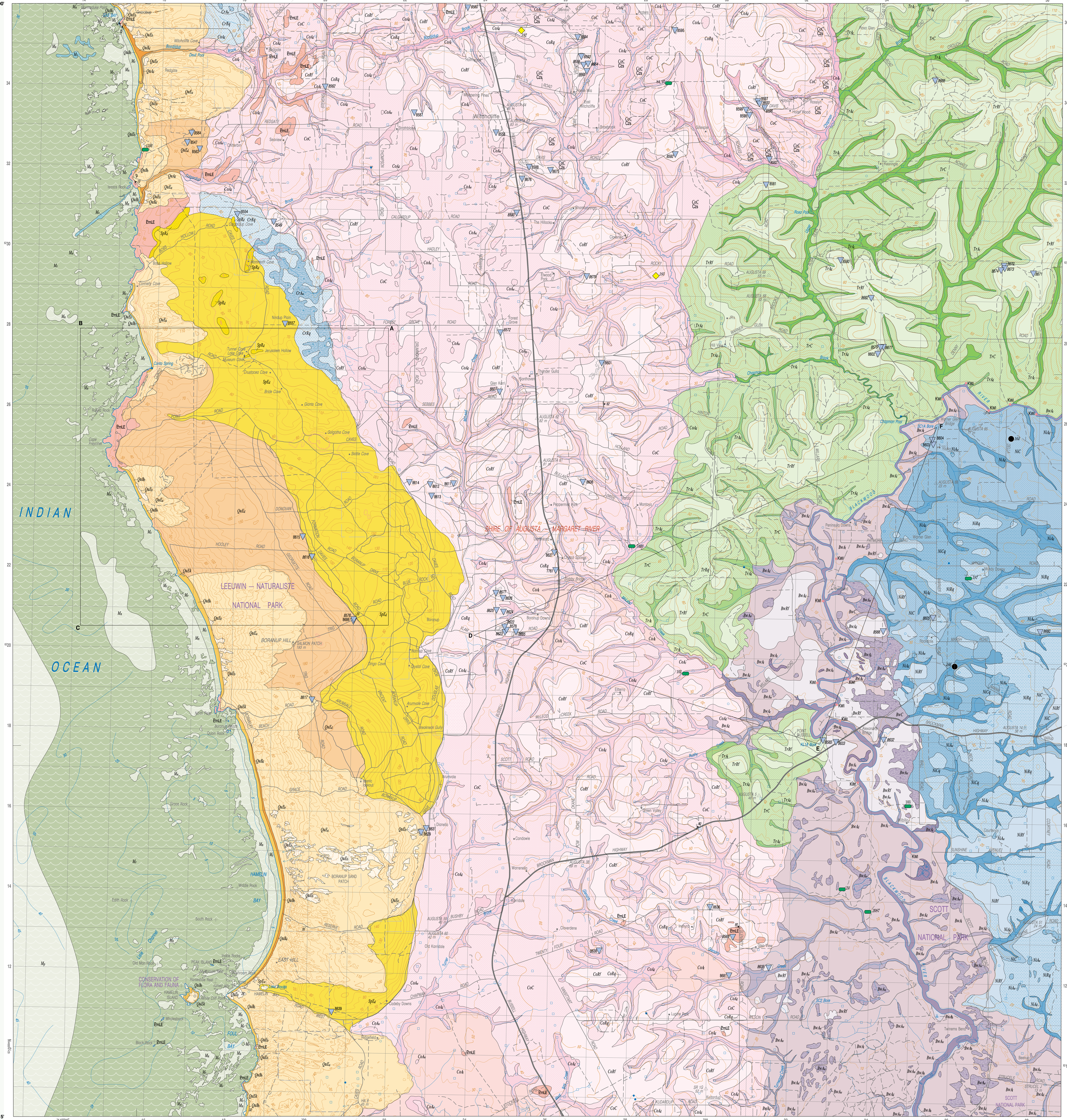
MINING JOURNAL LIMITED, 1997, Mining Annual Review, Volume 2 — Metals and minerals: London, Mining Journal Limited, 112p.

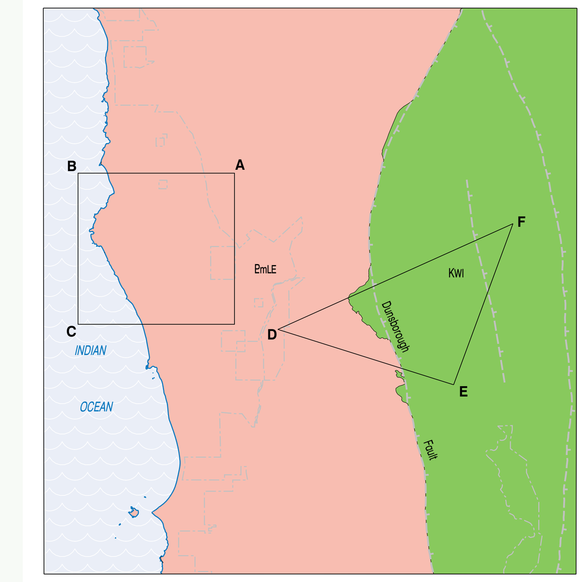
TOWNSEND, D. B., GAO, M., and MORGAN, W. R., 2000, Mines and mineral deposits of Western Australia: digital extract from MINEDEX — an explanatory note: Western Australia Geological Survey, Record 2000/13, 28p.



