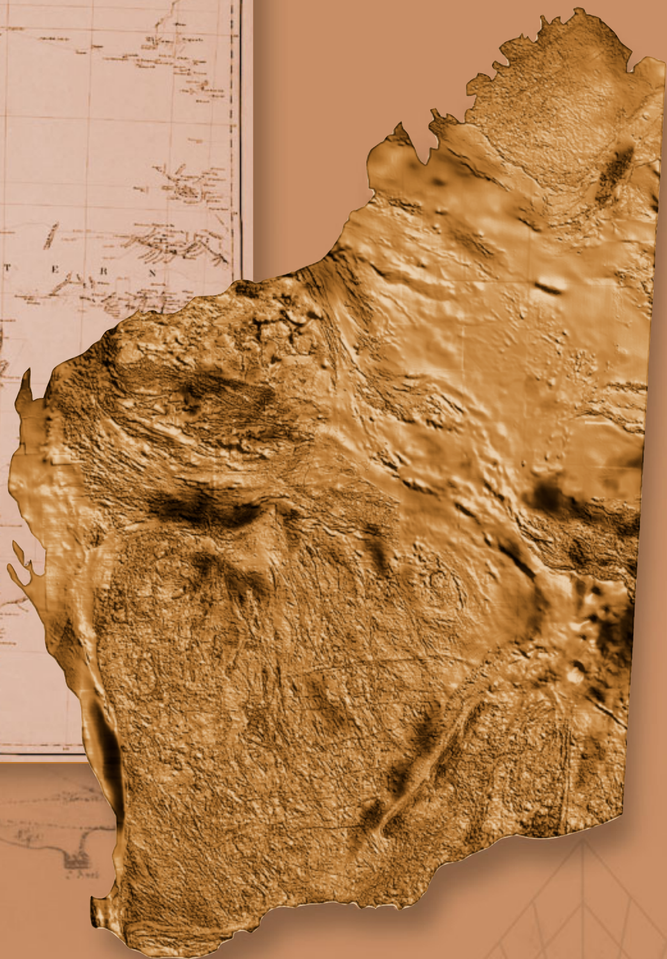
RECORD 2001/7

GOVERNMENT OF WESTERN AUSTRALIA

REGOLITH–LANDFORM RESOURCES OF THE HOWATHARRA 1:50 000 SHEET

by R. L. Langford



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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R. L. Langford

Perth 2001

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

DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
Tim Griffin

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Information Centre
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Regolith–landform resources of the Howatharra 1:50 000 sheet

by

R. L. Langford

Abstract

Regolith–landform mapping of the HOWATHARRA 1:50 000 map sheet, located about 440 km north of Perth and including the northen part of the City of Geraldton, has defined seven land systems, and provided a subdivision of the seabed materials and morphology. The onshore Northampton, Moresby, Casuarina, Spearwood, Greenough, Greenough Alluvium, and Quindalup Systems are defined on the basis of the dominant underlying parent materials. The Northampton System comprises low hills with an incised drainage pattern, and is underlain by Proterozoic rocks. The Moresby System comprises a plateau and sideslopes composed of residual materials and colluvial deposits over weathered Jurassic sedimentary rocks, with minor Proterozoic crystalline rocks. The Casuarina System is an undulating plateau composed of residual sand overlying weathered Jurassic strata. The Spearwood System is equivalent to the Pleistocene Tamala Limestone, and is composed of residual sand over calcarenite in a series of deflated dunes. The Greenough System is composed of alluvial terraces and channels related to the upper reaches of the Chapman River, and the Greenough Alluvium System is the local development of an alluvial plain on the Chapman and Greenough rivers. The Quindalup System is equivalent to the Safety Bay Sand, and comprises Holocene dunes and coastal deposits. The Marine System includes the offshore marine plain, and the nearshore reef, seabed, and shoreface.

Each land system has been divided into mapping units based on vegetation, landform elements and patterns, and regolith characteristics. These units, combined with knowledge of the subsurface geology, have been used to provide information on landuse, mineral potential, geological processes such as weathering and erosion, and hazards related to landforms. The most significant hazard is flooding of the alluvial channels at times of exceptional rainfall, either locally or in the larger catchment. Other possible hazards include wind erosion in the coastal dunes, and coastal erosion during storms.

The mineral resource potential of HOWATHARRA includes base metals and heavy minerals as well as a range of construction materials. Gravel, sand, limesand, and rock for aggregate and reclamation have all been extracted for use in construction and infrastructure development. No coal has been reported in the Jurassic Cattamarra Coal Measures within the map sheet area.

KEYWORDS: Geraldton, geomorphology, mineral resources, industrial minerals, construction materials, regolith, landforms, land use planning.

Introduction

The HOWATHARRA* 1:50 000 regolith–landform resources map is designed to facilitate landuse planning, the sustainable development of mineral resources, including construction materials (basic raw materials), and identification of hazards, both onshore and in shallow marine areas. The map is intended to be of use to Government departments and agencies, local government and public utilities, the resource, construction, agricultural, and tourism industries, and will be of interest to the general public.

The map provides information on the regolith and underlying rocks, on the landforms (landscape), topography and infrastructure, and on the mineral resources of the area. Regolith is the surficial material, of diverse origin, that rests on bedrock, and in engineering terms can also be referred to as soil. Land systems are identified as areas with recurring patterns of landform, regolith, and vegetation; each system contains discrete landform elements or materials. These regolith–landform units are related to geological and hydrogeological units, and can

* Capitalized names refer to standard 1:50 000 map sheets unless otherwise stated.

be used for identifying appropriate landuse as well as mineral resource potential.

The CD-ROM available in addition to the map and notes contains the data used in compiling the map and notes, the files necessary for viewing the data in a Geographical Information System (GIS) environment, and a self-loading version of the ArcExplorer software package (Appendix 1).

Location

The HOWATHARRA map sheet (SH 50-1-1840-IV) lies between latitudes 28°30' and 28°45'S, and longitudes 114°30' and 114°45'E (Fig. 1). The sheet lies in the Mid West Region of Western Australia, and covers parts of the City of Geraldton and the shires of Chapman Valley, Greenough, and Northampton. Perth, the capital city of Western Australia, lies about 440 km to the south-southeast. The land area of the sheet is 434 km^2, and the offshore area is about 244 km^2. The populations of the City of Geraldton and the three shires are about 21 000, 850, 12 600, and 3300 respectively, although all population centres extend onto the adjacent map sheets. A gazetteer of locations mentioned in the text is given in Appendix 2.

The HOWATHARRA map sheet is named after the townsite of Howatharra, which is located about 30 km north of Geraldton. Land in this vicinity was opened up for farming in the early 1900s, and a railway siding named Howatharra (Webb's Siding) was established there in 1908. Howatharra was gazetted a townsite in 1909, using the Aboriginal name of a nearby water source, Howatharra Spring, which is shown as Howetparrah Well on an 1872 map of the area (Department of Land Administration (DOLA) website). The map sheet was referred to as WOKATHERRA in an earlier geological survey (Jones, 1961).

Figure 1. Location of HOWATHARRA in Western Australia

Infrastructure

The City of Geraldton is at the northern end of the Brand Highway, and the southern end of the North West Coastal Highway. These two highways form one of the major road routes connecting Perth with the north of the State, the other being the inland Great Northern Highway. The North West Coastal Highway passes through Howatharra to the west of the Moresby Flat Topped Range. Chapman Valley Road, extending from Geraldton to the northeast, parallel to the Chapman River, is the only secondary road in the area. There are a number of named minor roads, mostly unsealed, and a network of sealed roads serving the urban areas in the northern part of the City of Geraldton and in Drummond Cove (Fig. 2).

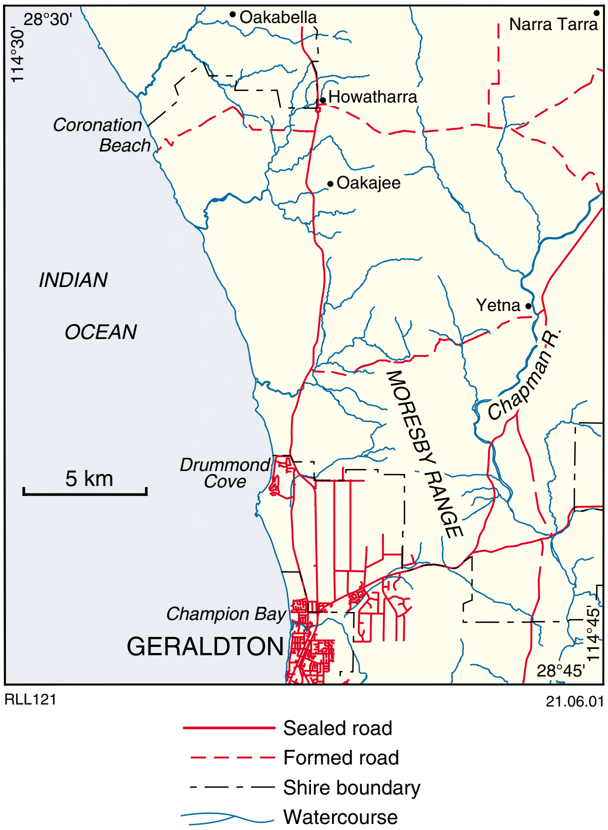

Figure 2. Infrastructure and drainage on Howatharra

The first State railway was built from Geraldton to Northampton in 1874 to serve the first venture mining for lead at Geraldine, and closed in 1955 (Walkaway Station Museum website). The lines head out of the city and pass north through Wokarena and Oakajee to Northampton, and northeast from Wokarena through Yetna and on to Nanson and Nabawa. Most embankments and cuttings are intact, and the bridge over the Chapman River at Yetna is still in use for farm traffic.

A rail link is planned along the Chapman River valley to connect Moonyoonooka on Geraldton to the proposed industrial development at Oakajee, about 20 km north of Geraldton (Department of Resources Development, 1999). Air and sea access to the area is through Geraldton Airport, located at Moonyoonooka about 15 km east of the city, and the Port of Geraldton, at the railhead in Champion Bay.

The Geraldton region has limited potable surface water resources, and relies heavily on groundwater supplies from the Allanooka Water Reserve, 50 km southeast of Geraldton. This is distributed through a pipeline that runs alongside the railway and road from Walkaway. Farms and smallholdings on Howatharra commonly rely on water bores and rainwater storage dams for their water supply.

Natural gas is available in the urban areas from the Bunbury–Dampier pipeline, and independent gas supplies are available from Arc Energy at Dongara and from Origin Energy's Beharra Springs Gas Facility, 35 km south of Dongara. The latter two are connected to Perth via the Parmelia natural gas pipeline.

Landuse

McArthur (1991) and Rogers (1996) documented the history of settlement in the region in detail, and local historical societies and museums also provide information on the history of the area. Aboriginal people have occupied the land for about 40 000 years prior to European settlement. Apart from Dutch vessels that passed the present site of the City of Geraldton on their way up the coast, the first European to explore the area was Lieutenant George Grey who, in 1839, having failed to reach North West Cape, was forced to walk from Shark Bay back to Fremantle. The Gregory brothers, who explored the district in 1846 and 1848, noted good agricultural land, and discovered lead on the Murchison River and coal on the Irwin River. The lead mine that was subsequently established was named Geraldine after Governor Charles Fitzgerald.

The town of Geraldton was gazetted in 1850, soon becoming the major port north of Fremantle, and in 1871 it was officially proclaimed a town. The name was most probably given by Surveyor General J. S. Roe, and honours Captain Charles Fitzgerald, Governor of Western Australia from 1848 to 1855. The city is located on Champion Bay, discovered by Commander D. Dring in the colonial schooner 'Champion' in January 1840. The bay was named by the Royal Navy hydrographic surveyor, J. L. Stokes, who surveyed it later that year (DOLA website).

Pastoral blocks were first established inland from 1849 to 1862. In the 1890s, Geraldton became the major port for the Murchison gold rushes, and by World War 1 had become the major centre for the surrounding wheat belt.

The dominant landuses on Howatharra are agricultural production, urban, infrastructure, and nature reserves. Urban development is expanding the City of

Geraldton along the coast to the north. Land has been reserved to the north of Geraldton in the Oakajee area for the future development of a steel mill, industrial complex, and port. Nature reserves occupy small parts of the Moresby Flat Topped Range and northward extensions of this distinctive plateau.

Based on the criteria given by Dye et al. (1990), no prime agricultural land has been identified on HOWATHARRA. However, high-quality land has been identified in the terraces along the Chapman River both in the City of Geraldton and in Chapman Valley (Dye et al., 1990). The area of high-quality agricultural land has been estimated from this regolith–landform survey as 2650 ha, or 6% of the total land area (Fig. 3). This total includes a small area of land that has been sterilized by urban, industrial, and infrastructure development.

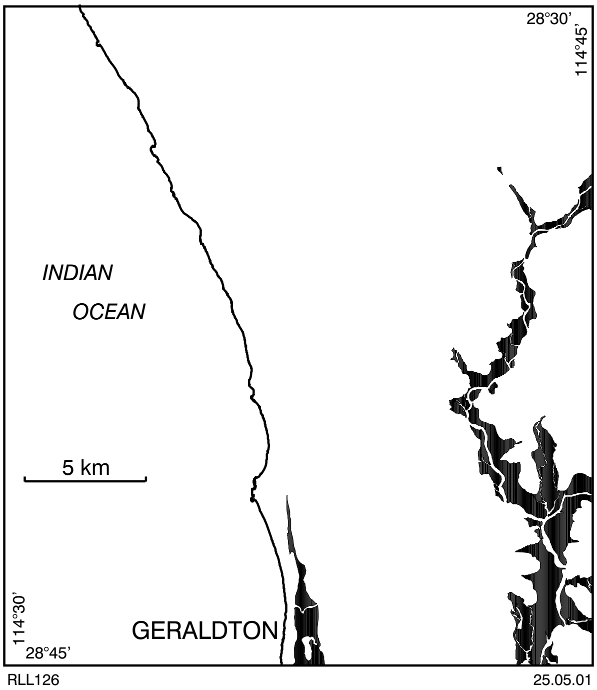

Figure 3. High-quality agricultural land on HOWATHARRA (*GaA*$_a$, *GaA*$_w$, *GeA*$_t$ and *GeA*$_w$ land system units, shaded black; after Dye et al., 1990)

The current mineral production on HOWATHARRA is limited to industrial or construction uses. Production is from a limesand operation north of the city, a number of gravel pits, mostly in the Moresby Flat Topped Range, and a few small sand pits supplying the building industry, mostly located close to the North West Coastal Highway. The Northampton mining region has a long mining history for lead and copper, with small mines and prospects scattered throughout the Northampton Complex. The early development of the area also saw the extraction of sandstone and granite from a few quarries, which were used for building, reclamation, and more recently as road metal.

Vegetation

HOWATHARRA lies in the Irwin Botanical District of the Northern Sandplains District, which is part of the Southwest Botanical Province (Beard, 1990; Rogers, 1996; Table 1). Two vegetation systems are present on HOWATHARRA. The Greenough Vegetation System forms a 5 to 15 km-wide strip along the coast, and corresponds with the Quindalup and Spearwood Land Systems of this study. The Northampton Vegetation System covers all the inland hilly areas underlain by the Proterozoic Northampton Complex and by Jurassic strata, corresponding with the Northampton, Casuarina, Moresby, Greenough, and Greenough Alluvium Land Systems.

Climate

The climate is classified as Extra-dry Mediterranean (Beard, 1990), and is characterized by mild, wet winters and warm to hot, dry summers (Tables 2 and 3). Rainfall

Table 1. Vegetation of the Greenough area

Soil and physiography	*Characteristic vegetation*
Greenough Vegetation System	
Recent dunes	*Acacia ligulata*
Rocky ridges near the coast	Thickets of *Acacia rostellifera, Melaleuca cardiophylla* and *M. huegelii*
Sand-covered limestone	Acacia–banksia scrub
Alluvial flats	Low forest of *Acacia rostellifera* and uncommon *Eucalyptus camaldulensis*
Creek lines	*Eucalyptus camaldulensis* and *Casuarina obesa*
Northampton Vegetation System	
Duricrust on flat-topped mesas	Scrub heath of *Gastrolobium oxyloboides*, *Allocasuarina campestris*, *Dryandra ashbyi*, *Isopogon divergens* and others
Sandy areas on mesas	Scrub heath of Banksia, Acacia, Dryandra and Allocasuarina spp.
Stony sideslopes of mesas	Thicket of *Melaleuca megacephala* and *Hakea pycnoneura*
Ferruginous sideslopes of mesas	*Allocasuarina campestris* and *Melaleuca uncinata*
Undulating red loamy soils over granite and granulite	Scrub of acacias and hakeas with scattered trees of *Eucalyptus loxophleba* and *E. camaldulensis*
Gravelly soils	Thickets of *Allocasuarina campestris*

SOURCE: Rogers (1996)

Table 2. Annual average monthly rainfall and rain days recorded at Narra Tarra (1899–1988), Nabawa (1905–2000), and Geraldton Water Supply (1877–1990)

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*	*Total*
Rainfall (mm)													
Nabawa[a]	7	12	15	23	65	101	95	65	36	21	11	6	456
Narra Tarra[b]	5	11	16	29	75	121	105	76	39	23	9	3	512
Geraldton[a]	6	9	13	24	70	116	92	66	30	18	8	4	455
Rain days													
Nabawa[a]	2	2	3	5	10	13	14	12	9	6	3	2	79
Narra Tarra[b]	1	1	2	4	8	12	12	10	6	4	2	1	63
Geraldton[a]	1	2	2	5	10	13	14	12	9	6	3	1	80

SOURCE: (a) Commonwealth Bureau of Meteorology website
(b) Rogers (1996)

Table 3. Annual average monthly temperature and evaporation recorded at Nabawa (1905–2000), temperature recorded at Geraldton Water Supply (1877–1990), and evaporation recorded at Geraldton

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*
Max. °C												
Nabawa[a]	34	34	32	28	23	20	18	19	22	25	29	32
Geraldton[a]	29	30	29	27	23	21	20	20	22	23	25	27
Min. °C												
Nabawa[a]	18	18	17	14	11	9	7	7	8	10	13	16
Geraldton[a]	18	19	18	16	13	12	10	11	11	13	15	17
Mean daily evaporation (mm/day)												
Nabawa[a]	11	8	8	5	3	2	2	2	3	5	7	10
Geraldton[b]	9	8	7	5	3	2	2	3	4	5	6	8

SOURCE: (a) Commonwealth Bureau of Meteorology website
(b) Rogers (1996)

ranges from 450 to over 500 mm a year, with the lowest rainfall on the coast north of Geraldton, and the highest on the hills around the Chapman Valley.

January and February are the hottest months for coastal areas influenced by heat troughs, and July and August are the coldest months (Table 3). Frosts can occur from June to September, averaging less than one day a year near the coast (Geraldton) to three days a year inland (Northampton). The area is noted for its strong summer winds (Table 4).

Table 4. Wind patterns in the Geraldton area

Controlling weather pattern	*Dominant wind directions*	*Characteristics*
Summer		
Subtropical high-pressure ridge	South through east to north	Strong (<28 knot) coastal sea breeze 10 am to noon
Trough between high	Calm	Delays or stops sea breeze
Winter		
Cold fronts from the Indian Ocean	East to northwest ahead of cold front	Erosive wind
	West to southwest behind cold front	Cool and moist wind

SOURCE: Rogers (1996)

Previous investigations

The land around what is now the City of Geraldton was explored by George Grey in 1839 (Grey, 1841), who noted on his maps that the hills were underlain by limestone, and that the valleys were fertile or rich country. The earliest geological descriptions that included HOWATHARRA were in the mid-1800s, but the first systematic survey was by Jones (1961). Playford et al. (1970) subsequently mapped the region at 1:250 000 scale. The most recent appraisal of the geology of HOWATHARRA is in an unpublished report by Gozzard et al. (1988) on the geology, hydrogeology, and mineral resources of the Geraldton region. There have recently been two surveys of the soils and landforms of the area around Geraldton (Dye et al., 1990; Rogers, 1996).

Land systems methodology

Regolith–landform mapping of GERALDTON was completed between July 1998 and August 1999 using 1 m-resolution colour orthophotographs flown in 1997 by Kevron Aerial Surveys for DOLA. The orthophotographs were combined with 5 m topographic contours from DOLA, and printed at 1:10 000 scale for field mapping. The offshore was mapped in shallow waters using the orthophotographs, and in deeper water using Landsat TM imagery enhanced by DOLA and combined with 2 m-resolution bathymetry supplied by the Department of Transport. A total of 323 sites were documented in the area, at which 265 photographs and 142 soil or rock samples were taken. Hand-augered soil samples accounted for 37 of the total samples collected. Thin sections were made of 13 metamorphic rocks and 11 sedimentary rocks and placed in the Geological Survey of Western Australia (GSWA) collection.

The mapping system used in this study is based on soil catenas (Milne, 1935). These are similar to regolith topo-sequences described by Pain et al. (1994), who chose to use this term (rather than the widely used soil catena) because they believed it to have a stronger geological context.