LANDSAT TM IMAGE WITH FIELD SITE LOCATIONS

Date of imagery: 12 March 1998

INTERPRETED ONSHORE BEDROCK GEOLOGY



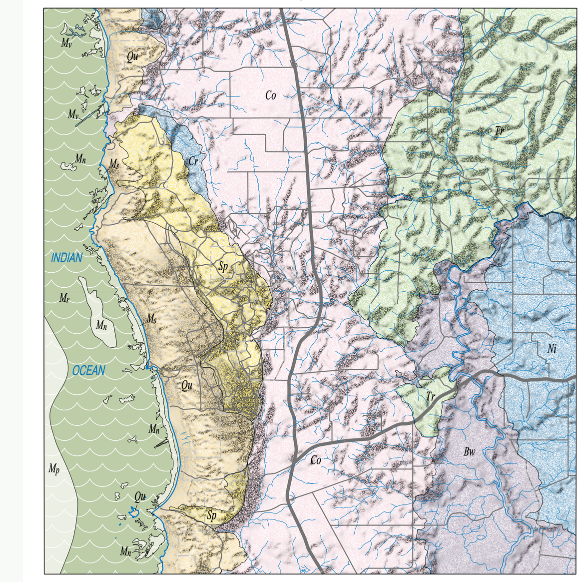
KARRIDALE — TOOKER

WESTERN AUSTRALIA 1 : 50 000 REGOLITH–LANDFORM RESOURCES SERIES

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SHEET 1929-IV, AND PART OF 1829-I FIRST EDITION 2002

SIMPLIFIED LAND SYSTEMS, SHADED RELIEF, INFRASTRUCTURE, AND DRAINAGE

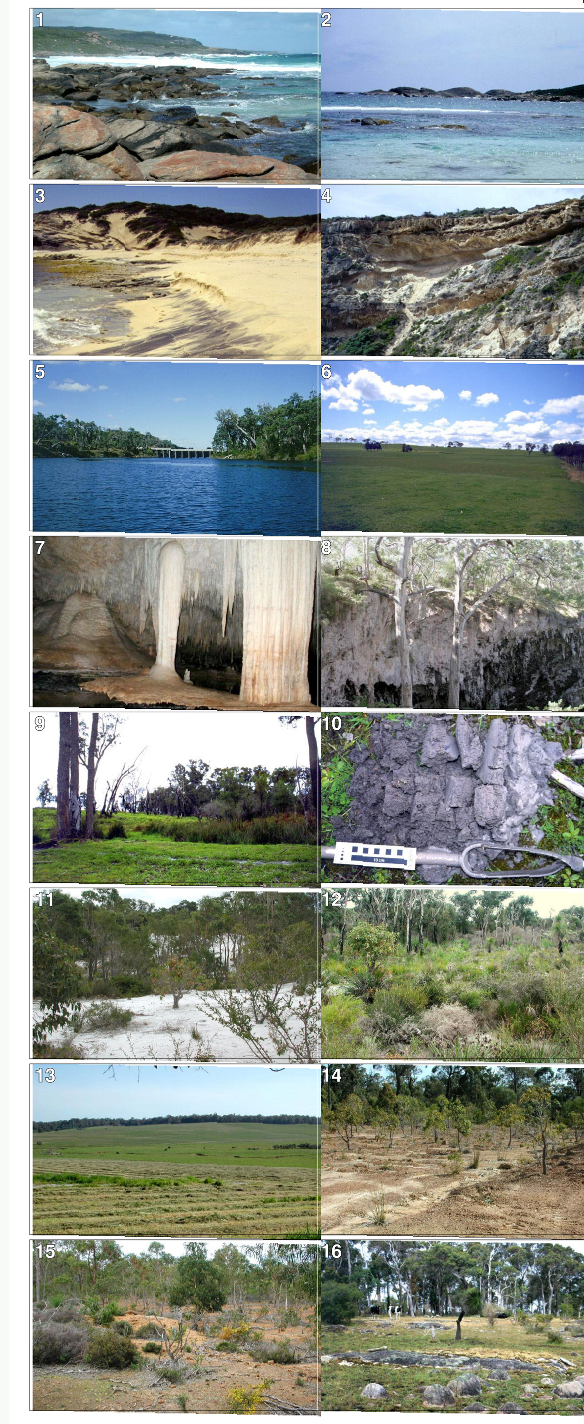


The Karridale—Tooker Regolith–Landform Resources map provides information on the regolith (soils) and underlying rocks, on the landforms (landscape), topography, infrastructure, and on the mineral and construction material resources of the Karridale—Tooker area. This map will be of value in landuse planning, the sustainable development of resources, and in identifying natural hazards, both onshore and in shallow nearshore areas.

The map also delineates land systems, which are areas of discrete recurring patterns of landform, regolith, materials, and vegetation. These patterns are related to geological and hydrogeological units, and form the basis of identifying landuse, including mineral resource potential.