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

Land systems have been used in Australia to define areas with recurring patterns of topography, soil, and vegetation (Christian and Stewart, 1953). The system is hierarchical, and divided into regions, provinces, zones, systems, and subsystems. HOWATHARRA lies in the Western Region, covering the western half of Western Australia (Bettenay, 1983; Rogers, 1996).

The naming of the land systems follows Rogers (1996) with one exception; the Tamala System is renamed the Spearwood System to avoid confusion with the Tamala Limestone geological unit. The scale of mapping means that the details and divisions of the units have also been modified or refined in this study relative to Rogers' (1996) regional study. The emphasis has moved towards regolith material at depth, together with its relationship to the underlying bedrock in a specific landform context.

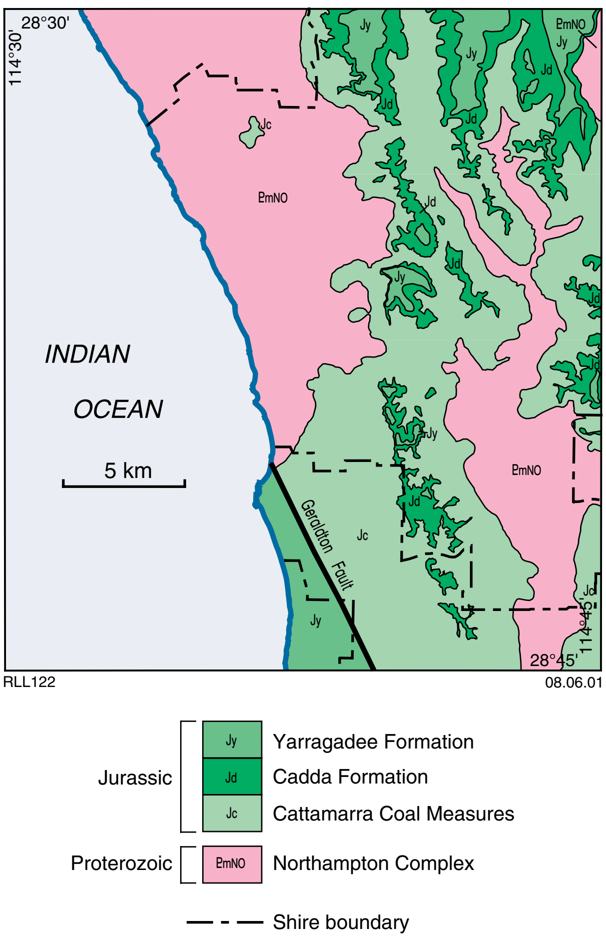

Figure 4. Interpreted onshore bedrock geology on HOWATHARRA

Geology and geomorphology

Proterozoic

The Northampton Complex (Fig. 4) is a Mesoproterozoic metamorphic complex within the Pinjarra Orogen that formed between 1150 and 1000 Ma (Myers, 1990; Tyler et al., 1998; Brugier et al., 1999). The complex consists of a group of high-grade metamorphic rocks that were originally sedimentary rocks cut by granitic and gabbroic intrusions. The dominant lithologies in the complex are granulite, granite, and migmatite (*ⱣmNO*; Playford et al., 1970), and regionally the complex is cut by younger mafic dykes (*Ᵽd*) and quartz veins (*q*). The dykes have been dated at c. 748 ± 17 Ma by Embleton and Schmidt (1985), and comparable dykes in the Pilbara have been dated at 755 ± 3 Ma by Wingate and Giddings (2000).

The Northampton Complex is well exposed in most low-lying areas on HOWATHARRA. There are a few exposures close to the overlying Jurassic sedimentary rocks, indicating that the contact between the two is probably an irregular unconformity, but the contact does not outcrop in the map area.

Mesozoic

The outcrop of Mesozoic strata of the Perth Basin on HOWATHARRA (Playford et al.,1976; Mory and Iasky, 1996) includes the Lower Jurassic Cattamarra Coal Measures (*Jc*), Middle Jurassic Cadda Formation (*Jd*), and Middle to Late Jurassic Yarragadee Formation (*Jy*). The Lower Triassic Kockatea Shale (*Ŧk*) is also present in parts of the subsurface, onlapping onto the basement in the southern part of HOWATHARRA.

Triassic

The Kockatea Shale (*Ŧk*) is the only part of the Triassic succession represented on HOWATHARRA, where it lies unconformably above the Northampton Complex. The dominant lithologies in the formation are sandstone and shale, which contains marine microfossils (Cockbain, 1990).

There are no exposures of the Kockatea Shale on HOWATHARRA, and the subsurface extent has been estimated by extrapolation from surface exposures and boreholes on GERALDTON (Koomberi, 1994; Langford, 2000). The thickness of the unit is estimated at 20 m or less, because the unit thins to the northeast beneath the overlying Jurassic sandstones.

Jurassic

The stratigraphic names for the Jurassic of the Perth Basin were originally defined by Playford et al. (1976). The Jurassic on HOWATHARRA was divided into the Chapman and Champion Bay Groups, and included six formations. All but one of these formations are not recognizable in the succession on HOWATHARRA. However, one of these formations, the Newmarracarra Limestone, is a distinctive regional indicator of a marine transgression in the Middle Jurassic. The area has now been correlated with the divisions into the Cattamarra Coal Measures (Playford and Low, 1972), Cadda Formation (Playford et al., 1976), and Yarragadee Formation (Backhouse, 1984) that have been used in the north Perth Basin for regional subsurface correlations (Mory and Iasky, 1996). The Cadda Formation (*Jd*) is characterized by the presence of lithologies related to the marine incursion, whereas the overlying and underlying formations are dominantly fluvial. The marine limestone in the Cadda Formation is referred to here as the Newmarracarra Limestone.

The Jurassic strata underlying most of the land area of HOWATHARRA can be divided into two broad areas; east and west of the Geraldton Fault (Fig. 4). To the west of the fault the subcrop comprises the Yarragadee Formation (*Jy*). The underlying Cadda Formation comprises sandstone with minor amounts of limestone and siltstone. There is one recorded exposure of highly weathered, slightly gravelly, medium-grained sandstone from the Yarragadee Formation located adjacent to the Chapman River northeast of Geraldton (MGA 270435E 6818130N). The north-northwest alignment of the Chapman River at this point, which lies on the downthrown side of the fault, is controlled by the Geraldton Fault or by the barrier formed by the Pleistocene dunes in the Spearwood System. The Yarragadee Formation was also identified in Borehole GS1 (MGA 269190E 6820955N), located near Waggrakine Primary School, which intersected 7 m of footslope colluvium over 14 m of Yarragadee Formation and 27 m of Cadda Formation limestone and sandstone (Koomberi, 1994). The Geraldton Fault is estimated to lie about 150 m to the northeast of this borehole.

East of the Geraldton Fault there are numerous exposures of the three formations. Rocks of the Cattamarra Coal Measures (*Jc*), which rest unconformably on the Triassic Kockatea Shale or Proterozoic Northampton Complex, have the most extensive outcrop of the three. There has been no coal or carbonaceous material identified in the weathered rock exposures of the Cattamarra Coal Measures in the area. The formation is exposed on the scarps and footslopes of all the hills in the Moresby Flat Topped Range and similar plateaus in the area.

The Cattamarra Coal Measures vary widely in thickness, with a maximum of around 190 m between Geraldton and the Moresby Flat Topped Range, and a progressive thinning towards the northeast. To the east of Mount Fairfax the thickness is about 120 m, and further north near Oakajee it is about 90 m. Further north along the scarp, the unit thins to around 50 m, and is absent in the northeast corner of the sheet where the Cadda Formation is interpreted to lie directly on the Northampton Complex. The base of the Mesozoic is estimated to dip at about 0.5° to the southwest from this high point.

The dominant lithology is sandstone, with minor siltstone and conglomerate (Fig. 5). The sandstone ranges from coarse to medium grained, and includes gravel and subrounded pebbles, typically up to 6 cm across, of milky white vein quartz. Thin siltstone units up to 0.5 m thick and pebbly horizons up to 6 cm wide are also present in the sandstone. The siltstone is typically thickly laminated (5–10 mm), and may include intraformational breccia in places. The conglomerate or pebbly sandstone includes clasts of white subrounded vein quartz, typically 5–10 cm across, or clasts of garnet-bearing felsic granulite up to 12 cm across in places. Planar or trough cross strata in the sandstone show no consistent palaeocurrent, with southerly, westerly and northwesterly directions recorded.

The Newmarracarra Limestone, within the Cadda Formation, is a minor, but distinctive, marine limestone horizon. The unit is shelly, and the carbonate is commonly totally replaced by iron oxides (Fig. 6). When weathered, this formation forms the prominent scarp that defines the plateau of the Moresby Flat Topped Range and adjacent hills. The unit is commonly poorly exposed, but otherwise is quite distinctive. The Cadda Formation outcrops on the top of every major hill in the area, and is estimated to be around 30 m thick. The formation has a consistent altitude over a wide area. In Bringo Cutting on NANSON, about 25 km east of Geraldton, the Newmarracarra Limestone is exposed close to Proterozoic basement at about 200 m Australian Height Datum (AHD). To the west, on the type locality of Round Hill on WALKAWAY (Playford et al., 1976), the unit outcrops at 200 m AHD, and in Evaluation Hole 4 on NANSON (MGA 282604E 6833211N) the unit was palynologically identified both 17 and 25 m below the surface of 223 m AHD (Backhouse, 1998; Hundi, 1999). The basement is 40 m below the surface in this drillhole, and all the overlying mudstone-dominated sequence has been assigned by Hundi (1999) to the

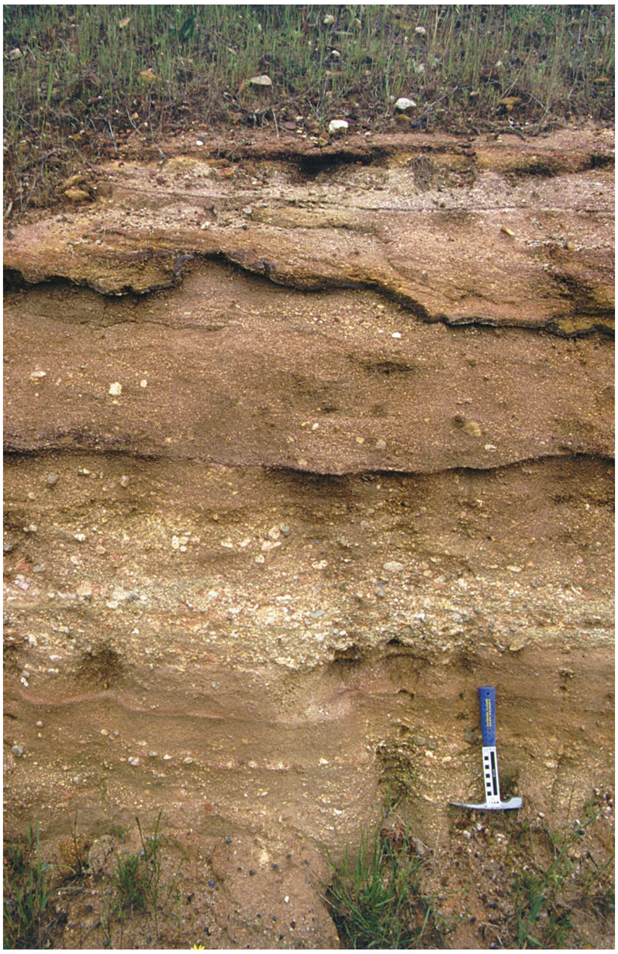

Figure 5. Pebbly sandstone and conglomerate of the Cattamarra Coal Measures *(Jc)* exposed in a road cutting on the Chapman Valley Road about 2 km north of Yetna (MGA 278155E 6834640N; GSWA Photograph No. 1402)

Chapman Group, rather than the Cadda Formation. Exposures on the southern end of the Moresby Flat Topped Range on HOWATHARRA lie between 175 and 190 m AHD, and an exposure north of Oakajee is at 190 m AHD. Thus, whereas the distribution of the underlying Cattamarra Coal Measures has been strongly influenced by the landform in the Proterozoic basement, on HOWATHARRA the Cadda Formation represents a widespread marine to estuarine incursion over an essentially flat land surface.

The Cadda Formation includes siltstone, sandstone, and limestone, although it is principally the limestone that distinguishes the unit from the underlying and overlying formations. The limestone is typically totally ferruginized, with abundant shell casts as the only indication of the original calcareous nature of the rock. Massive, shelly sandy limestone is present at a few localities, commonly with abundant shell debris of *Trigonia moorei* up to 5 cm across, but including other bivalves (Fig. 6), gastropods, ammonites, brachiopods, belemnites, and echinoids (McNamara and Brimmell, 1992). The best exposures of limestone are 2 km north of Mount Fairfax (MGA 274410E 6819480N), and 200 m south of the limestone there are exposures of ferruginized coarse-grained sandstone with abundant, subhorizontal plant stem casts, mostly 1–3 cm across, and up to 15 cm long. This unit was termed the Colalura Sandstone by Playford et al. (1976), and although this is another distinctive marker within the Cadda Formation, the unit cannot always be identified in the ferruginous duricrust.

The Yarragadee Formation is widespread on the plateau, but is typically weathered to a characteristic slightly silty, fine to medium quartz sand over duricrust gravel. The unit is at least 45 m thick on the plateau at the northern edge of the sheet, but the top is not exposed. Lithologically, the Yarragadee Formation is typically a slightly gravelly or pebbly medium- to coarse-grained sandstone with very thin to thin bedding (2–10 cm). The scarce pebbles are commonly subangular to subrounded quartz up to 2.5 cm across. Poorly bedded to massive siltstone and thinly laminated slightly sandy siltstone beds have also been noted within the formation.

Cainozoic

Cainozoic material on HOWATHARRA includes residual materials, and colluvial (mass wasting), fluvial, eolian, coastal, and marine deposits. They are spread over the entire sheet area and, although they are over 100 m thick in large dunes, they commonly form a veneer only a metre or so thick.

The oldest Cainozoic materials are the residual sands and duricrust gravels formed on the eroded plateau of the Casuarina and Moresby Systems. These materials formed in situ by weathering of the bedrock, probably mostly during the Oligocene (34–24 Ma; Hocking et al., 1987, 2001). However, their formation may have extended back to the Middle to Late Eocene (49–34 Ma; van de Graaff, 1983) as sea levels fell from highs of up to 300 m above the present level.

The erosion of the plateau to form the scarp and colluvial slopes largely pre-dates deposition of eolian sands of Pleistocene (< 1.8 Ma) age because these locally overlie the slope deposits. The widespread preservation of mottling and induration of the colluvial deposits indicates that they have been weathered in situ, and that they have not been significantly eroded. The maximum age of the colluvial slopes is unknown, but because the deposits have a uniform appearance down the hillslopes to near present-day sea level, they probably post-date the last major marine transgression (sea-level rise) in the Miocene (24–5 Ma).

The Lower to Middle Pleistocene Tamala Limestone, composed of calcarenite and residual quartz sand, is widespread both offshore and onshore, extending up to the flanks of the Moresby Flat Topped Range. Weathering of the formerly uniform calcareous dune sands has produced a calcarenite with a calcrete cap, overlain by residual sand. The combined thickness of these deflated transgressive barrier, parabolic, and longitudinal dunes is up to about 100 m, although the residual sand probably rarely exceeds

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Figure 6. Hinged bivalve shell pair (*Gresslya sanfordii*) and other broken shells in ferruginized Newmarracarra Limestone, 3.5 km west of Narra Tarra Bridge (MGA 274350E 6823560N; GSWA Photograph No. 1343)

20 m in thickness. Coastal and fluvial erosion of the Tamala Limestone took place in the Middle Pleistocene at a sea-level highstand of about 5 m. This formed an extensive north-northwesterly trending scarp that now lies behind the Holocene dunes. Corals that grew in shallow water about 3 km from this palaeoshoreline on GERALDTON have been dated by Stirling et al. (1998) at 120–132 ka before present (BP). Coastal erosion probably also took place between 105 and 85 ka at a sea-level low of around –20 m Chart Datum (lowest astronomical tide; CD).

The fluvial deposits in Oakabella Creek and the Chapman, Oakajee, and Buller rivers formed both prior to and following the deposition of the Pleistocene eolian sands (Wyrwoll, 1977, 1984; Langford, 2000). Based on the limited lithification and weathering, the older, coarser deposits that lie below the eolian deposits probably range in age from Pliocene to Early Pleistocene. The younger fluvial deposits have been deeply incised by present-day river channels and date from the Late Pleistocene to the Holocene. The erosional channels in Pleistocene limestone offshore from the mouths of Oakabella Creek, and the Oakajee, Buller, and Chapman rivers, probably relate to Pleistocene sea-level lowstands ranging from 105–40 ka BP.

The youngest Cainozoic deposits are eolian dunes and associated coastal deposits of the Safety Bay Sand. Two generations of parabolic dune formation are recognized on HOWATHARRA in these Holocene deposits. A third, older generation is recognized on GERALDTON (Langford, 2000), but has not been identified on HOWATHARRA.

Major geological structures

Only one major geological structure has been identified on HOWATHARRA, namely the Geraldton Fault (Fig. 4). This normal fault can be inferred from the stratigraphy identified in Greenough 1, GS6, and GS7 drillholes on GERALDTON, and GS1 drillhole on HOWATHARRA (Koomberi, 1994), from which a downthrow to the west of about 160 m is calculated. There is no geophysical evidence for the exact position of this fault on HOWATHARRA, but in adjacent areas to the south, the northward extension of aeromagnetic lineaments in the Dongara area (Mory and Iasky, 1996, fig. 39) has been used to refine the position of the fault on both GERALDTON and HOWATHARRA.

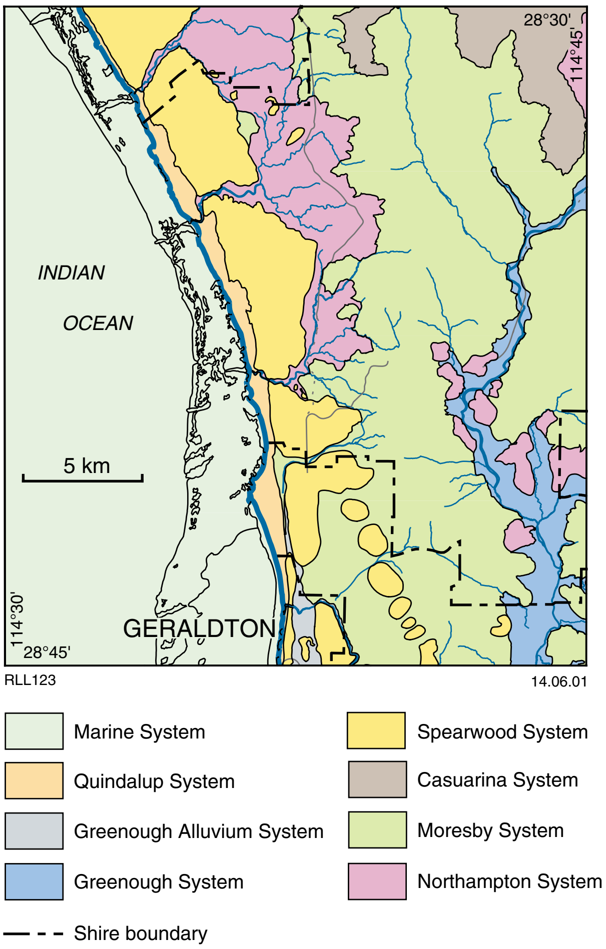

Figure 7. Distribution of land systems on Howatharra

Regolith–landform systems

The Geraldton sheet has been divided into seven regolith–landform land systems, plus a marine system (Fig. 7). The land system nomenclature is based on that defined by Rogers (1996), and to a lesser extent on the earlier work of Dye et al. (1990). The only departure here from the names used by Rogers (1996) is a change of the Tamala System to the Spearwood System. The Tamala Limestone is the stratigraphic name given to the calcarenite that underlies the Spearwood System. This makes the naming more compatible with that adopted for the geomorphic elements of McArthur and Bettenay (1960) and physiographic regions of Playford et al. (1976).

Northampton System (*No*)

Land of the Northampton System occupies 6500 ha (10%) of HOWATHARRA (Fig. 8, Table 5), and comprises low hills and rises with an incised drainage pattern (Fig. 9). The system overlies metamorphic rocks of the Proterozoic Northampton Complex. Fresh rock has been quarried for aggregate, and these rocks have been the source of historically important base metal production.

Landform and distribution

The Northampton System is composed of low hills and rises, up to 30 m in height, with gently inclined slopes, and abundant exposures of fresh to moderately weathered bedrock in places (Fig. 10). These are incised by numerous narrow stream channels that drain west to the ocean. The system was first described by Rogers (1996), who defined the landforms as gently undulating to rolling rises and low hills with narrow valleys. The system broadly ranges in altitude from 130 m AHD close to the Moresby Flat Topped Range down to 50 m AHD closer to the coast. At the northeastern edge of the sheet the system reaches up to 210 m AHD.