- Ms Marine shoreface
- Mn Marine nearshore
- Mp Marine offshore
- Mv Marine channel
- Mr Marine reef
- Qu Quindalup System — beach and dunefields
- Bw Blackwood System — estuary and river system
- Sp Spearwood System — deflated dunes
- Ni Nillup System — low hills and rises underlain by Cretaceous rocks
- Cr Caves Road System — shelf underlain by Proterozoic rocks
- Tr Treeton System — low hills underlain by Cretaceous rocks
- Co Cowaramup System — low hills underlain by Proterozoic rocks

LEGEND



MARINE — 12 181 ha 17%

QUINDALUP SYSTEM — 7 197 ha 10%

BLACKWOOD SYSTEM — 6 825 ha 9%

SPEARWOOD SYSTEM — 4 252 ha 6%

NILLUP SYSTEM — 5 191 ha 7%

CAVES ROAD SYSTEM — 559 ha 1%

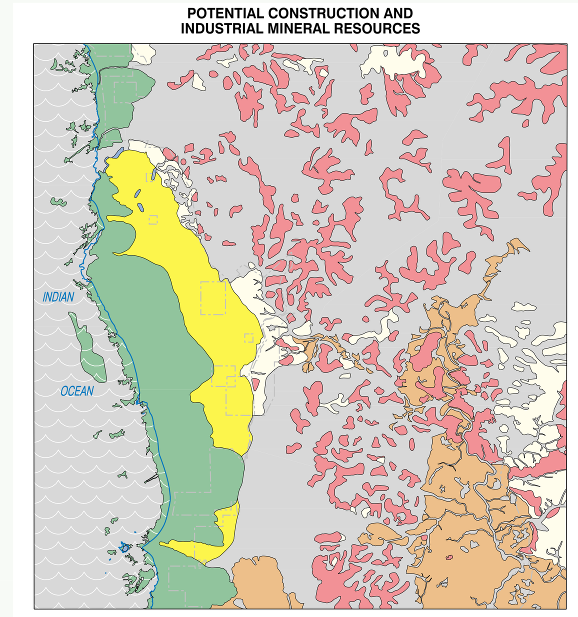
TREETON SYSTEM — 11 037 ha 15%

COWARAMUP SYSTEM — 25 480 ha 35%

REFERENCE

SYMBOLS

POTENTIAL CONSTRUCTION AND INDUSTRIAL MINERAL RESOURCES

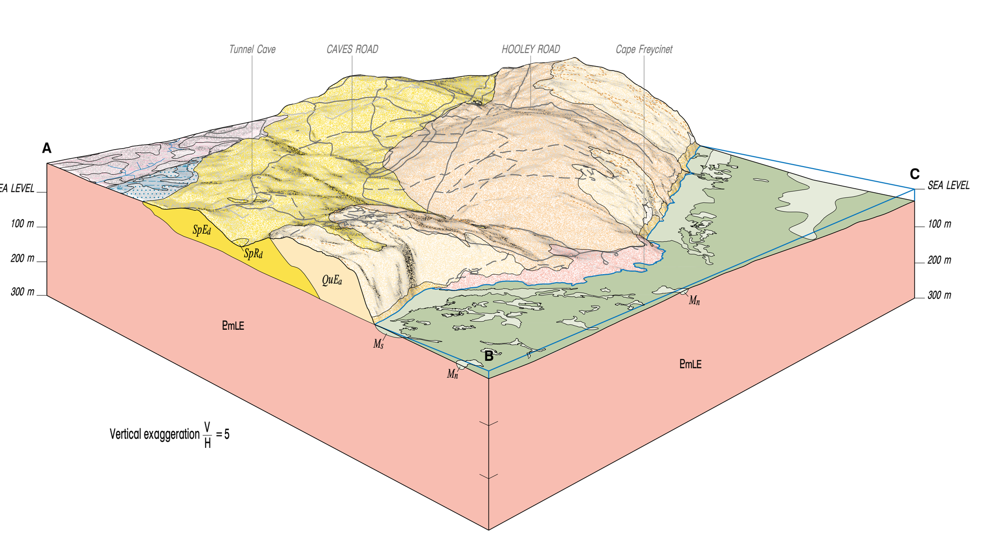


- Ferruginous gravel
- Red and yellow sand
- Limestone
- Limesand
- Sand and gravel
- White sand

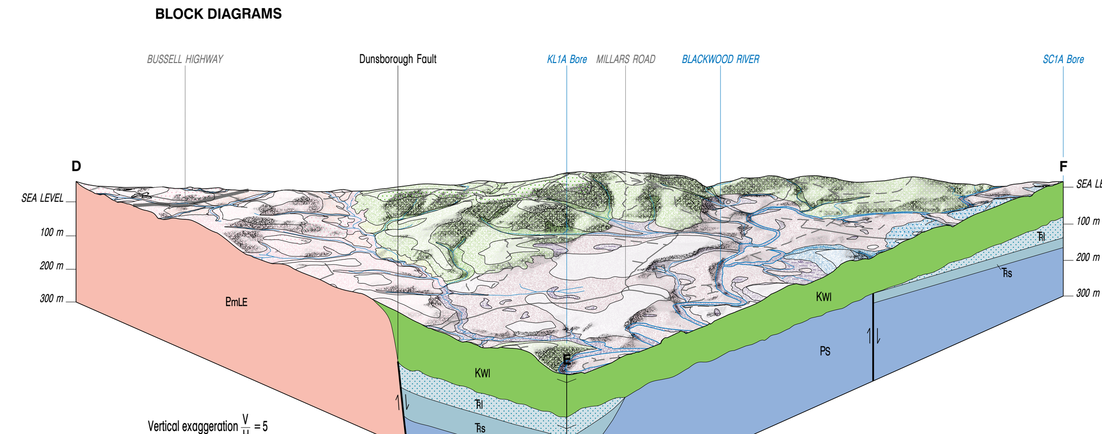
KARRIDALE—TOOKER MINERAL OCCURRENCES

Numbers refer to GSWA WAMIN mineral occurrence database

BLOCK DIAGRAMS



Vertical exaggeration $\frac{H}{V}$ = 5

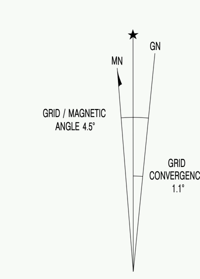


Vertical exaggeration $\frac{H}{V}$ = 5

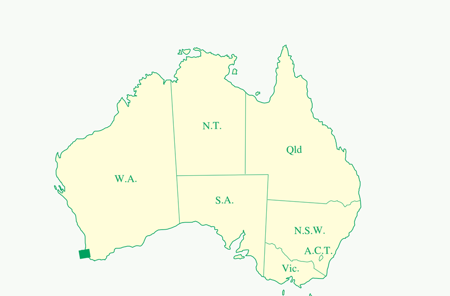
BEDROCK GEOLOGY

CRETACEOUS	Kwl	LEEDERVILLE FORMATION (Warnbro Group)
TRIASSIC	Tr	LESUEUR SANDSTONE
	Ts	SABINA SANDSTONE
PERMIAN	Ps	Sue Group
PROTEROZOIC	Emℓ	Leeuwin Complex

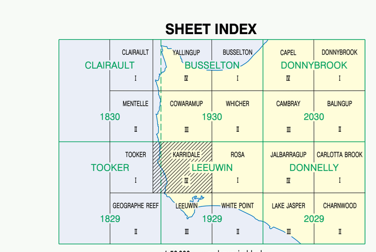
Normal fault, showing relative displacement



True north, grid north and magnetic north are shown diagrammatically for the centre of the map. Magnetic north is correct for 2002 and moves easterly by about 0.1° in 1 year.



SHEET INDEX



1:50 000 maps shown in black
1:100 000 maps shown in green

Geology by J. Marnham and G. Hall, 1998–2000

Subsurface geology by:
BADDOCK, L. J., 1994, Geology and hydrogeology of the Karridale Bore Line, Perth Basin: Western Australia Geological Survey Report 37, Professional Papers, p. 1–18.
BADDOCK, L. J., 1995, Geology and hydrogeology of the Scott Coastal Plain, Perth Basin: Western Australia Geological Survey Record 1995/7, 58p.
IASKY, R. P., 1993, A structural study of the Southern Perth Basin, Western Australia: Western Australia Geological Survey Report 31, 56p.

Edited by C. Strong and G. Loan

Cartography by S. Coldicutt, M. Vicentic, and K. Greenberg

Mineralization and rock commodity information from non-confidential data held in the WAMIN database, GSWA, at 31 July 2001.

Topography from the Department of Land Administration Sheet SI 50-9, 1929 and part of 1829, with modifications from geological field survey

Landsat Imagery supplied by 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

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Web www.mpr.wa.gov.au Email geological_survey@mpr.wa.gov.au

Plotted by the Geological Survey of Western Australia

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MARNHAM, J. and HALL, G., 2002, Karridale—Tooker, W.A. Sheet 1929-IV and part of 1829-I: Western Australia Geological Survey, 1:50 000 Regolith—Landform Resources Series

Department of Mineral and Petroleum Resources
Geological Survey of Western Australia

CLIVE BROWN, M.L.A.
MINISTER FOR STATE DEVELOPMENT

JIM LIMERICK
DIRECTOR GENERAL

TIM GRIFFIN
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
TOPOGRAPHIC DATUM: AUSTRALIAN HEIGHT DATUM (AHD)
HYDROGRAPHIC DATUM: LOWEST ASTRONOMICAL TIDE (LAT)