The Northampton System is located in three areas on HOWATHARRA. The largest area lies to the west of the northern extension of the Moresby Flat Topped Range, behind sand dunes of the Spearwood System. There are also patches of the Northampton System adjacent to the terraces and channels of the Chapman River in Chapman Valley. The third area is in the northeast corner of the sheet, adjacent to the plateau of the Casuarina System.

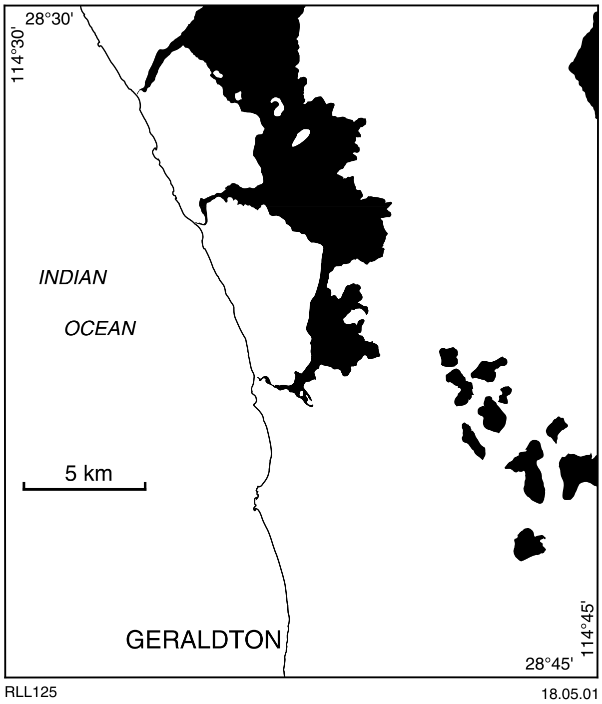

Figure 8. Distribution of the Northampton System (*No*) on HOWATHARRA

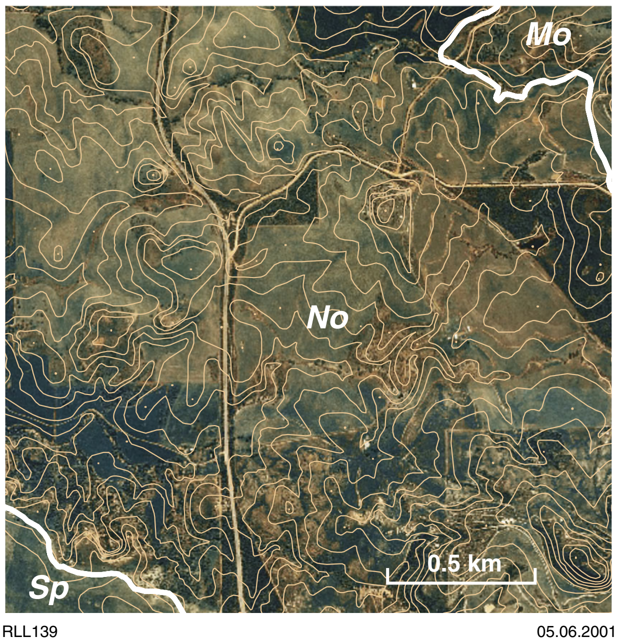

Figure 9. Low hills and rises of the Northampton System (*No*) adjacent to the North West Coastal Highway on HOWATHARRA, between the Spearwood System to the west (*Sp*) and the Moresby System to the east (*Mo*). Part of Oakajee Nature Reserve is located in the area of bush in the east of the scene. Orthophotograph with contours at 5 m

Regolith and rock materials

The regolith materials of the Northampton System are derived from the weathering of the underlying Proterozoic Northampton Complex. The dominant material is a thin colluvial soil containing abundant rock debris (*NoC*). The underlying metamorphic rocks are typically fresh to highly weathered, and are exposed on hillcrests and in stream beds throughout the area. The main lithologies in the complex are granulite and granite (*ⱣmNO*), and there are also outcrops of fine-grained gabbro dykes (*Ɽd*), and both quartz *(q)* and pegmatite *(p)* veins (Fig. 11). The granulite varies considerably in mafic mineral content, ranging from psammitic to pelitic, and was probably derived from the metamorphism of sedimentary rocks ranging from quartzite to mudstone.

Mineral resource potential

The dominant mineral resource potential in the Northampton System on HOWATHARRA is for base metals. The rocks of the Northampton System are also a potential source of hard rock aggregate or fill for land reclamation and sea walls. The duricrust gravels and residual sands that are dominant in the adjacent Moresby and Casuarina Systems are largely absent from the Northampton System.

The base metal exploitation of the area is detailed in the section on **Mineral resource potential** (p. 49). Lead

Table 5. Components of the Northampton System

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Undivided slopes *NoC* 5 383 ha (83%)	Colluvial Footslopes and sideslopes; mostly gently inclined; typically from 40–120 m AHD; up to 250 m around Protheroe Up to 0.3 m of loose soil with abundant gravel* and cobbles of weathered rock; over residual soil of mottled sandy clay to highly weathered granulite or granite gneiss	White Peak Road (MGA 268380E 6830250N) At least 0.45 m of rock debris or bedrock on low hills Brown, mottled red and light grey, silty clayey gravelly coarse quartz–feldspar sand derived from weathered granulite
Stream channel or banks NoA_c 446 ha (7%)	Alluvial Stream channel (bed and banks) or stream banks; level to moderately inclined; locally precipitous banks; mostly from sea level up to 120 m AHD Stream bed includes alluvium and weathered rock exposures. Banks of colluvial debris	South of Coronation Beach Road (MGA 265950E 6839615N) Rain has eroded down to a mottled hardpanized colluvium near the edge of the ploughed field Exposures of granulite, cut by 30 cm quartz vein, in stream channel; covered by at least 2 m of colluvium
Hillcrest NoR_c 379 ha (6%)	Residual Gently to moderately inclined crests to low hills and rises; mostly 60–140 m AHD Thin soil with abundant gravel and cobbles of weathered rock; over duricrust and weathered granulite or granite gneiss	Between Coronation Beach Road and North West Coastal Highway (MGA 266780E 6839015N) Moderately inclined, low hill characterized by abundant rock debris with outcrop of banded granulite in places Moderately to highly weathered, banded quartzo-feldspathic granulite
Talus slope NoC_t 84 ha (1%)	Colluvial Talus slope to scarps; gently to moderately inclined; mostly 80–120 m AHD Weathered rock debris; gravel and boulders in colluvial matrix	Southeast of Oakabella (MGA 265540E 6844730N) Prominent scarp about 3 m high in Jurassic sandstone and conglomerate above Proterozoic granulite Talus slope and footslope dominantly composed of granulite debris, with some exposures of granulite and pegmatite
Channel bench NoA_e 58 ha (<1%)	Alluvial Isolated areas on the lower reaches of Oakabella Creek and the Buller River; level to gently inclined bench about 1 m above stream bed; up to 100 m wide; mostly 5–20 m AHD Gravelly silty sand	Oakabella Creek (MGA 261060E 6841515N) Level channel bench, about 1–1.5 m above the river, extends to the colluvium at the foot of the limestone scarp Brown 7.5YR 4/4† slightly silty, gravelly, medium to coarse sand; derived from weathering of granulite and granite
Proterozoic Northampton Complex *ꝐmNO* 46 ha (<1%)	Bedrock Mostly scattered over hillslopes; also in stream beds, road cuttings, and quarries Fresh to weathered, undivided granulite and metamorphosed granite gneiss	South of Mount Rennie (MGA 279710E 6826725N) Gently inclined hillslope with abundant exposures of granulite Fine-grained, quartz–feldspar–garnet psammitic to semipelitic granulite with contorted banding; some bands have coarse (5–10 mm) garnet clusters or blebs; pegmatite both parallel to banding and cross cutting
Drainage depression NoA_d 42 ha (<1%)	Alluvial Level to gently inclined poorly drained depressions; mostly 80–100 m AHD adjacent to the Moresby Flat Topped Range; around 180 m AHD in the northeast Silty and clayey sand	North of Coronation Beach Road (MGA 267150E 6840720N) Depression extending north for 1 km; up to 100 m wide, with a poorly defined channel Alluvial silt, sand, and clay, exposed in the northern part of the channel

Table 5. (continued)

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Stream bed NoA_b 38 ha (<1%) (database only: not shown on map, within NoA_c)	Alluvial Narrow, sinuous stream bed 20–25 m wide on the lower reaches of Oakabella Creek, and the Oakajee and Buller rivers; dominantly level; mostly below 5 m AHD, but extends up to 60 m AHD Loose sand, silt, and mud above alluvial silty sandy clay; scarce weathered rock exposures	Oakajee River (MGA 263710E 6835950N) Exposures of older alluvium in the stream bed include brown alluvium and grey clay Olive brown 2.5YR 4/4, soft, slightly sandy clay
Terrace NoA_t 36 ha (<1%)	Alluvial Terrace above channel bench or stream channel; small, isolated areas less than 200 m wide on the lower reaches of the Oakabella Creek and the Oakajee River; mostly level, but locally moderately inclined; range from near sea level to 40 m AHD Dark brown to reddish brown silty sand, sandy gravel, and clay; poorly bedded in channel bank exposures	Oakajee River (MGA 263775E 6837030N) Moderately inclined, alluvial terrace flat Reddish brown 2.5YR 4/4 silty clayey, slightly gravelly, medium to coarse sand; mixed eolian quartz and subangular debris; vein quartz pebbles up to 10 mm; abundant subangular quartz gravel in places at the surface
Jurassic Cattamarra Coal Measures *Jc* 3 ha (<1%)	Bedrock Mostly forming small scarps above low hills underlain by Proterozoic rocks; also in road cuttings Undivided, weathered sandstone, siltstone, and conglomerate	Southeast of Oakabella (MGA 265540E 6844730N) Prominent scarp about 3 m high in sandstone and conglomerate; basal unit to Jurassic strata Conglomerate clasts of garnet-bearing felsic granulite up to 12 cm across; subrounded; basal 1–1.5 m of the succession is clast rich; above this the sandstone has fewer clasts
Proterozoic quartz vein *q* 1 ha (<1%)	Bedrock Ridges of hard rock Quartz vein; in situ and debris	700 m west of Carey Road (MGA 269765E 6831845N) Ridge trending southeast, with abundant quartz vein debris on the flanks, and boulders up to 0.75 m on the top; downslope debris includes well foliated quartz–feldspar–muscovite schist
Proterozoic dolerite or fine-grained gabbro dyke *Ed* <1 ha (<1%)	Bedrock Stream bed, hillcrest, or roadside cutting Fresh to highly weathered mafic intrusions; dolerite (very fine grained gabbro to microgabbro) and fine-grained gabbro	Road cutting on the North West Coastal Highway near Olsen Road (MGA 268115E 6837255N) Hillslope in low hills with moderately inclined slopes Banded felsic granulite cut by highly to completely weathered fine-grained (0.25–0.5 mm) gabbro dyke, 1.8 m wide
Swamp NoA_w <1 ha (<1%) (database only: not shown on map, within *NoC*)	Alluvial Slight hollow in gently inclined slopes; 95 m AHD Waterlogged sandy soil over colluvium	Wokatherra (MGA 274220E 6830040N) Swampy vegetation in small hollow between rock exposures on low, undulating hillcrest
Pegmatite *p* <1 ha (<1%)	Bedrock Eroded slopes Very coarse grained (pegmatitic) veins in granulite and granite gneiss	South of Mount Rennie (MGA 279710E 6826725N) East-northeasterly trending, vertical, 25 cm-wide pegmatite vein cutting quartz–feldspar–garnet granulite and layer-parallel pegmatite veins

* See Appendix 4 for grain-size definitions

† All colour names and notations in this publication refer to the Munsell soil colour notation (Munsell Color, 1994)

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Figure 10. Abundant exposures and exhumed corestones of fresh to moderately weathered granulite of the Northampton Complex on a low hillcrest in the Northampton System (NoR_c), 2.8 km west of Oakajee mine (MGA 266575E 6838545N; GSWA Photograph No. 1282)

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Figure 11. Stream bed exposures of a north-northeasterly trending fine-grained gabbro dyke (left) cutting pegmatite and semipelitic to pelitic granulite (right) of the Northampton Complex, 2.3 km north of Oakajee mine (MGA 270030E 6840600N; GSWA Photograph No. 1408)

mining in the district dates back to the middle of the 19th Century, and there was intermittent production until the 1950s. Recent exploration for further base metal resources has not identified significant mineralized bodies.

There is an abandoned quarry close to the North West Coastal Highway (*8338**) that was a source of strong to extremely strong rock (Appendix 6) used for aggregate and sea wall construction during development of the Geraldton port. The rock in the quarry is massive to banded and folded, granoblastic felsic granulite containing quartz, feldspar, garnet, tourmaline, and biotite. An abandoned quarry in the Oakajee Nature Reserve, presumed to be in granulite, is noted by Jones (1961). A quartz vein forming a prominent northwesterly trending ridge, exposed about 2 km north-northeast of White Peak (MGA 269740E 6831870N), may have been used as a source of ornamental stone, although there are no records to confirm this.

Active processes and hazards

The only significant agent driving regolith–landform processes at present is rainfall. Erosion is the dominant active process, as colluvium formation is not currently significant. Heavy rainfall does not normally result in flooding on the steeper slopes, but it often causes severe channel erosion in the streams, and gully erosion on clayey soils of the cleared hillslopes.

Landuse, vegetation, and drainage

The land has been extensively cleared of native vegetation, although there are some remnants in the drainage depressions and in blocks such as the Oakajee Nature Reserve. The dominant agricultural activities in the area, mostly in smallholdings, are grazing and cereal production. There is no urban or industrial development, but the North West Coastal Highway and the abandoned Geraldton–Northampton railway line both lie within this land system.

The Northampton System is characterized by a dendritic drainage pattern extending from the footslopes of the Moresby Flat Topped Range to several narrow channels leading to the ocean. These channels include the Oakabella Creek, Oakajee River, and Buller River, all of which are active in the wetter winter months, with little or no water present in the dry season.

Relationships

The Northampton System covers areas where deep erosion of a plateau underlain by Jurassic strata has exposed the underlying Proterozoic rocks. Erosion in the Northampton System is significant when compared to that in the Casuarina and Moresby Systems, with the deeply dissected low hills and rises of the system being a distinguishing feature.

Erosion of weathered rocks underlying the Northampton System in the Chapman Valley is a source of material for the alluvial deposits of both the Greenough and Greenough Alluvium Systems. To the west of the Moresby System, deposition of alluvium is largely within channels in the Northampton System. Eolian sands of the Quindalup and Spearwood Systems overlie the colluvial slopes and hillcrests of the Northampton System.

Geological history

The Northampton System is underlain by the Northampton Complex, a Mesoproterozoic (1150–1000 Ma) metamorphic complex within the Pinjarra Orogen cut by a Neoproterozoic dyke swarm dated at around 750 Ma (Wingate and Giddings, 2000). The complex was subsequently eroded and covered by Mesozoic sedimentary rocks, which have now been eroded to expose the older rocks. The absence of a thick duricrust cover indicates a major period of erosion after the Oligocene (34–24 Ma; Hocking et al., 1987). This landform development largely pre-dates the deposition of the eolian sands of the Pleistocene (1.8–0.04 Ma) Spearwood System because some hillcrests are covered in part by remnants of that system.

Exposures of Tamala Limestone in Oakabella Creek rest above alluvium and weathered Northampton Complex rocks, and are interbedded with exposures of older alluvium. Younger alluvium, capped by Holocene dune sand, sits above a colluvial limestone horizon (Fig. 12). A complex history of fluvial processes through the Pleistocene and into the Holocene has been determined for the area by Wyrwoll (1984). The maximum age of the colluvium is unknown, but it probably post-dates the last major transgression in the Miocene (24–5 Ma). The absence of mottling and induration of the deposits indicates that they may have been actively forming much more recently.

* Mineral occurrences are identified by the deposit number assigned by GSWA's Western Australian Mineral Occurrence database (WAMIN; see Appendix 5), and are shown in this text in italics.

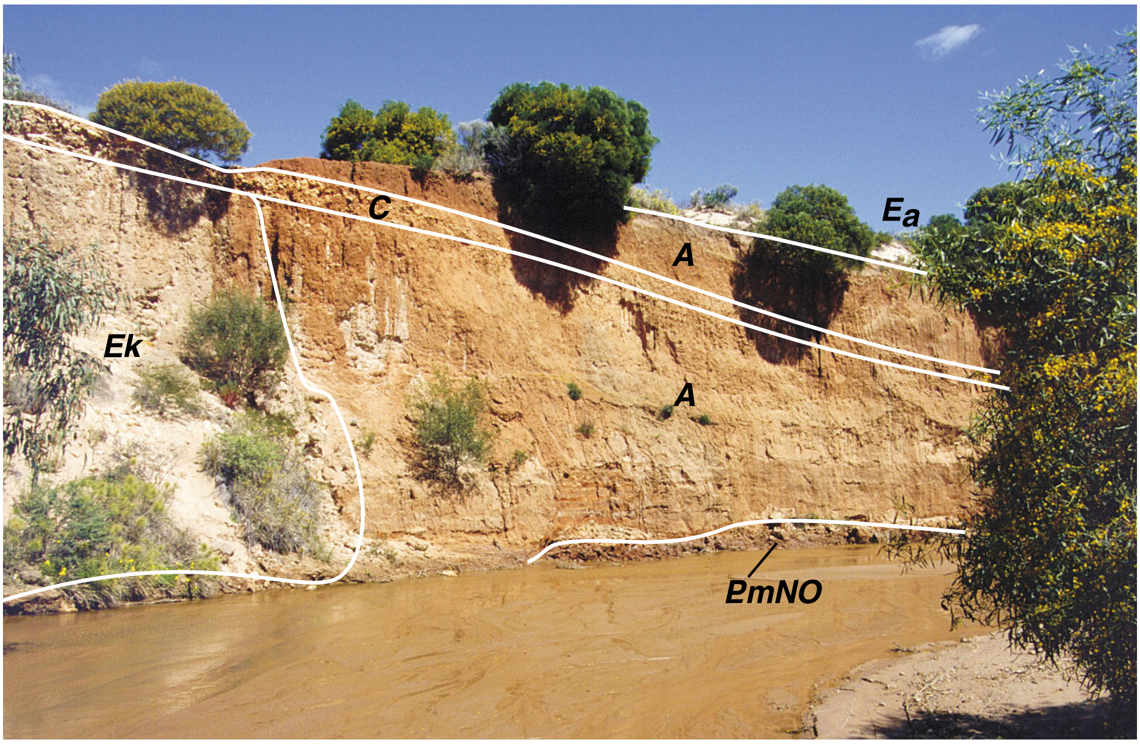

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Figure 12. Exposures of Pleistocene calcarenite (Tamala Limestone; *Ek*) and alluvium (*A*) in Oakabella Creek above weathered Northampton Complex rocks (*ⱣmNO*; MGA 261120E 6841400N). A colluvial limestone horizon (*C*) separates the older, coarser alluvium from the finer, younger alluvium, which is capped by Holocene dune sand (*E_a*; GSWA Photograph No. 1368)

Moresby System (*Mo*)

Land of the Moresby System occupies 22 400 ha (33%) of HOWATHARRA (Fig. 13, Table 6), and is a plateau with sideslopes composed of residual materials and colluvial deposits over weathered Jurassic rocks, along with minor occurrences of Proterozoic rocks. The cemented pisolitic duricrust on the summit surface is a source of gravel, and has been worked in a number of pits on the summits and upper slopes of the Moresby Flat Topped Range. There are also some small sand pits and two abandoned stone quarries.

Landform and distribution

The Moresby System is a relict plateau with associated footslopes and sideslopes (Fig. 14). The system was first described by Rogers (1996), who defined the landforms as level to gently undulating summit surfaces, moderate to steep sideslopes, and gently inclined footslopes. The plateau is composed of residual materials above scarps in weathered Jurassic sedimentary rocks (Fig. 15). Narrow talus slopes lie below most of the scarps. The extensive footslopes and sideslopes consist of thin colluvial materials over weathered rock, including minor outcrops of Proterozoic basement rocks. Narrow alluvial channels cut the colluvial slopes. The Moresby System occupies the bulk of the onshore area of HOWATHARRA, and is divided into two areas by the Greenough System along the Chapman River.

The larger area extends from Mount Fairfax in the south (Fig. 15) to the northern edge of the sheet. To the east of Geraldton, this part of the plateau is named the Moresby Flat Topped Range. The slopes and landforms of the plateau east of the Chapman River valley are similar to the Moresby Flat Topped Range. The plateau is locally gently inclined but overall forms a level surface ranging in altitude from 180 m AHD in the south to around 220 m AHD at the northern edge of the sheet. The scarps to the plateau form a narrow belt of locally precipitous to cliffed slopes above a moderately inclined to steep talus slope up to 300 m wide. The gently inclined sideslopes pass laterally into the adjacent Northampton, Greenough, and Spearwood Systems.

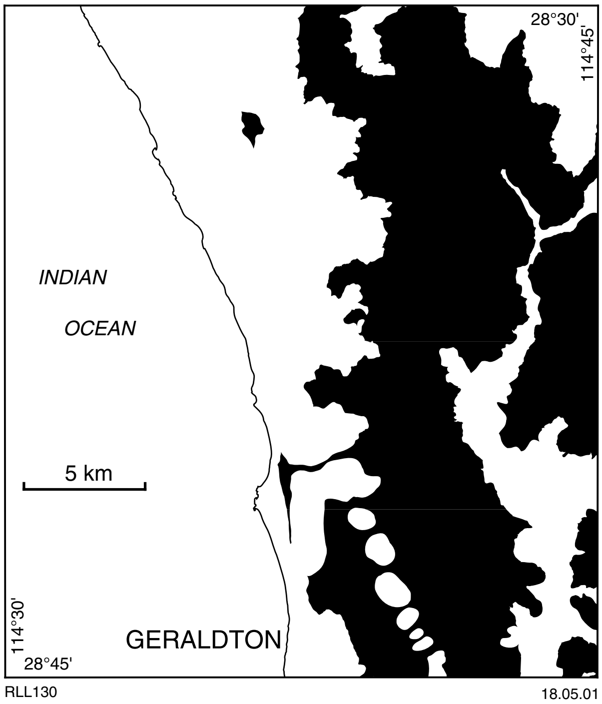

Figure 13. Distribution of the Moresby System (*Mo*) on HOWATHARRA

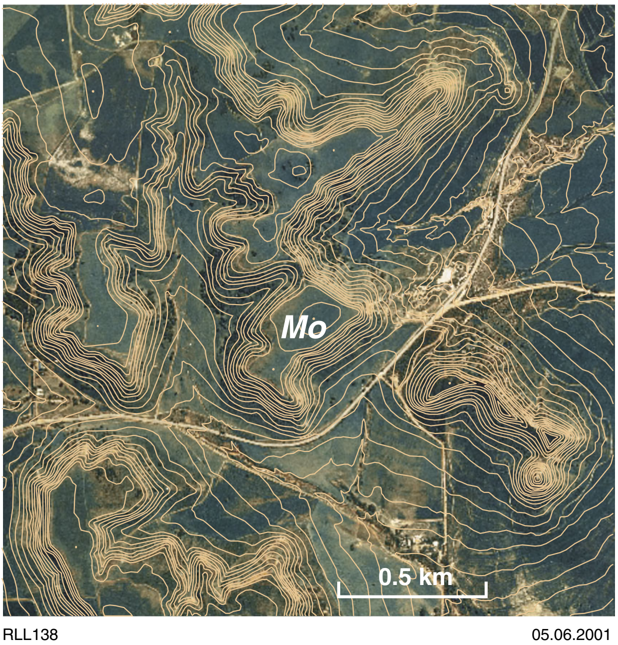

Figure 14. Level, dissected plateau surface of the Moresby Flat Topped Range above steep talus slopes and gently inclined footslopes in the Moresby System (*Mo*) adjacent to Chapman Valley Road on HOWATHARRA. Orthophotograph with contours at 5 m

At the northern end of the plateau on HOWATHARRA there is a double scarp, with the lower scarp at about 220 m AHD and the upper at around 250 m AHD. The lower scarp and plateau have formed in the Cadda Formation, which includes duricrust that is less susceptible to erosion. The upper scarp has formed in the more easily eroded overlying Yarragadee Formation.

Regolith and rock materials

The regolith materials of the Moresby System are derived from weathering and erosion of the underlying dominantly siliciclastic Jurassic strata *(Jc, Jd, Jy)*. There are also exposures in the lower parts of the colluvial footslopes of the Proterozoic Northampton Complex *(PmNO)*.

Cemented pisolitic duricrust is typically exposed on summit surfaces of the plateau, and can be up to 3 m thick ($MoRf_p$). A residual quartz sand, derived from the

Table 6. Components of the Moresby System

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Footslope colluvium *MoC$_f$* 14 809 ha (66%)	Colluvial Footslopes and undivided slopes on hillcrests; mostly southwesterly to westerly facing; dominantly gently inclined; range from 10–240 m AHD; typically 100–150 m AHD Around 1–2 m of colluvium; loose sandy soil over mottled red 10R 4/6 to strong brown 7.5YR 5/8 and grey 2.5YR 5/1, gravelly silty medium sand with ferruginous nodules up to 2 cm; over residual soil of mottled sandy clay to highly weathered silty sandstone	1.7 km northeast of Mount Fairfax (MGA 276070E 6819205N) Uniform slope, with break upslope onto proximal colluvium, and then up onto talus; 0.7 m of pale sand over mottled sandy clay (weathered colluvium) Mottled red 10R 4/6 or strong brown 7.5YR 5/6 and grey 2.5YR 5/1, sandy clay with subangular glassy medium to coarse quartz sand
Talus slope *MoC$_t$* 2 954 ha (13%)	Colluvial Talus slope to escarpment; steep to moderately inclined; range from 50–250 m AHD; typically 160–190 m AHD Weathered rock debris; gravel and boulders in colluvial matrix; mottled grey to red residual soil; abundant weathered rock exposures, including sandstone, siltstone, and limestone, in the upper part of the slope	Howatharra (MGA 269420E 6842975N) Steep scarp to escarpment about 15 m high capped by hard pebbly sandstone horizon 1–2 m thick; below is an exposure of about 6 m of sandstone; above is cemented duricrust gravel and debris of coarse sandstone Highly weathered, white, mottled red, fine- to medium-grained sandstone and pebbly sandstone above debris-strewn slope
Ferruginous duricrust gravel *MoRf$_p$* 2 181 ha (10%)	Residual Hillcrests and summit surface to plateau; moderately to gently inclined; ranging from 190–220 m AHD Ferruginous pisolitic duricrust with nodules up to 3 cm, over mottled soil with nodular appearance (weathered bedrock), over weathered sedimentary rocks	Cooper Street (MGA 270565E 6825975N) About 2 m of duricrust gravel overlain in the central pit area by up to 2 m of gritty sand (relict sand), and underlain by mottled soil; to the west there is some eolian sand over the duricrust Brownish yellow 10YR 6/6 nodules with dusky red 10R 3/4 quartz-rich interiors; subangular to subrounded quartz sand and fine gravel; cutans not fully preserved; minor vein-quartz pebbles up to 7 cm
Hillcrest *MoR$_c$* 773 ha (3%)	Residual Numerous, small, gently to moderately inclined hillcrests; ranging from 50–230 m AHD; mostly 120–170 m AHD Cemented duricrust, mottled soil, and moderately to highly weathered sandstone	Royce Road, White Peak (MGA 269020E 6829800N) Gently inclined hillcrest, with exposures in the roadside Loose nodular gravel, over mottled gravelly soil around 1 m thick, with some small exposures of highly weathered sandstone
Stream channel *MoA$_c$* 696 ha (3%)	Alluvial Stream channel; mostly level to gently inclined; typically 70–150 m AHD; typically 20–70 m wide; comprises stream bed and stream banks; seasonally active Stream bed in fresh weathered bedrock and thin alluvium; banks in eroded slope deposits	Northern end of Davis Road (MGA 270135E 6826800N) Incised stream channel in bedded alluvium over weathered arkose and mottled soil; alluvial sand up to 2 m thick; above the mottled soil is relict gravelly sand about 1.5 m thick Red, yellow, and white streaked alluvial sand over gravelly medium-grained sandstone (arkose)
Drainage depression *MoA$_d$* 480 ha (2%)	Alluvial Level to gently inclined depressions and channels, commonly adjacent to well developed alluvial channels; mostly 120–180 m AHD in tributaries of the Chapman River Slope deposits and alluvium; waterlogged in parts	Skeleton Gully (MGA 273390E 6838050N) Depression 100–200 m wide with a poorly defined channel; minimal clearing of native vegetation; some waterlogged areas and patches of water-dependent vegetation; part of the track seasonally inundated

Table 6. (continued)

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Quartz sand *MoRz* 323 ha (1%)	Residual Several large, sand-dominated patches on hillcrests to the escarpment; gently inclined; mostly 190–230 m AHD Loose, light brownish yellow, slightly gravelly, medium quartz sand over weathered duricrust and mottled soil	Northwest of Wokatherra (MGA 271310E 6833210N) Level hillcrest to escarpment; at least 0.9 m of residual sand over duricrust nodules; sand thickens towards the summit and is absent on the track to the south Very pale brown to yellow 10YR 7/4–7/6, slightly silty, gravelly, fine to medium quartz sand; nodules are weak, weathered, red 2.5YR 4/8, and up to 2 cm across, with thin cutans
Jurassic Cattamarra Coal Measures *Jc* 132 ha (<1%)	Bedrock Scarps, stream beds, eroded slopes, and road cuttings; mostly on gently inclined to steep slopes; up to 210 m AHD Weathered thinly bedded sandstone, gravelly sandstone, and laminated siltstone	Chapman Valley Road (MGA 277565E 6833490N) Roadside cutting in sandstone; 2 m exposed; 0.5 m thick siltstone unit above the sandstone; thickly laminated Moderately to highly weathered; probably slightly ferruginized; pebbly gravelly coarse-grained sandstone; bedding 2–5 cm (very thin); abundant cross-bedding in units 0.3–0.4 m thick; pebbles of subangular quartz and rock up to 2 cm common throughout
Swamp MoA_w 41 ha (<1%)	Alluvial Small, level patches of swampy or waterlogged ground; adjacent to alluvial channels or terrace, or behind dunes Waterlogged alluvial or colluvial silty sand	West of Chapman Road (MGA 267350E 6824650N) Flat area up to 300 m wide behind the Quindalup System dunes; seasonally waterlogged and can flood onto adjacent road Water-dependent vegetation on silty sand
Fan MoA_f 9 ha (< 1%)	Alluvial Level, southerly to southwesterly facing fan about 5–10 m AHD Alluvial silty sand	West of Chapman Road (MGA 267300E 6825250N) Between stream channel upstream and alluvial swamp downstream; fan-shaped deposit of alluvium at the mouth of the channel
Jurassic Cadda Formation *Jd* 8 ha (<1%)	Bedrock Exposures dominantly on the edge of the escarpment, at the top of the talus slope; steep to moderately inclined slopes; mostly 180–200 m AHD, but up to 230 m AHD in the north; forms prominent scarp line on many hills Strongly ferruginized sandy shelly limestone; typically residual material only, with no calcium carbonate preserved	1.8 km north-northwest of Mount Fairfax (MGA 274410E 6819480N) Exposures on both sides of the ridge, and on the opposite ridge, of very pale lichen-covered limestone about 1–2 m thick; above the limestone is less than 0.5 m of ferruginized mudstone, and above that there is ferruginized sandstone and duricrust; below the limestone is siltstone and fine-grained sandstone Slightly weathered sandy limestone with abundant shell debris, largely recrystallized, up to 5 cm across
Proterozoic Northampton Complex *PmNO* 6 ha (<1%)	Bedrock Stream beds and road cuttings; mostly below 150 m AHD Fresh to weathered, undivided granulite and metamorphosed granite gneiss	Murray–Yetna Road (MGA 276420E 6838440N) Roadside exposure of granulite; similar exposures 300 m to the north Fresh to moderately weathered; dark reddish grey 2.5YR 4/1 quartz–garnet(–mafic mineral) psammitic granulite; well developed granoblastic texture 0.2–0.3 mm; massive

Table 6. (continued)

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Landslide scar *MoC*$_l$ <1 ha (<1%) (database only: not shown on map, within *MoC*$_t$)	Colluvial Steep to very steep landslide scars on the western side of Mount Fairfax; southwesterly facing; 110–160 m AHD; up to 200 m long and 40 m wide Gravel to boulder debris; weathered bedrock and mass wasting deposits of sandy clayey silt	Mount Fairfax (MGA 274810E 6817970N) Large-scale erosional feature; with a slump in the lower slope and large blocks dislodged at the scarp; minor outwash downslope from the slump
Proterozoic fine-grained gabbro *Ed* <1 ha (<1%)	Bedrock Stream bed; fresh rock; adjacent to granulite exposures Dolerite or fine-grained gabbro dykes	Howatharra–Nanson Road (MGA 270030E 6840600N) Stream section through mafic dyke cutting banded semipelitic to pelitic granulite Fresh, dark grey, fine-grained gabbro (grain size around 1 mm)

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Figure 15. Duricrust-capped relict plateau (*MoRf*$_p$) above talus slopes (*MoC*$_t$) at the southern end of the Moresby Flat Topped Range. Weathered sandstone exposures on the flanks of Mount Fairfax in the distance (MGA 274410E 6819480N; GSWA Photograph No. 1805)

weathering of the underlying ferruginous duricrust, may be developed on hillcrests (*MoRz*). Weathered and ferruginized bedrock may be exposed on the scarp slope below the duricrust. On the upper scarp, exposed in the northern part of the Moresby System, the weathered bedrock is only weakly ferruginized and is dominantly sand. Talus slopes are well developed on HOWATHARRA, and are composed of bouldery to gravelly colluvium (*MoC*$_t$).

Mass wasting deposits on the colluvial slopes range in thickness from 1 m to more than 8 m (*MoC*$_f$). Weathered rock debris, gravel, and boulders dominate on the proximal slopes. On the more distal slopes, the colluvium grades to gravelly silty sand, which may be indurated and mottled. These deposits rest on weathered bedrock that ranges from a residual soil of mottled sandy clay to highly weathered silty sandstone. Narrow, seasonally active channels on the colluvial sideslopes and footslopes contain small amounts of fluvially deposited silty sandy clay (MoA_c).

Mineral resource potential

The dominant mineral resource potential in the Moresby System on HOWATHARRA is gravel for use as a construction material. The most prospective areas are on the more easily accessible parts of the plateau south of the Nanson–Howatharra Road, where parts of the gravel deposits are currently being worked.

The plateau east of the Chapman Valley Road, between Urch Road and Murphy Norris Road, is relatively easily accessible, and has been worked for gravel at one locality (*8488*). The Moresby Flat Topped Range to the south of Chapman Valley Range is relatively inaccessible, and has no gravel workings. However, there are some hillcrests in the footslopes to the range adjacent to the Narra Tarra – Moonyoonooka Road from which gravel has been extracted.

The more accessible parts of the range to the north of the Chapman Valley Road include some gravel pits, with the largest concentration being west of Yetna. In this area there are three areas intermittently being worked, mostly on gently to moderately inclined hillcrests and adjacent sideslopes.

Three abandoned stone quarries have been identified, although the extensive use of local stone in old buildings in Geraldton and the surrounding areas would indicate that there are other sources that can no longer be identified. The largest of the three is the White Peak quarry (*8355*), although the exact position is uncertain (Fig. 16). There is a small quarry situated on the northeastern end of a small flat-topped hill north of Chapman Road East (*3654*). The smallest quarry is located on the side of a hill 2 km northeast of Wokarena (*8480*), and all are in poorly jointed, bedded sandstone of the Cattamarra Coal Measures.

Active processes and hazards

Rainfall is the only significant agent driving regolith–landform processes in the Moresby System. Erosion is the dominant active process because duricrust and colluvium formation is not currently significant. Heavy rainfall does not normally result in flooding on the free-draining slopes, but it often causes severe channel erosion in the streams, and gully erosion on devegetated and disturbed ground on the scarps and talus slopes (Fig. 17).

Landslides have been noted on some scarps, notably on the western side of Mount Fairfax. Large-scale mass wasting has become more of a hazard since land clearance for grazing and cropping because the now removed native vegetation helped stabilize the slopes. Current agricultural

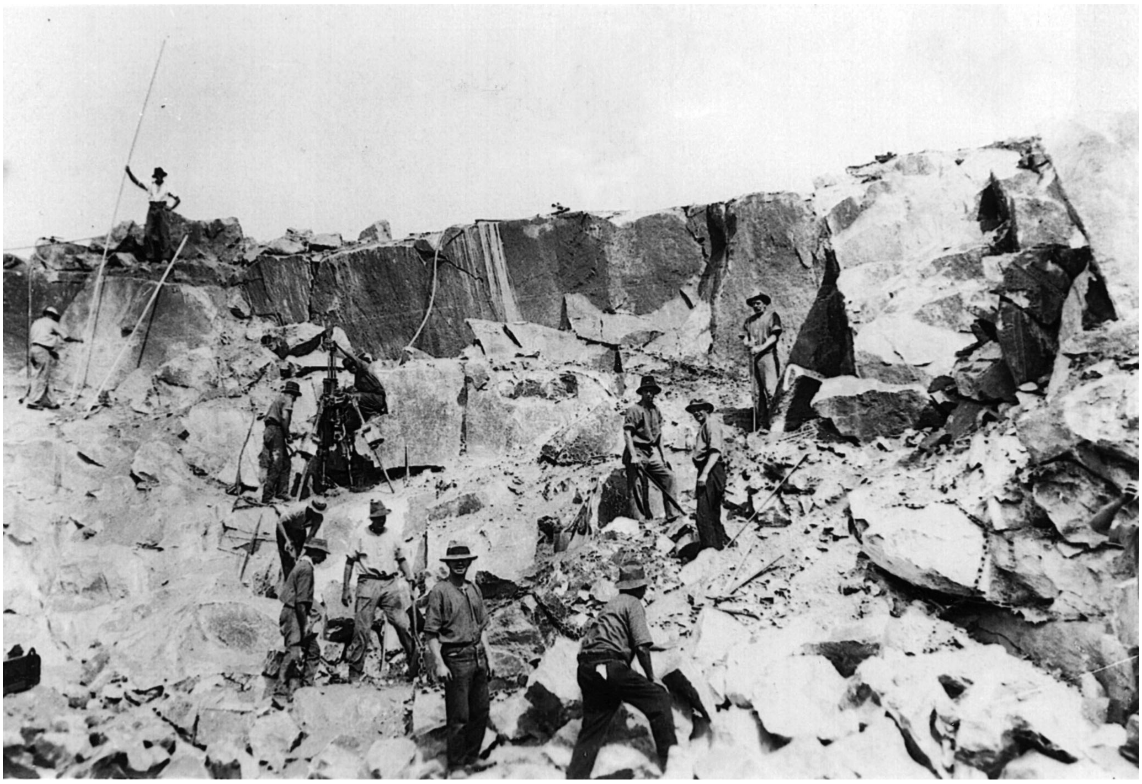

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Figure 16. Quarrymen at work in White Peak Quarry in 1926 (photograph A. C. Burns)

Figure 17. Badlands-style gully erosion on colluvial footslopes to the scarp (*MoC*$_f$), 1 km northeast of Howatharra (MGA 268690E 6842110N; GSWA Photograph No. 1395)

practices can lead to wind erosion of residual and colluvial sand on footslopes and hillcrests, but this is not a significant process on HOWATHARRA.

Landuse, vegetation, and drainage

Land within the Moresby System is mostly used for farming, and the land has mostly been cleared for cropping and grazing. Recently, high-value crops such as grapes and fruit trees have been introduced in areas where the water supply is good.

Some of the steeper sideslopes and gravelly summit surfaces of the plateau are only partially cleared of native vegetation, and there are also large areas of native bush, including several reserves. The four Class A nature reserves in the Moresby System on HOWATHARRA are Wokatherra, Oakajee, Howatharra, and Bella Vista.

The distal footslopes to the Moresby Flat Topped Range east of the City of Geraldton are mostly very gently inclined, and in the Waggrakine district are now being used for high-density urban development. Further south, these slopes extend down to the Chapman River, where they are deeply incised by the river channel.

There are numerous drainage channels feeding from the talus slope through the colluvial footslopes into either the Chapman River or one of several streams that traverse the adjacent Northampton System. These include the Oakabella Creek, Oakajee River, and Buller River. All these channels are active in the wetter winter months, with little or no water present in the dry season.

The largest drainage pattern in the Moresby System is along Skeleton Gully, which extends southwards from the northern edge of the sheet. This gully includes extensive drainage depressions as well as channelled sections, and is distinct from the terraced channels of the Chapman River to the south. Dolby's Gully, draining from the Moresby Flat Topped Range towards Drummond Cove, is the only stream in the Moresby System to extend nearly to the coast. Unlike the incised streams to the north, this one debouches into a small alluvial fan behind the Quindalup System dunes.

Relationships

The plateau that characterizes the Moresby System is a relict of the plateau that forms the Casuarina System to the north. The scarp, talus slope, and footslopes of the Moresby System distinguish it from the Casuarina System.

Erosion of weathered rocks underlying the Moresby System is a source of material for the alluvial deposits of both the Greenough System and the Greenough Alluvium System. The Moresby System passes laterally downslope into the Greenough System in Chapman Valley. East of the Moresby Flat Topped Range, the Moresby System is cut by the Chapman River and overlain by the Greenough Alluvium System.

The colluvial footslopes and associated channels of the Moresby System also pass downslope into the low hills of the Northampton System. The distinction between the two systems is based primarily on the relationship of the hillslopes to the prominent escarpment formed in Jurassic rocks, so there are scattered exposures of Northampton Complex metamorphic rocks in the Moresby System footslopes.