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

WESTERN AUSTRALIA 1 : 50 000 REGOLITH–LANDFORM RESOURCES SERIES

KARRIDALE — TOOKER

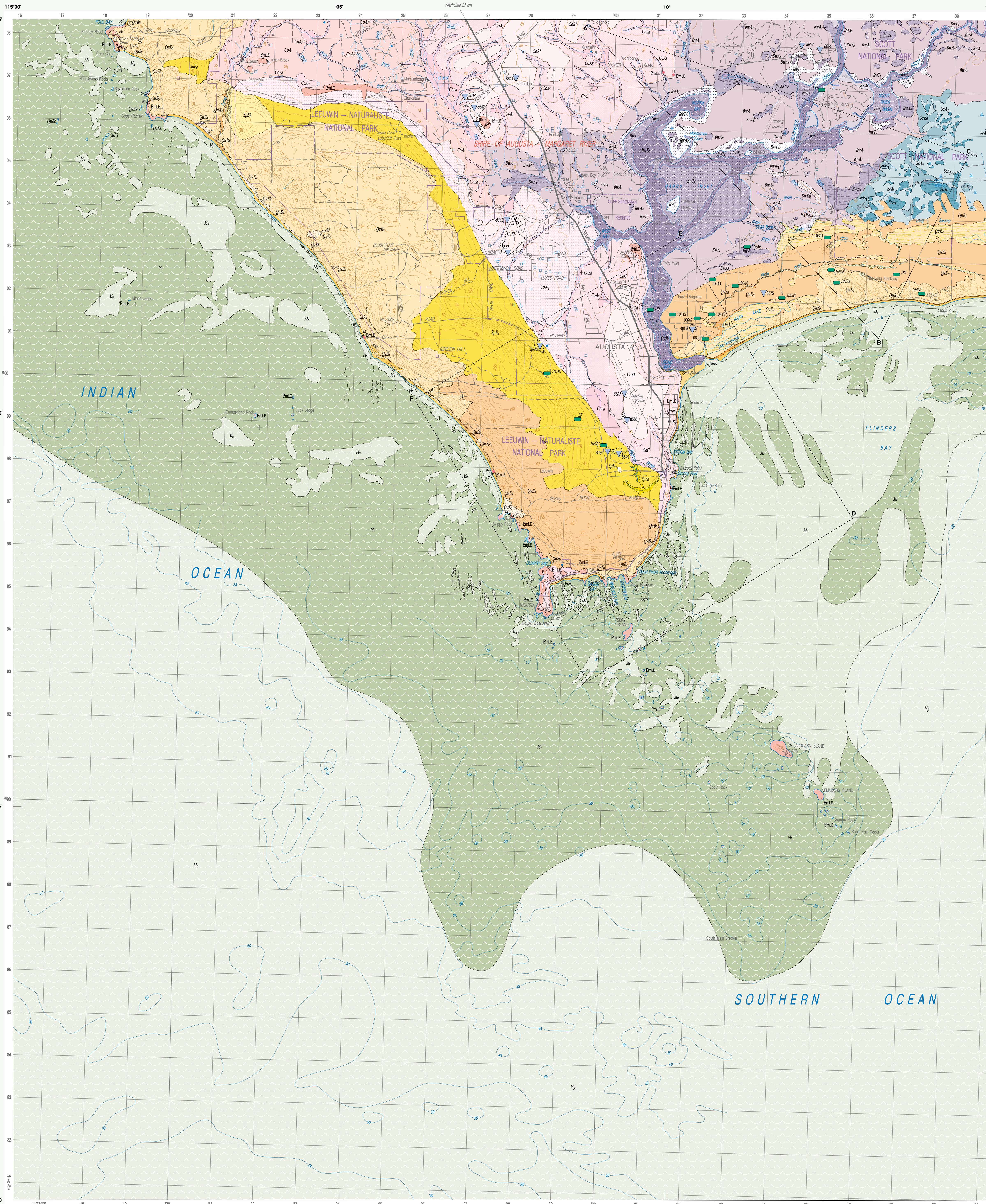
SHEET 1929-IV, AND PART OF 1829-I FIRST EDITION 2002

LEEUWIN

WESTERN AUSTRALIA 1:50 000 REGOLITH–LANDFORM RESOURCES SERIES

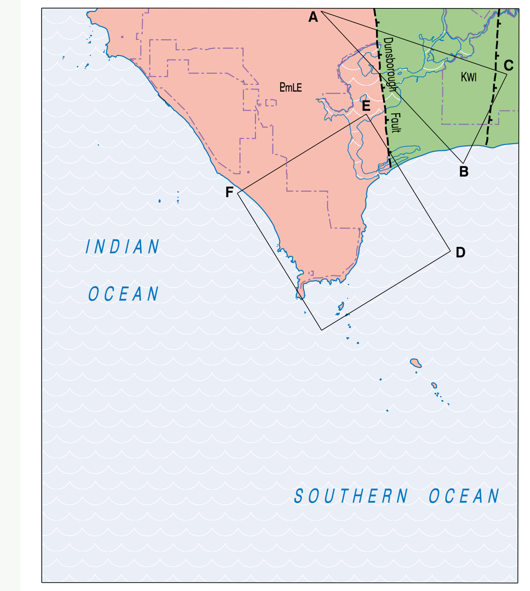
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SHEET 1929-III FIRST EDITION 2002



LANDSAT TM IMAGE WITH FIELD SITE LOCATIONS

INTERPRETED ONSHORE BEDROCK GEOLOGY



SIMPLIFIED LAND SYSTEMS, SHADED RELIEF, INFRASTRUCTURE, AND DRAINAGE

The Leeuwin Regolith–Landform Resources map provides information on the regolith (soils) and underlying rocks, on the landforms (landscape; topography), infrastructure, and on the mineral and construction material resources of LEEUWIN. This map will be of value in landuse planning, the sustainable development of resources, and in identifying natural hazards, both onshore and in nearshore areas.

The map also delineates land systems, which are areas of discrete recurring patterns of landform, regolith, materials, and vegetation. These patterns are related to geological and hydrogeological units, and form the basis of identifying landuse, including mineral resource potential.