Geological history

The Moresby System is underlain by Jurassic (205–141 Ma) sedimentary rocks (Playford et al., 1976) that have been weathered and eroded to form a dissected plateau surface of Cainozoic age (65–1.8 Ma). The Jurassic strata are here divided into three formations, the Cattamarra Coal Measures, Cadda Formation, and Yarragadee Formation, with the Cadda Formation including the very distinctive Newmarracarra Limestone unit. To the north and east of Geraldton this plateau is underlain in part by Cretaceous rocks (141–65 Ma), which are also weathered.

Duricrust formation was probably mostly during the Oligocene (34–24 Ma; Hocking et al., 1987), but may have extended back to the Middle to Late Eocene (55–34 Ma; van de Graaff, 1983) as sea levels fell from highs of up to 300 m above the present level. Duricrust development in the Newmarracarra Limestone, involving total removal of the carbonate, has created a distinctive, hard layer that is a dominant factor in the development of an erosional scarp in the plateau.

The erosion of the plateau to form the scarp and colluvial slopes pre-dates the deposition of the eolian sands of the Pleistocene (1.8–0.04 Ma) Spearwood System because the slopes are covered in part by remnants of that system on the western flanks of the Moresby Flat Topped Range. The maximum age of the colluvium is unknown, but it probably post-dates the last major transgression in the Miocene (24–5 Ma). The widespread preservation of mottling and induration of the deposits indicates that they have been weathered in situ, and that they have not been significantly eroded since formation.

The development of an alluvial fan behind the Quaternary dunes near Drummond Cove indicates that fluvial processes have continued to the present day.

Casuarina System (*Ca*)

Land of the Casuarina System occupies 2250 ha (3%) of HOWATHARRA (Fig. 18, Table 7), and is an undulating plateau composed of residual sand overlying weathered Jurassic sedimentary rocks. The cemented pisolitic duricrust on low scarps is a minor source of gravel, and sand has also been extracted from within the system.

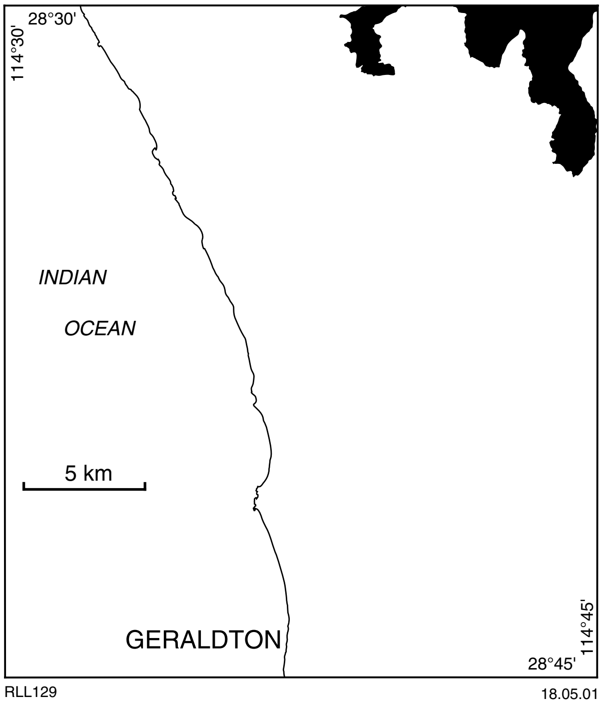

Figure 18. Distribution of the Casuarina System (*Ca*) on HOWATHARRA

Landform and distribution

The Casuarina System is a plateau comprising gently inclined slopes, dominantly easterly facing, with broad, flat fluvial channels draining to the south (Fig. 19). The system was first described by Rogers (1996), who defined the landforms over a much larger area as dominantly level to gently undulating sandplain. The system ranges in altitude from 150 m AHD in the south to over 250 m AHD at the northern edge of the sheet.

The Casuarina System occupies two areas on the northern edge of HOWATHARRA. Both areas are bounded to the west, at least in part, by a scarp slope in the adjacent Moresby System. Erosion of the plateau on its eastern margin has exposed rocks of the Northampton Complex underlying the Northampton System.

Regolith and rock materials

The regolith materials of the Casuarina System are derived from the weathering of the underlying Jurassic sedimentary rocks, mostly belonging to the Cadda *(Jd)* and Yarragadee Formations *(Jy)*. These siliciclastic sedimentary rocks weather to form ferruginous duricrust overlying mottled residual soil (Fig. 20). The duricrust has decomposed in situ to form a thick veneer of sand over the plateau (*CaRz*), which has not been severely eroded, unlike the adjacent Moresby System.

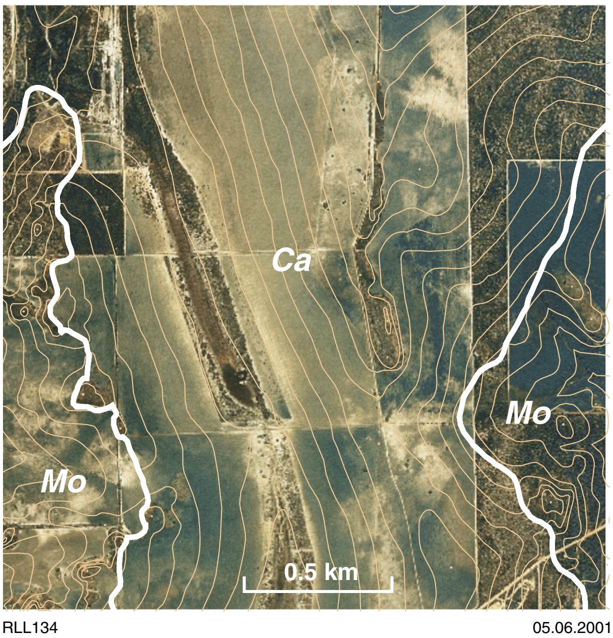

Figure 19. Swampy drainage depression in undulating residual sandplain of the Casuarina System, with a gravelly hillcrest to the right (*Ca*), adjacent to the Moresby System (*Mo*), west of Narra Tarra. Orthophotograph with contours at 5 m

Mineral resource potential

The mineral resource potential of the Casuarina System is limited because the area is dominated by a thick cover of quartz sand. The sand is not often extracted because better material is available in the Spearwood System. However, there is a large sand pit that is now the site for the Shire of Nabawa's refuse disposal located on the Nabawa–Yetna Road (*8467*).

Exposures of duricrust suitable for gravel extraction are not common because the veneer of sand has been eroded away only on a few hillcrests. There is only one gravel pit in the area (*8468*), adjacent to the Nabawa–Yetna Road, where at least 2 m of cemented duricrust gravel is now exposed in the pit walls.

Active processes and hazards

The only significant agent driving regolith–landform processes at present is rainfall. Erosion by sheetwash, however, is minor, and the free-draining nature of the thick sandy soils has significantly reduced the possibility of gully erosion or channel formation. The broad drainage

Table 7. Components of the Casuarina System

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Quartz sand *CaRz* 2 106 ha (94%)	Residual Gently inclined, dominantly easterly to southeasterly facing slopes; mostly 180–250 m AHD Thick residual quartz sand over weathered duricrust; yellowish brown 10YR 5/8 to brownish yellow 10YR 6/8, slightly silty, fine to medium quartz sand	North of Nabawa–Yetna Road (MGA 278460E 6842220N) Very gently inclined hillcrest in low hills; at least 1.2 m of residual sand Yellowish brown 10YR 5/8, slightly silty, fine to medium quartz sand; mostly less than 0.35 mm; poorly sorted up to 1 mm
Hillcrest CaR_c 77 ha (3%)	Residual Mostly moderately to gently inclined slopes on hillcrests ranging up to 240 m AHD Cemented duricrust gravel overlying mottled soil	Gravel pit, Nabawa–Yetna Road (MGA 278575E 6841490N) Gently inclined hillslope in low hills; shallow pit in at least 2 m of uniform cemented duricrust gravel Mottled red 10R 5/6 and brownish yellow 10YR 6/6 to pale yellow 2.5YR 7/4 pisolitic duricrust; nodules 10–20 mm with red rinds; cutans thin or absent; cores of medium quartz sand
Drainage depression CaA_d 62 ha (3%)	Alluvial Level to gently inclined depression up to 260 m wide; 150–200 m AHD, draining south Waterlogged grey silty sand	North of Nabawa–Yetna Road (MGA 277260E 6843520N) Waterlogged, level alluvial swamp; vegetation was cleared right through the hollow but rising water tables necessitated revegetation Light grey sand below a dark grey organic layer

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Figure 20. Northwesterly facing scarp composed of cemented duricrust gravel over mottled soil, on a hillcrest (CaR_c) at the edge of the Casuarina System sandplain (MGA 277120E 6842295N; GSWA Photograph No. 1382)

depressions have been enhanced by clearing of native vegetation, and, although not subject to flooding, they can become waterlogged in the wet season.

Wind erosion is a minor problem in this area, but to the southwest of Geraldton the Victoria Plateau is locally characterized by eolian dunes. The steeper slopes of this part of the plateau are dominated by fluvial processes that do not allow eolian features to form.

Landuse, vegetation, and drainage

The land has been extensively cleared of native vegetation, although there are some remnants in the drainage depressions and in blocks such as the Protheroe Nature Reserve located west of Narra Tarra Mine. The dominant agricultural activities are grazing and cereal production.

The Casuarina System is characterized in part by the absence of major drainage channels. There are some minor channels on slopes between the Casuarina and Moresby Systems. The dominant drainage landform is drainage depressions, in which the slopes grade from the adjacent hillside into an indistinct channel, often marshy and sometimes forming small seasonal ponds.

Relationships

The dominant plateau landform of the Casuarina System is similar to the plateau on the Moresby Range, which forms part of the Moresby System. These plateaus are contiguous in the northern part of HOWATHARRA, lying mostly around 180 to 250 m AHD. Erosion of the Casuarina System plateau is minor compared to that in the Moresby and Northampton Systems.

Geological history

The Casuarina System is underlain by flat-lying Jurassic (205–141 Ma) sedimentary rocks (Playford et al., 1976). These strata have been weathered and eroded to form a plateau surface of Cainozoic age (<65 Ma). The dominant underlying unit is the Yarragadee Formation, but the plateau is also eroded down through the Cadda Formation and Cattamarra Coal Measures. To the north and east of HOWATHARRA this plateau is underlain in part by Cretaceous rocks (141–65 Ma).

Thick duricrust covers the undulating eroded land surface formed in the Jurassic strata, and was probably developed mostly during the Oligocene (34–24 Ma; Hocking et al., 1987). Duricrust formation may also have extended back to the Middle to Late Eocene (55–34 Ma; van de Graaff, 1983) as sea levels fell from highs of up to 300 m above the present level. The weathering of the duricrust in situ to form the present thick blanket of quartz sand probably pre-dates the deposition of the eolian sands of the Pleistocene (1.8 – 0.04 Ma).

Spearwood System (*Sp*)

The Spearwood System occupies 7300 ha (11%) of HOWATHARRA (Fig. 21, Table 8), and is equivalent to the Pleistocene Tamala Limestone. The system is composed of residual sand overlying calcarenite in a series of deflated dunes, with extensive exposures of limestone in relict coastal cliffs (Fig. 22). The sand is worked in small pits for use in the building industry, and the calcarenite is a potential source of rock for land reclamation. Heavy mineral occurrences have been identified in the Chapman Valley and around Wokarena, but the resource potential for this commodity is low when compared to the proven resources in strandlines such as those at Eneabba to the south.

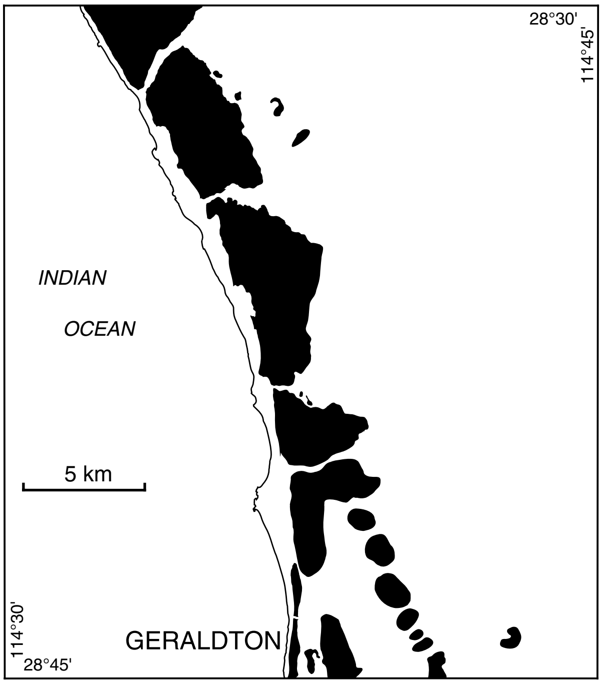

Figure 21. Distribution of the Spearwood System (*Sp*) on HOWATHARRA

Landform and distribution

The Spearwood System is a series of large, gently inclined dunes, some with moderately steep rocky slopes, mostly facing west to west-southwest (Fig. 22). The system was first described by Rogers (1996) as the Tamala System. Rogers (1996) defines the landforms as low hills parallel to the coast. Physiographically, the system is referred to as the Spearwood Dune System (McArthur and Bettenay, 1960). The dominantly eolian deflated dunes and swales have been formed by southerly winds, and morphologically are a combination of parabolic, longitudinal, and transgressive barrier dunes.

The dunes have been eroded by coastal processes that were active about 125 000 years ago to form a series of westerly to west-southwesterly facing scarps that extend from Drummond Cove to the northern edge of the sheet. Fluvial or estuarine processes, probably active at the same time, have produced similar scarps along Oakabella Creek, Oakajee River, and Buller River. Associated with this old coastline, which formed at a 5 m sea-level high, there is a rare marine facies of biogenic reef that can be seen at Cape Burney on GERALDTON (Johnson et al., 1995).

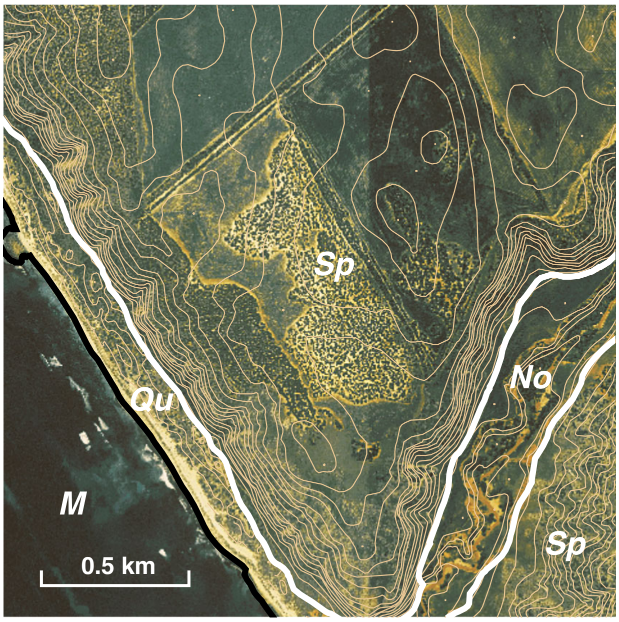

Figure 22. Tamala Limestone exposed in the Spearwood System (*Sp*) on HOWATHARRA. Degraded scarps and cliffs are cut into gently inclined deflated dunes with limestone beneath densely vegetated areas. Adjacent to the Marine System (*M*) and dunes of the Quindalup System (*Qu*) to the west, and cut by Oakabella Creek in the Northampton System (*No*). Orthophotograph with contours at 5 m

The Spearwood System is best described as three discrete areas. The largest of these is a broadly continuous belt that extends parallel to the coast from the City of Geraldton to the northern edge of the sheet. This belt is separated from the Marine System by a near continuous belt of the Quindalup System ranging from 150 m to over 1 km wide.

The second area is composed of a number of isolated relict dunes on the western flanks of the Moresby Flat Topped Range. To the north these dunes are contiguous with the belt of coastal dunes, but are isolated from the Quindalup and Marine Systems by their position on the colluvial footslopes of the Moresby System.

The smallest area is a single relict dune that lies adjacent to the Narra Tarra – Moonyoonooka Road in the Chapman Valley. The dune lies between the Moresby and Greenough Systems, and probably relates to a higher sea-level stand when the area was marine to estuarine.

Regolith and rock materials

The Spearwood System is dominated by two types of regolith and rock materials. The dominant exposed

Table 8. Components of the Spearwood System

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Deflated dunes *SpE* 5786 ha (79%)	Eolian Low hills and rises of deflated transgressive barrier, parabolic, and longitudinal dunes; dominantly southwesterly to westerly facing slopes to dune ridges; dominantly gently inclined; mostly 75–95 m AHD, ranging from 10–135 m AHD Yellowish brown 10YR 5/8 to reddish yellow 7.5YR 6/8 residual quartz sand over calcarenite; minor exposures of calcrete over calcarenite	Coronation Beach Road (MGA 263540E 6840285N) Shallow sand pit excavated to 1.5 m depth; some exposed calcrete 0.5–1.0 m across Reddish-brownish yellow 7.5-10YR 6/8, slightly silty, medium quartz sand with minor black mineral or oxide
Calcarenite *SpEk* 763 ha (10%)	Eolian Gently to moderately inclined, southwesterly to westerly facing slopes; hillcrests and ridges exposing the cores of the dune system; mostly 50–120 m AHD White to pale brown calcrete above calcarenite composed of lithified carbonate-rich shell and quartz sand; locally overlain by brown to reddish brown residual sand	About 1.5 km north of the Buller River (MGA 266525E 6831235N) Abundant exposures of Tamala Limestone extending at least 300 m west towards the coast; overlain by residual sand Brownish red, medium quartz sand over calcarenite
Calcarenite *SpAk* 310 ha (4%)	Alluvial Degraded scarp or cliffs; moderately inclined to steep scarp slopes adjacent to incised stream channel; mostly 30–80 m AHD White to pale brown calcrete above calcarenite composed of lithified carbonate-rich shell and quartz sand; calcarenite and calcrete rock fragments	Adjacent to Oakabella Creek (MGA 261900E 6842100N) Extensive slopes dominated by calcarenite (Tamala Limestone) exposures and patches of calcarenite debris; above rubbly footslopes
Footslope colluvium SpC_f 277 ha (4%)	Colluvial Footslopes to degraded scarp of coastal calcarenite; dominantly gently inclined, with moderately inclined upper slopes; some level to very gently inclined lower slopes; mostly southwesterly to westerly facing; 5–40 m AHD, up to 75 m AHD Decomposed calcareous eolian shell and quartz sand; calcarenite and calcrete rock fragments	North of the Buller River near the coast (MGA 266285E 6829900N) At least 1.0 m of gravelly soil on the level distal footslopes to the limestone escarpment Strong brown 7.5YR 4/6, dense, silty, slightly gravelly, medium quartz sand with limestone fragments
Calcarenite *SpBk* 164 ha (2%)	Coastal Degraded scarp or cliffs; moderately inclined to steep scarp slopes on palaeoshoreline; southwesterly to westerly facing; mostly 15–75 m AHD White to pale brown calcrete above calcarenite composed of lithified carbonate-rich shell and quartz sand; calcarenite and calcrete rock fragments	North of the Buller River (MGA 266285E 6830775N) Moderately inclined degraded scarp in exposed limestone with a progressively shallowing footslope facing west; partially covered by younger dune sand
Swampy swale SpE_w 14 ha (< 1%)	Eolian Seasonally waterlogged hollow in dune system; level to gently inclined; 3–4 m AHD Peaty or organic soil over residual quartz sand	North of Drummond Cove (MGA 266900E 6827600N) Level ground with water-dependent vegetation; waterlogged swale behind younger dunes

regolith was deposited as calcareous dune sand, but has weathered by surface leaching and groundwater precipitation to form yellow and red residual quartz sand (*SpE*; Fig. 23). This lies above a white to light brown, strong calcrete (*SpEk*). The calcrete is a relatively thin, hard surface-coating to the underlying variably lithified calcarenite (limestone), which is the dominant composition of the material at depth. The calcarenite, calcrete capping, and residual sand are usually referred to as the Tamala Limestone (Fig. 24). The coarse- to medium-grained calcarenite is composed largely of skeletal fragments of foraminiferids and molluscs, with variable amounts of quartz sand.

The footslopes to the scarps that lie both parallel to the coast and along major drainage lines are composed of calcareous colluvium (SpC_f). These formed during the marine regression by disintegration and erosion of the adjacent limestone scarp that was created at the previous sea-level highstand (*SpBk, SpAk)* .

Mineral resource potential

The Spearwood System is a source of building sand, and is a potential source of construction limestone and fill material for land reclamation. There are a number of small pits in the area from which sand is being or has been extracted (Fig. 23).

Sand is widespread throughout the system, but is of variable quality. The more silty red sands are preferred for building pads, and these are commonly located close to the limestone. Nearly all areas of the Spearwood 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 dominantly on coastal scarps, but include some parts of hillcrests. The limestone is either sparsely vegetated or covered in remnant vegetation.

Mineral exploration has identified areas on the west side of the Chapman Valley (*8405*; Yates, 1991) and east of the North West Coastal Highway near Wokarena (*8406*; Woods and Associates, 1991) that are prospective for heavy minerals. These concentrations include titanium and zirconium minerals as well as garnet. The potential for finding economic concentrations of heavy mineral sands is considered to be poor.

Active processes and hazards

Rainfall and wind erosion are minor agents driving current regolith–landform processes in the Spearwood System. There are no known significant hazards in the Spearwood System, although there is a risk associated with the steeper limestone slopes where rock overhangs and evidence of rock collapse have been recorded.

Landuse, vegetation, and drainage

The Spearwood System has been extensively cleared for cropping and grazing, dominantly in areas where the soil

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Figure 23. Light yellowish brown 10YR 6/8 residual quartz sand (*SpE*) in a sand pit adjacent to the North West Coastal Highway (MGA $_2$67965E $_{68}$31405N; GSWA Photograph No. 458)

is sandy. Urban development has extended from the City of Geraldton onto the dunes both to the east and north. This land is favoured for urban development because the soils are agriculturally poor, and because of the elevated position the land affords. There are plans for industrial development on the large dunes around the Oakajee River.

Areas underlain by limestone are mostly uncleared, particularly on the steeper slopes facing the ocean. The limestone exposures on dunecrests are commonly uncleared or partially cleared because the ground is unsuitable for most agricultural activities.

The sandy soils are free draining, and there are no mappable channels or streams. There are, however, several major drainage channels cutting the Spearwood System that are part of the Northampton System.

Relationships

The sand and limestone of the Spearwood System sit above colluvial deposits of the Moresby and Northampton Systems. They are interbedded with fluvial deposits of the

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Figure 24. Tamala Limestone rubble on the coastal scarp (*SpBk*) above colluvial slopes (*SpC_f*) of the Spearwood System, 1 km north of the Buller River (MGA 266285E 6830775N). Parabolic dunes (*$QuE1_a$*) of the Quindalup System in the background (GSWA Photograph No. 1440)

Greenough Alluvium System in the northern part of the City of Geraldton. The dunes of the Spearwood System are overlain by the dunes of the Quindalup System in a broad belt parallel to the coast.

Geological history

The Spearwood System is the equivalent of the Pleistocene (1.8–0.04 Ma) Tamala Limestone, which is fully described by Playford et al. (1976). The Tamala Limestone formed as a series of dunes and associated minor marine deposits that also form several lines of offshore islands and reefs. The best examples of these islands are within the Houtman–Abrolhos Group, 50 to 100 km west of Geraldton. Locally, the offshore reefs are dominantly composed of Tamala Limestone, which was formed by eolian processes and eroded by coastal processes during various sea-level high- and lowstands. The edge of the nearshore platform and included reefs marks a sea-level low of about –20 m AHD that probably dates from about 80 ka.

The best constrained of the sea-level highstands on HOWATHARRA is associated with the deposition of a marine reef facies (Johnson et al., 1995), and a line of sea cliffs 0.25 to 1.2 km inland from the present-day coast. The reef has been constrained in age to a narrow interval from about 128 to 121 ka (Stirling et al., 1998). The sea cliffs associated with this interglacial sea-level highstand either lie behind Holocene dunes of the Quindalup System, or are partially obscured by these younger dunes. The dunes were lithified to limestone prior to being over-steepened by marine erosion at a coastline that was about 5 m above the present sea level. Fluvial erosion of the scarp followed, and these eroded slopes are now composed of limestone exposures or are covered by colluvial deposits of pre-Holocene age.

Greenough System (*Ge*)

The Greenough System occupies 2950 ha (4%) of HOWATHARRA (Fig. 25, Table 9), and is composed of alluvial terraces and channels in the middle reaches of the Chapman River (Fig. 26). The system may be a source of sand and gravel for construction, or clay for brickmaking.

Landform and distribution

The Greenough System is characterized by dominantly level to very gently inclined fluvial terraces, and locally moderately steep to cliffed terrace scarps adjacent to channels of the Chapman River. The Greenough System lies adjacent to the plateau and hills of the Moresby System, and low hills of the Northampton System, from which the colluvial footslopes pass laterally downslope into the terraces of the Greenough System (Fig. 26). The river channel that characterizes the system drops from 120 m AHD at the edge of NANSON to 40 m AHD where the Chapman River passes onto GERALDTON.

The Greenough System is a regionally significant system that was mapped by Rogers (1996) to include the river beds, terraces, and flats associated with the Greenough, Murchison, Hutt, and Chapman river systems. The Greenough System only occurs in the east of HOWATHARRA, mostly in a single, northerly trending area that extends through the sheet.

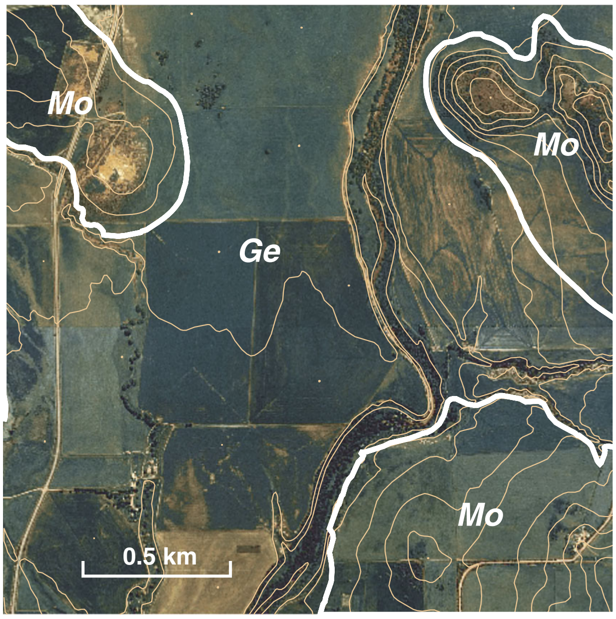

Figure 26. Broad alluvial terrace cut by the Chapman River in the Greenough System (*Ge*) on HOWATHARRA, adjacent to low hills and scarps in the Moresby System (*Mo*). Orthophotograph with contours at 5 m

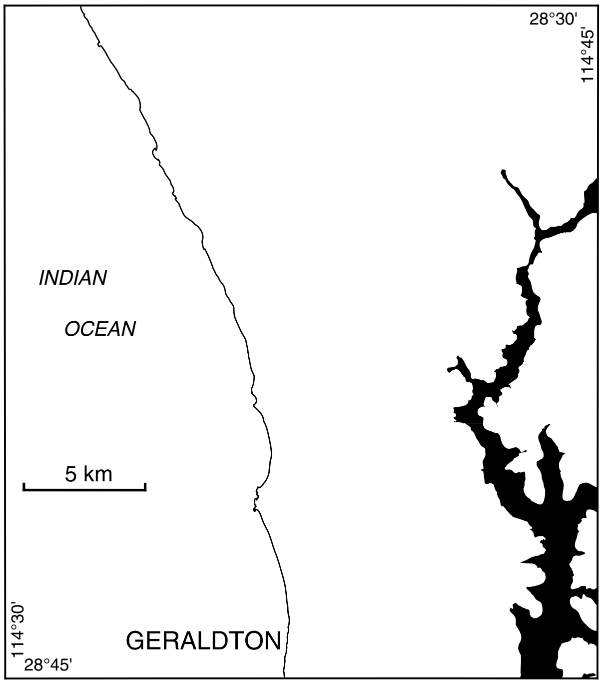

Figure 25. Distribution of the Greenough System (*Ge*) on HOWATHARRA

Regolith and rock materials

The Greenough System formed by fluvial deposition from the Chapman River on terraced flood plains and in valleys between the adjacent escarpments (GeA_l). The alluvium in the terraces is typically yellowish red 5YR 4/6 silty sand, gravelly in parts, with grey clay horizons (Fig. 27). Incised channels in the terraces expose up to 10 m of silty sand in the stream banks (GeA_c). The stream channels are dominantly erosional, with some rock exposures and minor deposits of sandy silt. The rocks in the streams belong to both the Northampton Complex *(EmNO)* and overlying Jurassic Cattamarra Coal Measures *(Jc)*.

Mineral resource potential

The terraces in the Greenough System contain clayey and silty alluvial deposits that could be a source of sand and gravel for fill. There is only one pit from which fluvial deposits of sand and gravel have been extracted, and no indication that these materials have been worked recently. There is some mineral resource potential for brick clay, with samples from one locality at Narra Tarra proving suitable (*6519*).

Active processes and hazards

The only significant active processes are stream erosion, flooding, and sedimentation associated with rainfall. Heavy rainfall can cause local flooding in poorly drained depressions on the terraces adjacent to the Chapman River,

Table 9. Components of the Greenough System

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Alluvial terrace GeA_t 2 312 ha (78%)	Alluvial Terrace, locally incised by stream channels (stream bed and stream banks); dominantly level to very gently inclined; southeasterly to southwesterly facing; mostly 50–100 m AHD; up to 125 m AHD Yellowish red to red, gravelly to silty sand; some grey clay	Morrell Road, Narra Tarra (MGA 277835E 6823860N) Roadside cutting 4 m high About 0.5–0.8 m of red silty sand, over 2 m of red gravelly sand and gravel, over at least 1 m of grey clay with red mottling
Stream channel (bed and banks) or banks GeA_c 370 ha (12%)	Alluvial Gently to moderately inclined stream banks and adjacent level stream bed; mostly 50–120 m AHD Banks in terrace sand, gravel, and clay; some rock exposures in the bed	Close to the Chapman River, 1.7 km east of Mount Sommer (MGA 274775E 6828825N) Incised distal sheetwash with some poor bedding where reworked adjacent to the incised stream channel; gullying and erosion of the channel sides; exposed rock in the stream bed Jurassic conglomerate; pebbly sandstone with smooth, subrounded white quartz up to 12 cm
Stream bed GeA_b 182 ha (6%) (database only: not shown on map, within GeA_c)	Alluvial Bed up to 150 m wide adjacent to stream banks, or bed with very narrow (<5 m) banks; mostly level, locally gently to moderately inclined; 40–100 m AHD; often water-filled Silt, sand, gravel, and boulders; some rock exposures	Farm track across the Chapman River, Yetna (MGA 277380E 6832700N) Narrow stream bed, less than 40 m across; shallow water, seasonally flooded Sand and gravel; minor silt
Drainage depression GeA_d 33 ha (1%)	Alluvial Depression up to 200 m wide; numerous small channels; level to very gently inclined; 50–70 m AHD and also around 100 m AHD Silty sand and clay; partially waterlogged	West of Narra Tarra – Moonyoonooka Road (MGA 277300E 6819350N) Level area with a number of shallow, indistinct channels leading south into a single stream channel Seasonally waterlogged or flooded alluvial terrace deposits; mostly silty sand
Channel bench GeA_e 32 ha (1%)	Alluvial Narrow bench up to 125 m wide between stream channel bed and stream banks; level to gently inclined; several around 45–70 m AHD, and one 120–130 m AHD Silty sand and clay; seasonally waterlogged or flooded	Chapman River near Morrell Road, Narra Tarra (MGA 277700E 6823840N) Channel bench about 0.5–1.0 m above the stream bed of the Chapman River; 1.3 km long and up to 125 m wide, on the north side of the river Silty sand and clay, with some rock exposures adjacent to the channel
Swamp GeA_w 26 ha (1%)	Alluvial Swampy drainage depressions or hollows; level to very gently inclined; 70–90 m AHD Silty sand and clay; seasonally waterlogged	Between the Chapman River and Morrell Road (MGA 276760E 6826950N) Swampy area up to 400 m across, formed on a drainage line between the alluvial terrace and adjacent footslopes Water-dependant vegetation on silty, clayey sand
Jurassic Cattamarra Coal Measures *Jc* <1 ha (<1%)	Bedrock Single exposure in a low rise on the alluvial terrace, less than 100 m across	2 km northeast of Red Hill (MGA 274805E 6828190N)

Table 9. (continued)

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Jurassic Cattamarra Coal Measures (cont.)	Weathered sandstone and siltstone	Small scarp, exposing 6–8 m of weathered rocks ranging from siltstone to conglomerate (exposed at the top of the scarp); no duricrust development, and only minor ferruginization Pebbly sandstone (conglomerate) with clasts of white subrounded vein quartz typically 5–10 cm across, and white weathered gravelly siltstone – fine-grained sandstone (arkose)
Proterozoic Northampton Complex *ꝐmNO* <1 ha (<1%)	Bedrock Small exposures in the stream bed of the Chapman River and tributaries Semipelitic granulite, granite, and pegmatite	1 km west of Narra Tarra on the south side of stream bed (MGA 277610E 6823800N) Exposures of finely banded fine-grained semipelitic granulite and coarse-grained granite and pegmatite up to 1 m thick; sand, gravel, and boulders in the stream
Proterozoic dolerite or fine-grained gabbro *Ꝑd* <1 ha (<1%)	Bedrock Small exposure in a stream bed Mafic dyke adjacent to exposures of granulite	Chapman Road East (MGA 278070E 6824665N) 4 m-deep stream channel about 25 m wide, with exposures of gabbro and granulite. Inferred dyke contact probably trends north or northeast Fresh, dark grey, very strong, very fine grained gabbro (~0.1 mm)

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Figure 27. Alluvial terrace in the Greenough System (*GeA_t*) exposed in 4 m-high road cutting north of the Narra Tarra bridge on Morrell Road (MGA 277835E 6823860N), showing silty sand over gravelly sand and grey clay (GSWA Photograph No. 1810)

and severe channel erosion both in the river and its tributaries. The moderately inclined stream banks can be undercut by stream erosion in times of flood, and in places show signs of previous collapse.

Landuse, vegetation, and drainage

Land within the Greenough System is mainly used for grazing and cropping, with no urban or industrial development. Much of the native vegetation has been cleared, except in the Chapman River channel. Most of the channel is reserved as Vacant Crown Land.

The Chapman River is an important regional drainage channel, extending from Yuna, about 65 km northeast of Geraldton, to the ocean at Geraldton. The river channel widens from about 90 m at the edge of the NANSON sheet, to between 150 and 250 m wide at the edge of the GERALDTON sheet. Water volumes in the channel are markedly seasonal in flow, reducing to a shallow, easily traversed stream in the dry season.

Relationships

The Greenough System passes to the southwest into the Greenough Alluvium System on GERALDTON. The boundary between these two systems is defined by a change in landform from narrow terraces to a broad alluvial plain. The source of the material in the Greenough System is, in part, the weathered sedimentary rocks and duricrust of the surrounding Moresby and Northampton Systems, but there is also a contribution from the catchment to the east along Chapman River East and northeast along the Chapman River.

There is a sand dune of the Spearwood System situated on the flanks of the Moresby Flat Topped Range to the east of Mount Fairfax, adjacent to the terraces of the Greenough System. The dune probably pre-dates the formation of the terrace surface.

Geological history

The fluvial deposits in the Greenough System are similar in age to the eolian dunes of the Spearwood System. Some of the terrace formation can probably be assigned to the Pleistocene red alluvium unit of Wyrwoll (1984). This unit post-dates the 120 ka marine transgression closer to the present-day coast, but can only be constrained at the upper end to being older than 40 ka. Although aggradation took place over a considerable period, the nature of the deposits indicates that infrequent large-scale flood events in a braided stream environment were the dominant mechanism of deposition (Wyrwoll, 1984). There is very little evidence of Holocene deposition; the dominant present-day features are deep channels in eroded terraces.

Greenough Alluvium System (*Ga*)

The Greenough Alluvium System occupies less than 400 ha (1%) of HOWATHARRA (Fig. 28, Table 10), and is the result of the development of an alluvial plain on the Chapman and Greenough rivers. The system is a potential source of sand and gravel.

Landform and distribution

The Greenough Alluvium System is a level alluvial plain with a narrow stream channel. The 10–15 m-high banks to the channel are moderately steep to steep, and cliffed in some places. The system has formed by fluvial deposition from the Chapman River on flood plains between dunes of the Spearwood and Quindalup Systems, and the footslopes to the Moresby System inland (Fig. 29).

The Greenough Alluvium System is confined to an area adjacent to the Chapman River behind the sand dunes in the northern part of the City of Geraldton. The plain here ranges in altitude from 5–12 m AHD, and the stream bed of the Chapman River drops from 10 m AHD to below sea level in the tidal part of the river channel.

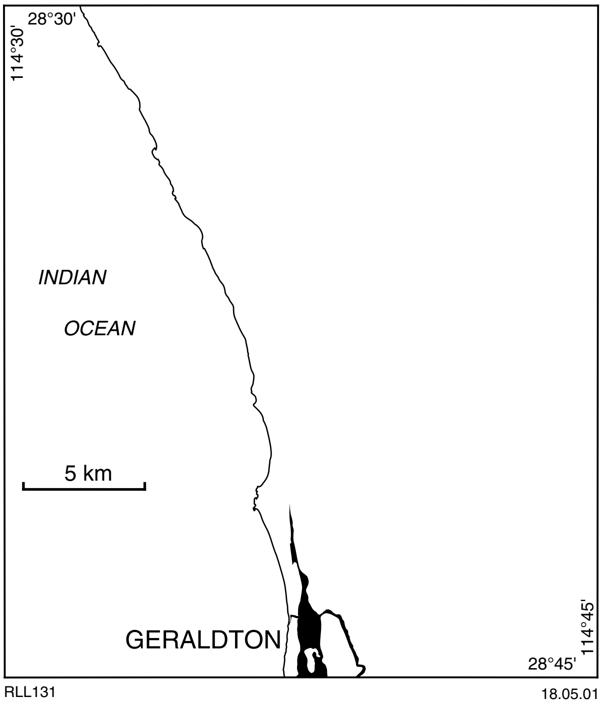

Figure 28. Distribution of the Greenough Alluvium System (*Ga*) on HOWATHARRA

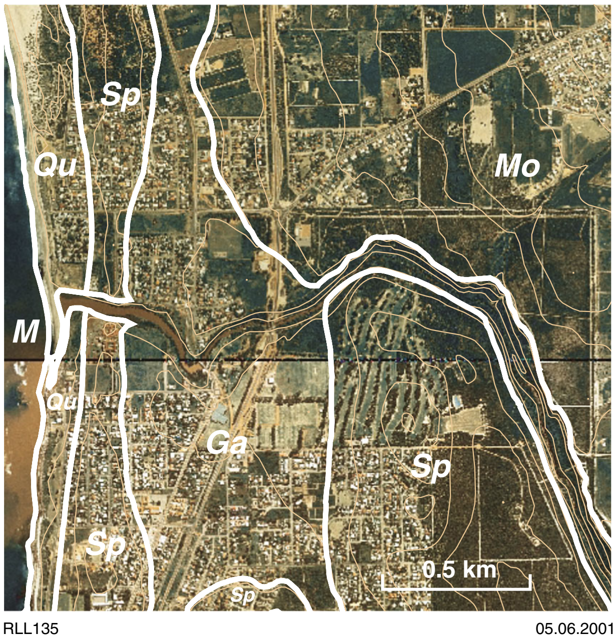

Figure 29. Chapman River channel and narrow alluvial plain in the Greenough Alluvium System (*Ga*) to the north of the City of Geraldton on HOWATHARRA. Adjacent to gently inclined footslopes of the Moresby System (*Mo*) to the east, and dunes of the Spearwood System (*Sp*), with the Marine System (*M*) and younger dunes of the Quindalup System (*Qu*) to the west. Orthophotograph with contours at 5 m

Regolith and rock materials

The Greenough Alluvium System on HOWATHARRA was formed by fluvial deposition from the Chapman River (*GaAa*). The alluvium is dominantly firm to stiff, slightly sandy clay with minor sand and gravel. Limestone clasts up to cobble size may be present, and some areas include grey clay horizons. The river bed and banks include exposures of Tamala Limestone and Jurassic sedimentary rocks.

Mineral resource potential

The Greenough Alluvium System contains alluvial deposits that are a potential source of sand and gravel for fill. There is a rehabilitated pit within these fluvial deposits located north of Eastbourne Road, Sunset Beach (*8447*), although the pit also extends into sand of the adjacent Spearwood System.