M_s	M_n	M_p	M_r

M_s Marine shoreface
M_n Marine nearshore
M_p Marine offshore
M_r Marine reef

- *Qu* Quindalup System — beach and dunefields
- *Bw* Blackwood System — estuary and river system
- *Sp* Spearwood System — deflated dunes
- *Sc* Scott System — mixed deflated dunes and river system
- *Co* Cowaramup System — low hills underlain by Proterozoic rocks

SCALE 1:250 000

0 5 10 Kilometres

LEGEND

M

MARINE — 48 094 ha 82%

Extensive offshore sandplain. Level to gently inclined nearshore, and level to very gently inclined shoreface, formed dominantly of submerged rocky platforms and reefs (1); small emergent rocky reefs, stacks, and islands in the nearshore environment (2); minor patches of nearshore and shoreface sand.

Sand deposits are composed mostly of shell fragments and quartz grains. Rock reefs and platforms are formed from Leeuwin Complex (1) or calcarenite of eolian and beach origin (2).

Possible source of limesand for agricultural applications, and sand and limestone for construction.

Active processes include erosion and deposition by tides, currents, and wave action. The rocky coastline and shallow reefs are a hazard to boats. Rapid deposition and erosion of coastal deposits can occur during storms.

Primarily used for fishing and recreation.

Sand of Holocene age mostly underlain by Leeuwin Complex rocks.

Qu

QUINDALUP SYSTEM — 4 857 ha 6%

Mostly parabolic dunes, swales, and blowouts; sandy beaches and foredunes common along the coast (3). Gently to steeply inclined slopes, occasionally very steep to precipitous. Older deflated dunes form cliffs and rocky headlands. Multiple overlapping dune formations with intervening palaeosols.

Dominantly calcareous eolian sand composed of shell fragments, quartz, and minor garnet and other heavy minerals (4), overlying a core of weakly lithified calcarenite. Organic sandy soils occur in swales.

Source of limesand, sand, and limestone. Some potential for heavy mineral sands within the beach and dune sands.

Eolian processes active in the dunes, and coastal processes on the beaches. Major hazards are collapse or subsidence of calcarenite, particularly overhanging cliffs. Migrating sand from blowouts and steeper dune faces is a minor hazard.

Landuses include conservation, recreation and tourism, and minor urban development and grazing.

Overlies older dunes of the Spearwood System, and the Proterozoic rocks of the Leeuwin Complex (4).

Bw

BLACKWOOD SYSTEM — 4 271 ha 5%

Blackwood River, with associated adjacent terrace of level to very gently inclined plain dotted with swampy hollows, and estuary including some islands, and intertidal and supratidal flats. The river has cut down through the Leederville Formation in places (5).

Sand and gravel common on the alluvial terraces. Ferruginous gravel on hillcrests. Low-lying swampy areas are filled with organic sandy soils.

Source of yellow sand (6) and ferruginous gravel. Some potential for heavy minerals sands.

Active processes include channel erosion, and flooding and waterlogging along the river.

Used for grazing and conservation, with urban development around Augusta. Natural vegetation remains along much of the Blackwood River and in a few nature reserves

The materials of the Blackwood System overlie Cretaceous and Proterozoic rocks.

Sp

SPEARWOOD SYSTEM — 1 548 ha 2%

Ridge composed of a series of deflated parabolic dunes (7) and swales. Gently to moderately inclined slopes, with rare steep to precipitous rocky slopes or cliffs that overhang in places. Hosts karstic features (8) such as caves, dolines, and subsurface drainage systems formed during an earlier, wetter period.

Red to brown, residual quartz sand over calcrete-surfaced calcarenite. Organic sandy soils occur in swales.

Source of limestone and building sand.

Steep rocky slopes and karstic features may be prone to subsidence or collapse, and are a hazard to people, stock, and machinery. Cleared westerly slopes are prone to erosion by prevailing southwesterly winds.

Uses include conservation, tourism, and recreation. Small areas have been cleared for grazing and urban development.

Overlain by the dunes of the Quindalup System, and overlies Leeuwin Complex rocks. Formed by eolian processes during the Pleistocene, and modified by surface water and groundwater leaching and precipitation.

Sc

SCOTT SYSTEM — 649 ha <1%

Flat to gently inclined, undulating terraces with closed and open drainage depressions, and low rises; surrounded by low-lying poorly drained swampy areas.

Leached quartz sand occurs on dry sandy rises (9; from Tille and Lantzke, 1990). Some areas of yellow sand. Mixture of fluvial and eolian deposits; waterlogged soils commonly have organic accumulations (10).

Alluvial terraces are a possible source of sand and gravel. Sandy rises are a potential source of white sand. Some potential for heavy mineral sands.

Waterlogging and flooding occur during winter.

Landuses include grazing, conservation, and some cropping. Vegetation has been cleared in places for grazing, and other areas have been set aside for nature reserves. Some drainage channels have been dug.

Fluvial to coastal zone between the Blackwood and Quindalup Systems. Overlies Cretaceous and Proterozoic rocks.

Co

COWARAMUP SYSTEM — 4 341 ha 5%

Low hills to rises with gently to moderately inclined slopes and swampy drainage depressions. Level to gently undulating areas north of Caves Road.

Residual materials (11) and colluvial deposits overlying weathered rocks of the Leeuwin Complex. Hillcrests are commonly capped by ferruginous gravel or duricrust, and leached quartz sand. Exposures of granulite common.

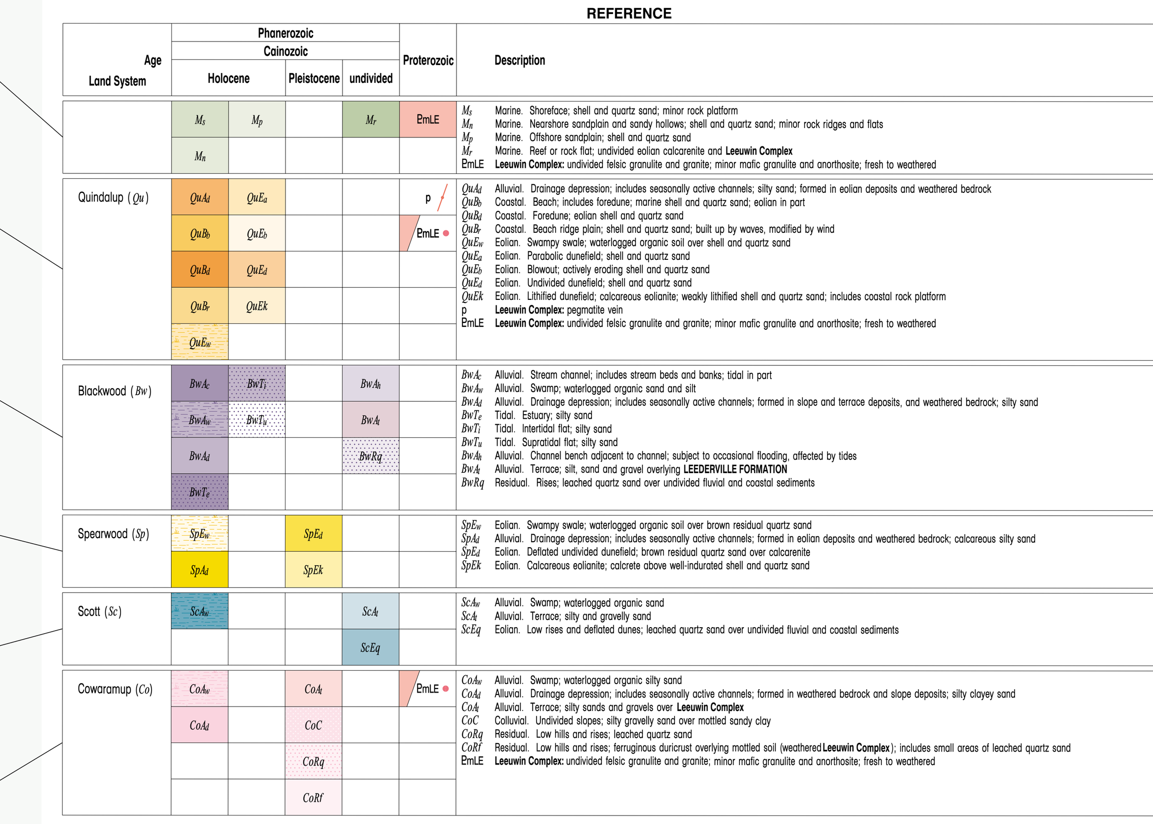
Source of gravel (12) and quartz sand. Potential source of rammed-earth building materials, hard rock aggregate, and dimension stone.

Waterlogging occurs during the winter in areas of low slope, and erosion can occur in cleared areas during heavy rain.

Landuses include viticulture, grazing, urban development, recreation, and tourism.

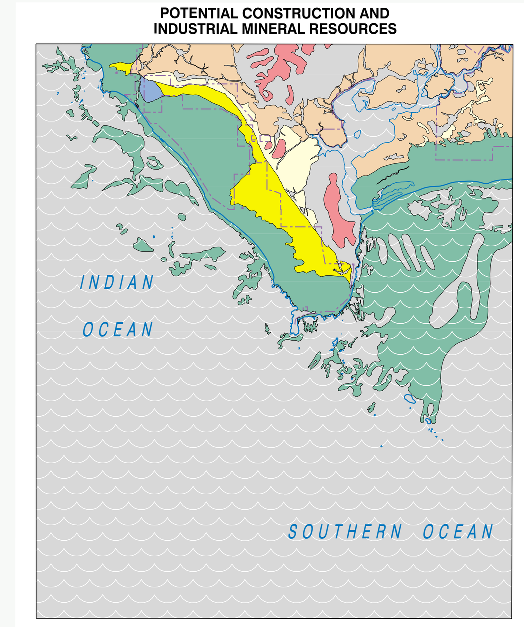
Overlain by the materials of the Quindalup and Spearwood Systems. Underlain by Leeuwin Complex rocks. To the east, the Leeuwin Complex is onlapped in places by the Leederville Formation.