Active processes and hazards

Historically, the most significant process with an associated hazard is flooding of the Chapman River. There are many newspaper accounts of flooding, notably in 1862, 1872, 1888, and 1952. As recently as 1999, large parts of the Greenough Flats and Chapman River – Bootenal – Walkaway area on GERALDTON were flooded following heavy rain locally and in the hinterland. On HOWATHARRA the recent flooding was confined to the river channel (Fig. 30). The beach sand barring the Chapman River mouth

Table 10. Components of the Greenough Alluvium System

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Alluvial plain GaA_a 311 ha (83%)	Alluvial Level plain up to 250 m wide; 5–15 m AHD Silty sandy clay with limestone debris, over sandy gravel	Corner of Webberton Road and Anderson Street (MGA 268830E 6817830N) New drainage sump excavated in level alluvial plain to over 3 m deep, exposing mottled sandy clay Firm to stiff, yellowish red 5YR 4/6, slightly sandy clay
Stream channel banks GaA_c 37 ha (10%)	Alluvial Mostly moderately inclined stream channel banks up to 60 m wide and 10 m high; locally steep to cliffed; up to 20 m AHD Colluvial silty sand, eolian sand, limestone, and weathered sandstone	Chapman River (MGA 270335E 6817460N) Very steep stream channel banks; boulders and exposures of calcrete (limestone) in the mid to upper part of the channel slope; eolian sand in paddock above Calcrete below residual sand
Stream bed GaA_b 27 ha (7%) (database only: not shown on map, within GaA_c)	Alluvial Level to gently inclined stream bed, distinct from adjacent channel banks; up to 80 m wide; sea level to 10 m AHD Mostly water filled; silt or sand with some rock exposures and debris	West of Fairfax Road, Moresby (MGA 269800E 6819130N) Track across stream bed; coarse to medium sand; some silty parts; partially water-filled and seasonally flooded
Swamp GaA_w 2 ha (<1%)	Alluvial Level to very gently inclined; around 8 m AHD; reclaimed Formerly waterlogged organic soil over silty sandy clay	Pinna Way, Sunset Beach (MGA 268090E 68205700N) Slightly wetter area identified on aerial photographs taken in 1956

is liable to severe erosion or destruction during these flooding events, but is quickly re-established by winter storm and wave action. During seasonal increases in run-off the banks of the stream channels are often eroded. This can be severe in areas where tracks have damaged the banks.

Landuse, vegetation, and drainage

The land of the Greenough Alluvium System on HOWATHARRA is used mainly for urban, recreational, and industrial uses, but there is also some horticulture north of the Chapman River on this system. The flat nature of the ground makes it a suitable location for extending the development of the City of Geraldton. Almost all native vegetation has been cleared, except in river channels. There is one major drainage channel, the Chapman River, located both between the Moresby System colluvial footslopes and Spearwood System sand dunes, and cutting through the terrace deposits of the Greenough Alluvium System.

Relationships

The source of the material in the Greenough Alluvium System is, in part, the weathered sedimentary rock and duricrust of the surrounding Moresby System, but there is also a contribution from the larger catchment to the east and northeast along the Chapman River, and southeast along the Greenough River on GERALDTON. Sections through the alluvium, exposed in terraces along the Chapman River, show the alluvium to be interbedded with calcarenite (Tamala Limestone) of the Spearwood System. To the north of Sunset Beach, alluvium of the Greenough Alluvium System is overlain by Holocene sand dunes of the Quindalup System.

Geological history

Deposition of the thicker fluvial deposits in the Greenough Alluvium System on HOWATHARRA largely pre-dates the formation of the eolian dunes of the Spearwood System, but cannot be further constrained in age. On the alluvial plain there are rises of Spearwood System sand and

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Figure 30. Flooding of the Chapman River (*GaA$_c$*) at Chapman River Bridge (MGA $_2$68260E $_{68}$19610N) following heavy rain, May 1999 (GSWA Photograph No. 1264)

limestone as relics of the flooded eolian land surface. A thin veneer of younger alluvium, typically less than 5 m thick, covers these relics.

There is some evidence of Holocene deposition adjacent to active river channels, but the younger parts of the alluvial plain are probably Pleistocene (Wyrwoll, 1984) and post-date the 120 ka marine transgression.

Quindalup System (*Qu*)

The Quindalup System occupies 1550 ha (2%) of HOWATHARRA (Fig. 31, Table 11), and is equivalent to the Holocene Safety Bay Sand, which comprises calcareous sand in dunes and coastal deposits. The system is an important source of limesand for agricultural applications, but there is only limited potential for heavy mineral deposits.

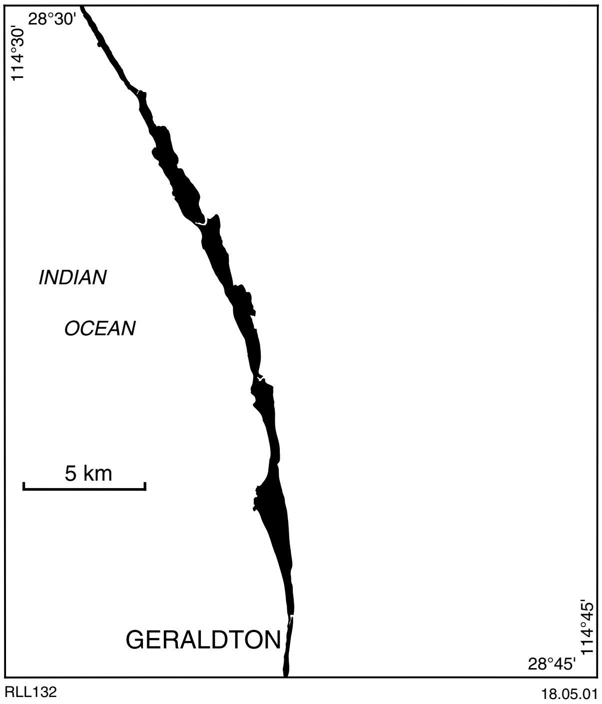

Figure 31. Distribution of the Quindalup System (*Qu*) on HOWATHARRA

Distribution and landform

The Quindalup System comprises a belt of eolian parabolic dunes and swales ranging from 150 m up to 1.2 km wide, parallel to the coast on HOWATHARRA (Figs 24 and 32). The sections of the Quindalup System north of Oakabella Creek and south of the Chapman River are much narrower than the central part of the belt. The Quindalup System between Drummond Cove and the Oakajee River is characterized by large blowouts (Fig. 33). The Quindalup System includes older deflated dunefields composed of calcareous soils overlying weakly lithified calcarenite. In the area between the Oakajee River and Oakabella Creek there are older, deflated dunes within the Quindalup System that are exposed behind the younger dunes. The western margin of the Quindalup System is a beach backed by a foredune (Fig. 34). A beach ridge plain up to 470 m wide has developed behind the foredune at a number of localities along the coast.

Slopes range from very short (<10 m) and moderately steep to very steep on easterly facing foredune fronts, to long (up to 270 m) and gentle on the deflated older dunes. Relief ranges from 1.5 m on the beach ridge plains to 25 m in the larger dunes. The parabolic dunes mostly have gently to moderately steep faces, although they are steep in some places on the east-northeasterly facing advancing dune front. Although mostly less than 35 m AHD, these dunes have advanced onto the underlying Tamala Limestone to an altitude of up to 92 m AHD between the Oakajee and Buller rivers. Crests in the parabolic dunes trend dominantly 350°, broadly ranging from northwest to north-northeast.

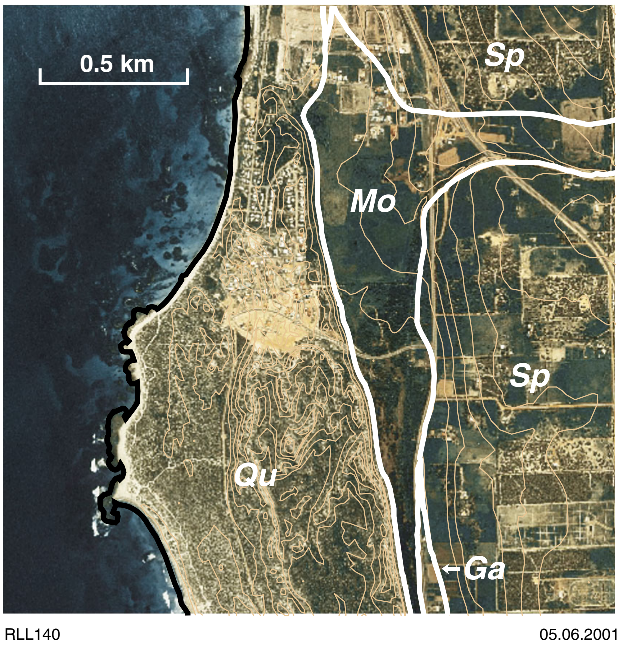

Figure 32. Beach, foredune, and level beach ridge plain west of parabolic dunes in the Quindalup System (*Qu*) at Drummond Cove on HOWATHARRA. Fluvial deposits of the Moresby (Mo) and Greenough Alluvium (Ga) Systems, and deflated dunes of the Spearwood System (*Sp*) to the east, with the Marine System (M) to the west. Orthophotograph with contours at 5 m

Regolith and rock materials

The dominant material in the Quindalup System is eolian sand composed of comminuted shell debris and quartz grains, with a minor component of garnet and other heavy minerals. The shell material comes from the marine environment, and has been transported by marine and coastal processes into the dominantly eolian environment.

The eolian sands are largely unconsolidated to weakly lithified, well-sorted, calcareous medium sand (Fig. 35). The younger parabolic dunes ($QuE1_a$) may have very weakly cemented calcarenite cores. Carbonate clasts are subrounded, smooth, flat to elongate shell fragments, and the quartz is subrounded and glassy. Many of the sands contain minor amounts of subrounded pink garnet. The source of these clasts is both reworked marine shell and fluvial quartz sand, with the latter mainly from weathered Jurassic and Proterozoic rocks in the hinterland. The older, deflated dunes (*QuE2*) are composed of calcareous soils

Table 11. Components of the Quindalup System

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Parabolic dunefield *QuE1$_a$* 924 ha (60%)	Eolian Belts of dunes up to 1 km wide, mostly moderately to gently inclined; steeply inclined ridges forming a parabolic pattern in places; dominantly westerly to southwesterly facing; mostly less than 25 m AHD, but up to 90 m AHD Shell and quartz sand	South of Drummond Cove (MGA 266620E 6824450N) At least 1.2 m of sand on moderately inclined dune crest Very pale brown 10YR 8/4, medium shell and quartz sand with minor pink garnet and black oxide
Blowout *QuE1$_b$* 200 ha (13%)	Eolian Several blowouts up to 2 km long and 500 m wide; mostly gently inclined, locally steep; slope aspect west to southwest; mostly less than 30 m AHD, but up to 45 m Actively eroding shell and quartz sand	North of Drummond Cove (MGA 266635E 6829080N) Sandpit about 20–25 m square and 6 m deep in very gently inclined blowout; Tamala Limestone on the hills to the east Very pale brown 10YR 7/3, medium shell and quartz sand with minor pink garnet
Beach ridge plain *QuB$_r$* 165 ha (11%)	Coastal Numerous elongate low ridges built up by waves and modified by wind, lying behind the foredune in belts up to 450 m wide; level to gently inclined; westerly facing; up to 10 m AHD Eolian shell and quartz sand	South of Drummond Cove (MGA 266435E 6824525N) Thin layer of organic soil indicates dune mobility; further south there is a clear beach ridge plain morphology but here there have been many blowouts (now revegetated) and the pattern is unclear Very pale brown 10YR 7/4, medium to coarse quartz and shell sand with some weakly cemented calcarenite sand and gravel
Beach *QuB$_b$* 106 ha (7%)	Coastal Narrow, laterally extensive, gently to moderately inclined simple slope built up by waves; almost continuous along the coast, 25–80 m wide; very gently to moderately inclined, sloping southwesterly to westerly; low water up to 4 m AHD; rarely over 6 m AHD Marine shell and quartz sand; eolian in part	North of Coronation Beach (MGA 261400E 6839895N) Catena from sea level through foreshore to dunefield; moderately inclined beach Very pale brown 10YR 8/2, medium to coarse quartz and shell sand
Foredune *QuB$_d$* 106 ha (7%) (database only: not shown on map, within *QuB$_b$*)	Coastal Narrow, laterally extensive, gently to moderately inclined southwesterly to westerly facing slopes built up by wind from material from the adjacent beach; almost continuous along the coast, 10–80 m wide; mostly less than 5 m AHD; rarely up to 9 m AHD Eolian shell and quartz sand; marine in part	South of Drummond Cove (MGA 266260E 6824240N) At least 1.2 m of sand on the top of the foredune about 3–5 m above the dunefield to the east; the foredune is smaller to the north; the front of the foredune (east) has a 15° slope Very pale brown 10YR 7/3, medium shell and quartz sand with minor pink garnet
Older dunefield QuE2 28 ha (2%)	Eolian Mostly gently inclined, ranging from level to moderately inclined; slope aspect northwest to north; mostly 5–40 m AHD, but up to 60 m AHD Eolian shell and quartz sand	Track to Oakajee from Coronation Beach Road (MGA 262470E 6838725N) Gently inclined deflated dune; at least 1.2 m of dark organic calcareous sand over light brown nodular calcareous sand Light brown 7.5YR 6/4, medium to coarse quartz and carbonate sand; moderately weak nodules up to 8 mm with well developed cutans ~0.5 mm thick

Table 11. (continued)

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence*
Wave-cut rock platform *QuB$_p$* 19ha (1%)	Coastal Platforms on the seaward side of the beach, up to 150 m wide; dominantly very gently inclined, westerly to southwesterly facing; between low and high water Undivided calcarenite (mostly Tamala Limestone), coral limestone, and beach rock	Kempton Street foreshore (MGA 267465E 6818725N) Gently inclined rock platform with karst top surface extending about 100 m along beach; beach sand and foredune to the east Beach rock consisting of cemented shell and sand with some quartz up to 3 mm
Swampy swale *QuE1$_w$* 3 ha (<1%)	Eolian Level to moderately inclined depression; 28–35 m AHD Waterlogged organic soil over eolian shell and quartz sand	South of the Oakajee River (MGA 264600E 6834700N) Swampy vegetation in a hollow between dune ridges

overlying moderately weak calcarenite with a moderately strong calcrete cutan up to 8 mm thick. At Sunset Beach the foredune has been constructed with alluvial and reworked eolian sand, and anthropogenic debris. The character of the dune, and its susceptibility to erosion, contrast markedly with the natural material thrown up by storm activity (Fig. 36).

Calcium carbonate content varies considerably (Table 12), ranging from about 38 to 75%. The beach sands (*QuB$_b$*) are coarser grained than the adjacent eolian deposits, and also include beach rock (*QuB$_r$*), which is a lithified beach deposit formed at, or slightly above, the zone of wave action (Fig. 37).

Mineral resource potential

The Quindalup System is an important source of limesand for agricultural applications. There are also quarries in the older, lithified calcarenites for material to be used in road-base construction. Sands in the system can also be used for construction and for beach rebuilding.

There is one intermittently active limesand operation within the Quindalup System, based in the advancing front of the dunes about 15 km north of Geraldton (*8444*). There is limited potential for titanium and zirconium minerals, and garnet, in the beach and dune sands.

Active processes and hazards

Marine transport of reworked shell and quartz is the dominant process in the coastal zone, resulting in seasonal deposition and erosion of beaches and river bars. This process is most active during storms, when there is often a significant increase in the erosion of coastal deposits. Beach regeneration is usually a natural seasonal process, and only in exceptional circumstances, such as cyclonic weather systems, has there been long-lasting change.

An important process in the Quindalup System is eolian transport of dune sand, which is most active in blowouts (Fig. 33) and areas where the vegetation has been damaged or stripped. The morphology of the parabolic dunes indicates a wind direction mainly from the south or south-southwest, which is well illustrated by the migration of sand northwards through the Southgate Dunes on GERALDTON.

Migrating sand from blowouts is a minor hazard, and storm wave action is an important factor in erosion and deposition along the narrow coastal zone. The steep dune faces and loose sand make navigation over the dunes hazardous both on foot and by vehicle.

Landuse, vegetation, and drainage

Landuse within the Quindalup System is dominantly recreational, but includes some urban development at Sunset Beach and Drummond Cove. Much of the system is covered by natural vegetation and includes large areas of Vacant Crown Land. Only small areas have been cleared for cropping or grazing.

Recreational use of the younger dunes and beaches by four-wheel and bike drivers, and people seeking access to the coast, has destroyed the stabilizing vegetation cover in places, leading to degradation by eolian processes. The flatter, older dunes, covered by less alkaline soils, are the only areas that that are suitable for cropping and grazing when cleared. All the dunes and beach deposits are underlain by well-drained sand in which neither perm-anent channels nor gullies have formed.

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Figure 33. Blowout in parabolic dunes of the Quindalup System (*QuE1$_b$*) south of Oakabella Creek (MGA $_2$61180E $_{68}$40425N; GSWA Photograph No. 1356)

RLL115 11.05.01

Figure 34. Beach (*QuB$_b$*) backed by 1 m-high foredune (*QuB$_d$*) on the western margin of the Quindalup System about 1.5 km south of Oakabella Creek (MGA $_2$61400E $_{68}$39895N; GSWA Photograph No. 1355)

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Figure 35. Soil auger sample from older, deflated dunes (*QuE2*) 3 km north of Oakajee, composed of light brown 7.5YR 6/4 calcareous soil with moderately weak calcarenite nodules (MGA 262470E 6838725N; GSWA Photograph No. 1357)

RLL117 11.05.01

Figure 36. Foredune reconstruction at Sunset Beach (MGA 267450E 6820650N), using soil and anthropogenic debris, contrasting markedly with the pale beach sand thrown up by storm activity. Foredune (QuB_d) is about 3 m high above the beach (QuB_b) in the foreground (GSWA Photograph No. 1436)

Table 12. Calcium carbonate ($CaCO_3$) content of selected sand samples from the Quindalup System

Map symbol	*Sample number*	*Location*	*Description*	*$CaCO_3$ (%)*
QuB_b	168573	North of Oakabella Creek (MGA 259270E 6843330N)	Beach Light grey 2.5YR 7/2 slightly gravelly medium to coarse sand; quartz and shell with minor glassy or smooth pink garnet	38.5
QuB_d	168567	North of Coronation Beach (MGA 261400E 6839895N)	Foredune Very pale brown 10YR 8/2 medium to coarse quartz and shell sand	48.2
QuB_d	168551	South of Drummond Cove (MGA 266260E 6824240N)	Foredune Very pale brown 10YR 7/3 medium shell and quartz sand with minor pink garnet	59.2
$QuE1_b$	168556	Limesand pit north of Drummond Cove (MGA 266635E 6829080N)	Blowout Very pale brown 10YR 7/3 medium shell and quartz sand with minor pink garnet	60.7
$QuE1_a$	168550	South of Drummond Cove (MGA 266435E 6824525N)	Parabolic dunes Very pale brown 10YR 7/4 medium to coarse quartz and shell sand with some weakly cemented calcarenite sand and gravel	65.0
$QuE1_a$	168549	South of Drummond Cove (MGA 266620E 6824450N)	Parabolic dunes Very pale brown 10YR 8/4 medium shell and quartz sand with minor pink garnet and black oxide	75.4
QuE2	168568	Track to Oakajee from Coronation Beach Road (MGA 262470E 6838725N)	Older deflated dunefield Light brown 7.5YR 6/4 medium to coarse quartz and carbonate sand; moderately weak nodules up to 8 mm with well developed cutans ~0.5 mm thick	54.1

NOTE: Analysed by Chemistry Centre, WA

Relationships

The Quindalup System is currently active, and overlies fluvial, eolian, and colluvial sediments of the Greenough Alluvium, Spearwood, Moresby, and Northampton Systems to the east. Beach deposits in the system and sands in the adjacent shoreface, part of the Marine System, cover reefs and rock flats, probably within the Tamala Limestone. Both the younger and older dunes of the Quindalup System lie against a westerly facing scarp or colluvial footslopes in the Spearwood System (Tamala Limestone) that formed at the 120 ka sea-level high of about 5 m AHD.

Geological history

The Quindalup System is composed of the Holocene (<40 000 years BP) Safety Bay Sand, which is defined as the coastal sand dunes and shallow marine to littoral sands (Passmore, 1967, 1970). The older Quindalup System dunes probably formed during the 5000 years BP sea-level highstand of up to 3 m AHD (Playford, 1983).

RLL118 11.05.01

Figure 37. Wave-cut rock platform (*QuB*$_p$) near Oakabella Creek (MGA 260540E 6841540N), composed of light grey 10YR 7/2 moderately strong to strong calcarenite (Tamala Limestone; GSWA Photograph No. 1372)

Marine System (*M*)

The Marine System occupies 24 400 ha (36%) of HOWATHARRA (Fig. 38, Table 13), and includes the offshore marine plain, nearshore seabed, and adjacent shoreface (Fig. 39). Reefs form a significant proportion of the nearshore. The shallow waters hold potential resources of limesand, sand, and limestone.

Morphology and distribution

The Marine System occupies the western part of the HOWATHARRA sheet, and includes all seabed materials and morphological features up to the low tide mark (CD). The major components of the Marine System are an offshore level marine plain, covered by water in excess of 20 m depth, and nearshore level to gently inclined seabed, typically under 5 to 10 m of water, adjacent to a gently inclined shoreface.

The nearshore and inshore zones include abundant low, submerged rocky ridges or reefs. The reefs are often exposed in the littoral zone, between high and low water, as inshore or nearshore rock platforms, such as at Drummond Cove. Erosional channels offshore from most of the streams and rivers are a relict of the fluvial palaeochannels associated with a Pleistocene sea-level lowstand.