REFERENCE



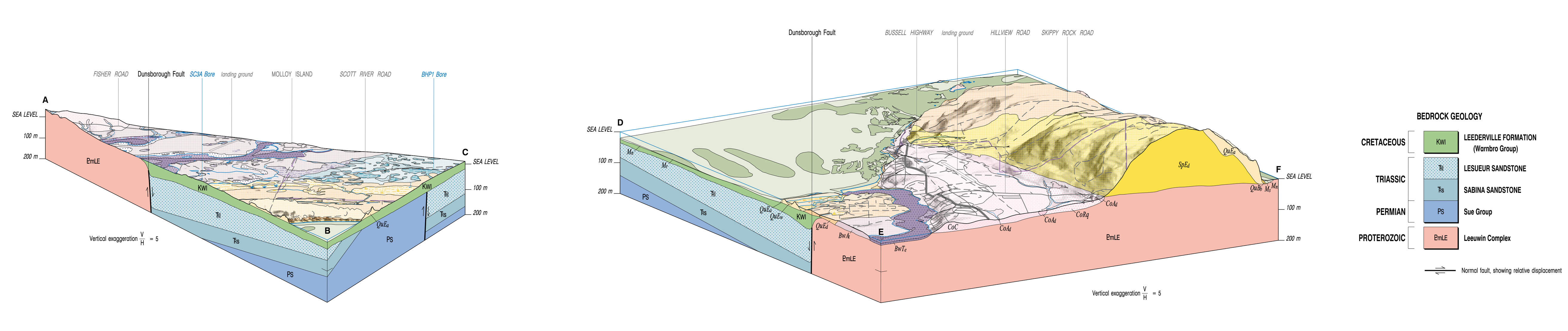
SYMBOLS

POTENTIAL CONSTRUCTION AND INDUSTRIAL MINERAL RESOURCES



- Ferruginous gravel
- Red and yellow sand
- Limestone
- Limesand
- Sand and gravel
- White sand

BLOCK DIAGRAMS



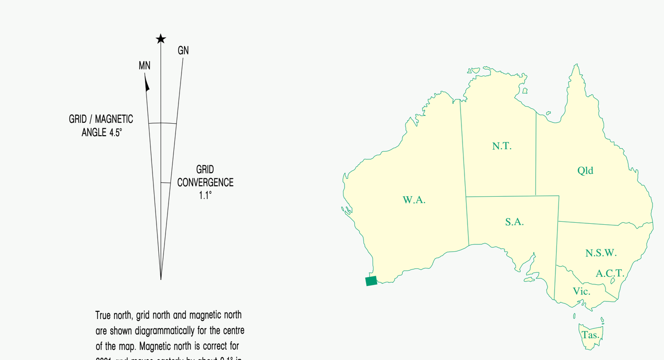
LEEUWIN MINERAL OCCURRENCES

NUMBER*	COMMODITY	EASTING	NORTHING
SPECIALITY METAL — HM, Ilm			
Regolith — alluvial to beach placers			
25	HM	329280	6199180
130	HM	336700	6202720
180	HM	334860	6207020
181	HM	330940	6201780
10642	HM	329900	6198580
10643	HM	328540	6200240
10644	HM Ilm	332380	6202520
10645	HM Ilm	331460	6201680
10646	HM Ilm	333180	6203300
10647	HM Ilm	332040	6201600
10648	HM Ilm	332920	6202380
10649	HM Ilm	332380	6201700
10650	HM Ilm	332240	6201120
10651	HM Ilm	335060	6203560
10652	HM Ilm	334020	6202120
10653	HM Ilm	335160	6202800
10654	HM Ilm	335300	6202500
10655	HM	337300	6202280
CONSTRUCTION MATERIAL — Gvl, Lsd, Lst, Sv			
Undivided			
8567	Gvl	327565	6203075
8568	Gvl	326770	6206070
8574	Sv	328360	6200895
8575	Lsd	333590	6202240
8585	Gvl	330440	6199190
8586	Sv	330000	6198440
8641	Gvl	327675	6207180
8642	Gvl	326710	6206460
8644	Gvl	326485	6206715
8645	Gvl	327535	6203845
8649	Sv	330260	6198405
8653	Lst	331935	6201345
8655	Sv	334800	6207980
8657	Sv	334375	6208070
8687	Gvl	330365	6199820

* KEY TO OPERATING STATUS

Bold numbers (i.e. 8567)	Operating quarry
Bold and italic numbers (i.e. 8574)	Abandoned mine or quarry
Plain numbers (i.e. 111)	Mineral deposit
Italic numbers (i.e. 25)	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 2001 and moves easterly by about 0.1° in 1 year.

Geology by J. Marnham and G. Hall, 1998–2000

Subsurface geology by:

BADDOCK, L. J., 1994, Geology and hydrogeology of the Karridale Bore Line, Perth Basin: Western Australia Geological Survey Report 37, Professional Papers, p. 1–18.

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

Edited by C. Strong and C. Brien

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Photograph 9 reproduced from Tille, P. J., and Lantzke, N. C., 1990, Busselton—Margaret River—Augusta Land Capability Study: Western Australia Department of Agriculture, Land Resource Series No. 5, 91p.

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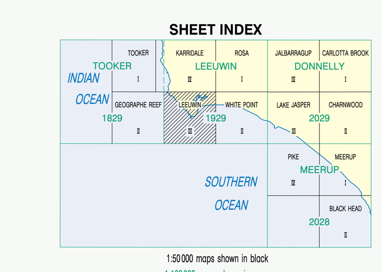
SHEET INDEX



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