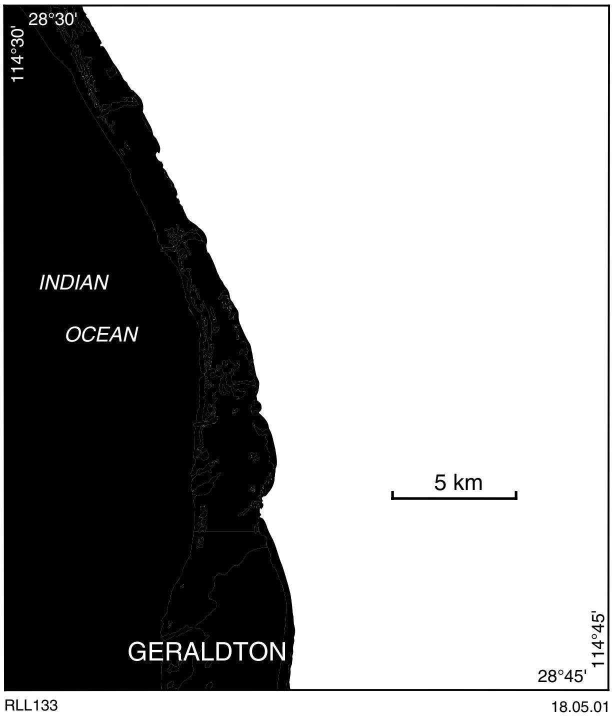

Figure 38. Distribution of the Marine System (*M*) on HOWATHARRA

Seabed materials

The seabed is dominantly covered with poorly sorted shell and quartz sand. This has formed by a variety of processes, including the reworking of fluvially sourced material from weathered hinterland rocks, erosion of the reefs, and biogenic processes. The reefs or rock flats are composed of calcarenite, and commonly have a coating of biogenic reef growth on the surface (M_r). The calcarenite is eolian in origin, and is mostly Tamala Limestone as found onshore in the Spearwood System.

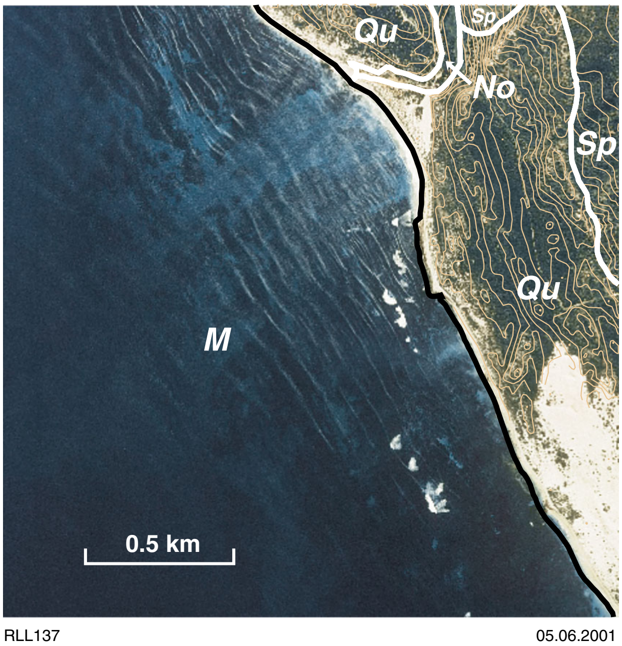

Figure 39. Seabed reef and sand plain morphology in the Marine System (*M*) west of the Oakajee River on HOWATHARRA, with a relict fluvial channel extending west from the river mouth. Orthophotograph with contours at 5 m

Mineral resource potential

The Marine System is a possible source of limesand, sand, or limestone for agricultural applications, construction, beach rebuilding, or land reclamation. Much of the offshore area on HOWATHARRA is covered by water in excess of 20 m depth, which significantly reduces the potential for dredging. The shallow nearshore and inshore areas are underlain by calcareous sands that may be a source of limesand. Beneath the sand, and underlying all the reefs, is Tamala Limestone, which is quarried in onshore areas of GERALDTON for armour stone and fill.

The nearshore sands are a suitable source of material for beach reconstruction because this sand most closely matches that in existing beaches, and is not contaminated by silty material that may affect slope angles and erosion (Fig. 36).

Active processes and hazards

The Marine System is the most active area on HOWATHARRA, with constantly active processes that include erosion and deposition by marine tides, currents, and wave

Table 13. Components of the Marine System

Unit name, map symbol, and area	*Process, landform, and material*	*Typical occurrence (based on bathymetry and enhanced imagery)*
Offshore sand plain M_p 16 775 ha (68%)	Marine Offshore sand plain; level; –15 m CD deepening to the southwest to more than –35 m CD Shell and quartz sand	6.7 km west of the mouth of the Chapman River (MGA 260900E 6820450N) Level plain at 13 fathoms (23.8 m), shelving westwards Coarse grey sand in a seabed grab sample noted on Chart Aus036[(a)]
Reef or rock flat M_r 4817 ha (20%)	Marine Reef or rock flat; mostly gently inclined; but with some moderately inclined ridges up to 2 m high; exposed at low tide and extending offshore to around -15 m CD Undivided eolian calcarenite, biogenic reef and beach rock; minor shell and quartz sand	Drummond Cove (MGA 266300E 6825740N) Numerous near-circular reefs up to 50 m across in 1–2 m of water Coral limestone; exposed above water in nearby wave cut platform (QuB_p)
Nearshore sand plain and sandy hollows M_n 2180 ha (9%)	Marine Nearshore sand plain and sandy hollows; level to gently inclined; –5 to –15 m CD in the north; –10 to –20 m CD to the south Shell and quartz sand; minor rock ridges and flats	2.5 km northwest of the mouth of Oakabella Creek (MGA 258670E 6842730N) Patch of sandy seabed; up to 1.8 km long and 0.4 km across; water depth 5–7 m CD; between northwesterly trending reef ridges Phototone interpreted as sand with little or no vegetation cover
Shore face M_s 425 ha (2%)	Marine Shore face; mostly gentle slopes; 0 to –5 m CD in the north, deepening to –10 m CD to the south Shell and quartz sand; minor rock platform	Drummond Cove (MGA 266460E 6825700N) Level to very gently inclined patch of sandy seabed; interspersed with reef knolls; water depth 0–2 m CD Phototone interpreted as sand with little or no vegetation cover; contiguous with medium to coarse quartz and shell sand on the beach (QuB_b)
Channel M_v 212 ha (1%)	Alluvial Channel; relict erosional fluvial channel; level to gently inclined; narrow; –5 to –22 m CD	West of the mouth of the Oakajee River (MGA 262790E 6835580N) Palaeochannel extending nearly 2 km offshore to offshore plain; aligned with river; eroded up to 2 m below seabed Partially filled with marine sand; some exposed reef

NOTE: (a) Bolton et al. (1946)

action. The most active part of the system is the inshore area, which extends from the limit of wave action at depth, up to the lower edge of the beach. On HOWATHARRA, the inshore zone mostly extends down to 5 m below CD, but can also extend to 10 m below CD in areas where nearshore reefs modify wave action. Longshore drift from south to north is constantly modifying the inshore shoreface, as well as the adjacent beach in the Quindalup System.

Shallow reefs are a dominant characteristic of the nearshore zone. The reefs are composed of limestone, with additional biogenic reef growth on the surface, and are a hazard to shipping.

During storms there is often a significant increase in wave action, related in part to the shallow reefs on the nearshore shelf. These waves can rapidly erode inshore deposits, and may damage reefs. Regeneration of the shoreface and adjacent beach is usually a naturally occurring seasonal process, and only in exceptional circumstances, such as cyclonic weather systems, will there be long-lasting damage in the inshore zone.

Seabed use

The seabed has a significant impact on shipping, the local fishing industry, and recreation. Seabed materials and morphology have some importance for both recreational and commercial fishing because the location of reefs, and the composition of seabed materials, can be factors in finding fish and crayfish stocks. The position of reefs and ease of excavation of seabed materials is of interest for the proposed port and industrial development at Oakajee.

Relationships

The seabed is a currently active regime that is underlain by undivided older reefs composed of the Pleistocene Tamala Limestone. The marine processes offshore are closely linked to the coastal and eolian processes in the adjacent Quindalup System.

Geological history

The age of the seabed materials ranges from Pleistocene to Holocene because the older reefs are often covered by a variable thickness of younger biogenic growth. The limestone that forms the reefs rests unconformably on the Proterozoic Northampton Complex or Jurassic Yarragadee Formation. A postulated northward extension of the Geraldton Fault parallels the coast of the northern part of HOWATHARRA (Fig. 4), but the extent to which the fault has controlled the position of the coast is uncertain.

Mineral resource potential

Overview

The mineral resource potential of HOWATHARRA is limited to base metals, heavy minerals, and a small range of construction and industrial minerals (Fig. 40). This group of construction and industrial minerals, including gravel, sand, limestone, limesand, stone, and clay, is also referred to as basic raw materials. There is potential for the extraction of large quantities of all of these basic raw materials except clay, but at present there is a limited market that is adequately serviced by existing extractive operations in the region. There are no recorded occurrences of coal in the Jurassic Cattamarra Coal Measures beneath HOWATHARRA. The mineral resources of the Mid West were reviewed by Flint et al. (2000).

The mineral occurrences on the map are grouped into mineral commodity and mineralization style as described in Appendix 5.

Ferruginous gravel

The ferruginous duricrust capping hills in the Moresby System ranges from strongly cemented to loose, and overlies mottled residual soil. The thickest duricrust on HOWATHARRA was dominantly formed by weathering of the siltstone, limestone, and sandstone of the Jurassic Cadda Formation, but sandstone of both the underlying Cattamarra Coal Measures and overlying Yarragadee Formation also form duricrust gravel deposits.

The extraction of gravel resources is limited by a number of factors, including land ownership and conservation requirements. Gravel resources are always located on steep-sided summit surfaces of the plateau, making vehicular access so difficult that this can effectively sterilize the resource. Looser gravels are preferred for road building because they can be easily excavated and require no further processing. These gravels can be up to 2 m thick, and are used for roadbase, farm tracks, and unsealed shire roads. If the duricrust is strongly cemented it may prove very difficult to extract gravel for road building, and if the looser parts of such deposits are less than 1 m thick they may be subeconomic.

Sand

Thick deposits of yellow and red sand have been formed by the weathering of calcareous sand in the Spearwood System. 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. There are a number of intermittently operated or abandoned sand pits located adjacent to the North West Coastal Highway (Fig. 23; *8453–8455*).

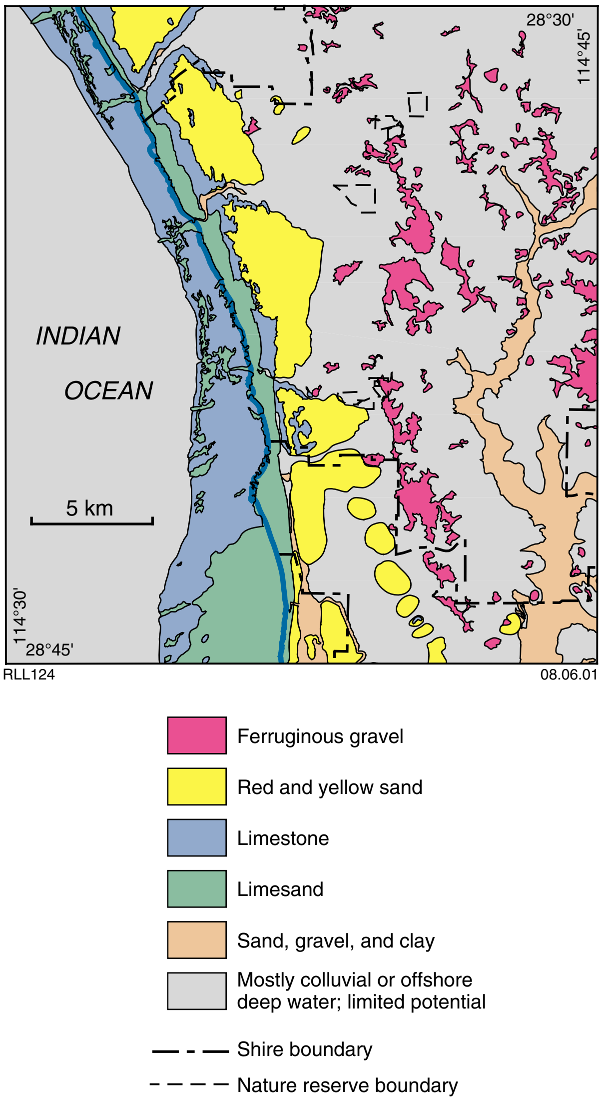

Figure 40. Construction material and industrial mineral resource potential of HOWATHARRA

Sand and gravel

Fluvial deposits are commonly good sources of sand and gravel for low-grade construction aggregate such as building-site fill. Grading and composition, as well as the available thickness, determine the viability of such materials. Deposits with little gravel, especially coarse fractions such as cobbles or boulders, are generally preferred. The presence of clay, particularly cracking clays, can cause drainage problems at construction sites, although some silt and clay is needed for cohesion.

Sand from the Spearwood System is preferred locally as a source of fill because it is better graded and less silty and clayey than the fluvial deposits. There are no significant sand and gravel pits on HOWATHARRA, although there is a small abandoned operation at Yetna (*8456*); however, the Greenough System in particular may provide suitable sources of sand and gravel for local use in the absence of other sources.

Limestone

The calcarenite and calcrete of the Spearwood System (Tamala Limestone), and the weakly cemented calcarenite of the Quindalup System (Safety Bay Sand) are referred to in the extractive industry as limestone. Limestone can be used as a raw material for cement, as an aggregate or roadbase, as a dimension stone (building stone), for large-scale fill or reclamation, and in a variety of industrial applications (Abeysinghe, 1998). In the Geraldton area, the only use of limestone has been road construction and reclamation, but there are no known limestone extraction sites on HOWATHARRA.

Limesand

Limesand is commonly used to correct soil deficiencies because it helps to reduce soil acidity, and increases calcium and magnesium levels, both of which increase the supply of other nutrients. Limesand can also be used as a source of lime, and there are two operations at Dongara, south of HOWATHARRA, that produce lime for the mining industry.

Limesand is composed of comminuted shell fragments of marine origin, with minor quantities of quartz and other minerals derived from weathering and erosion of rocks inland. The calcium carbonate content of the loose sands that form the Quindalup System is typically over 50% (Table 12), and has been analyzed at up to 75.4% for a sand from the dunes south of Drummond Cove.

The preferred conditions for limesand operations are blowouts in the mobile dunes, followed by vegetated dunes. The operation at the northern end of dunes near White Peak (*8444*) is on the advancing front of a large blowout.

Common clay

The alluvial deposits of the Chapman Valley are prospective for common clays. One sample from fluvial terraces near Narra Tarra has been tested and found to be suitable for brick making (*6519*), but no work has been done on the extent or viability of such deposits.

Stone

There are several abandoned stone quarries in Northampton Complex granulite that were used as a source of fill, aggregate, or sea-wall construction material, with the largest located adjacent to the North West Coastal Highway north of the Buller River (*8338*). Quartz veins in the complex may also have been quarried on a small scale, probably for ornamental stone. Three abandoned building-stone quarries have been identified in Jurassic sandstone (*3654*, *8355, 8480*), although there are probably other sources that can no longer be identified. The known quarries are in poorly jointed, bedded sandstone of the Cattamarra Coal Measures, which historically has been referred to as the Greenough Sandstone. The White Peak quarry (*8355*), active in the 1920s during construction of the railway (Fig. 16), was a source of stone for fill and construction.

Titanium, zirconium, and garnet

Eolian and coastal sands in the Swan Coastal Plain contain minor amounts of garnet and heavy mineral sands, which contain titanium and zirconium minerals. The most important economic deposits are in the Eneabba Strandline to the south of HOWATHARRA. This feature may have equivalents in the Spearwood System on HOWATHARRA.

Exploratory drilling has identified an area of low-grade heavy mineral accumulation (*8405*) up to 1 km in strike length and 480 m wide on the west side of the Chapman Valley (Yates, 1991). The sand contains up to 4.3% heavy minerals, with the thickest intersection of 14 m at 1.3%. The area of mineralization defined by Yates (1991) coincides with a body of eolian sands of the Spearwood System. The mineralization is insufficient to warrant resource calculation, and there are no other mapped bodies of eolian sand in the Chapman Valley that could host this style of mineralization.

Woods and Associates (1991, 1992) completed a shallow drilling program in an area east of the North West Coastal Highway near Wokarena. They defined a mineral occurrence (*8406*) with a number of intersections of over 1% heavy minerals, with a maximum of 2.9%.

Garnet is commonly associated with heavy mineral sands, and there are economic quantities north of HOWATHARRA at Port Gregory, about 75 km north-northwest of Geraldton. Exploration in the Quaternary beach and eolian sands north of Geraldton (New Consolidated Goldfields (A'sia) Proprietary Limited, 1967) identified highly localized heavy mineral concentrations of up to 19.2%, with garnet constituting 70–85% of the minerals. However, the concentration of heavy minerals in these sands is typically less than 1%, and is predominantly garnet, with some ilmenite. There are no recorded economic concentrations of heavy mineral sands on HOWATHARRA.

Base metals

The Northampton Complex is prospective for lead, copper, and silver, and was the location of the State's first lead mine at Geraldine, north of HOWATHARRA, about 120 km north of Geraldton. There are extensive exposures of the complex on HOWATHARRA, and there have been a number of mines located on vein-hosted sulfide mineralization in the complex. The six named mines on HOWATHARRA are, from north to south through the area: Narra Tarra (*4433*), Protheroe South (*6146*; Fig. 41), Narra Tarra East (*6147*), Oakajee (*6148*), Gelirah (*8352*), Gray's (*8441*) (referred to as Saxon in some references), and White Peak (*8348*). There is a comprehensive review of the mineralization and mining history in Byrne (1990), from which the data for the mining history in Figure 42 was extracted. The lead and copper mineralization of the district is also detailed in Blockley (1971) and Marston (1979). The mining history up to the 1960s is detailed by Kelly (1962).

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Figure 41. Shaft at the Protheroe South lead prospect in the foreground, and spoil heaps around Narra Tarra lead–copper–silver mine to the north (MGA 279735E 6843725N; GSWA Photograph No. 1378)

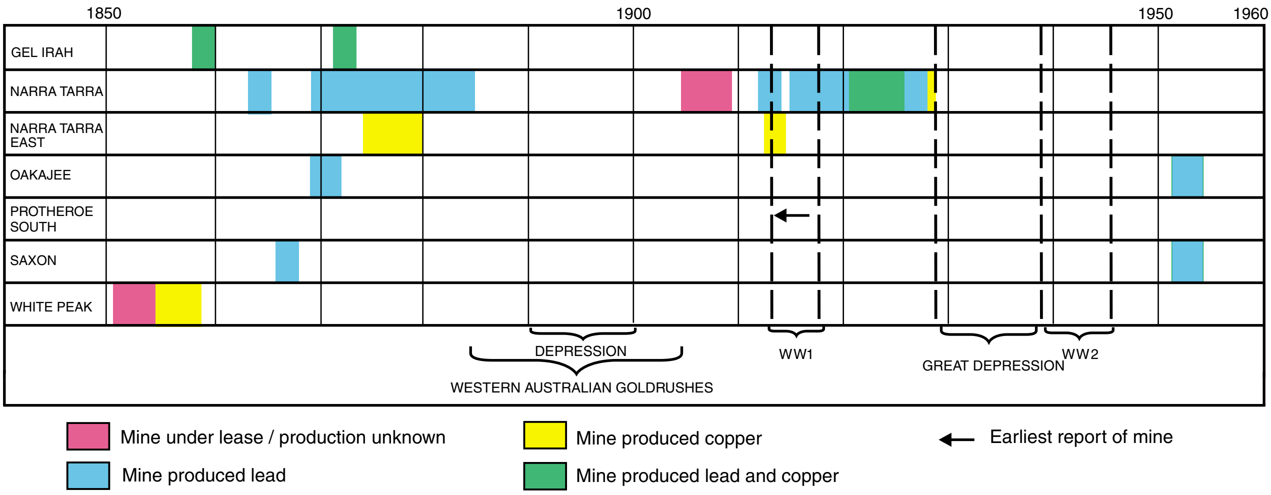

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Figure 42. Base metal mining history of Howatharra. After Byrne (1990). No production recorded from the Protheroe South mine

The earliest reference to the mineralization of the area is in Gregory (1861), who noted the valuable discoveries of lead and copper lodes that almost invariably trend 032°, parallel to dykes of 'whinstone, quartz, or porphyry'. Brown (1871) reported on the mining in the district, providing details of three mines on Howatharra: Oakajee lead mine, Gelirah copper mine, and Narra Tarra mine. At the time of his visit in 1871 only the Oakajee mine was operating. Brown (1871) postulated a hydrothermal origin for the veins, noting that at Gelirah and Narra Tarra they trend northeast. His suggestion, however, that Gray's Lode and White Peak Lode are probable southerly extensions of the lodes at Gelirah does not match the local north-easterly trend.

Table 14. Hydrogeology of rock units on HOWATHARRA

Land systems	*Stratigraphic unit*	*Age*	*Hydrogeology*
Spearwood and below coast Greenough Alluvium and water	Tamala Limestone	Pleistocene	Groundwater salinity increases towards the and with depth. Bores and wells are shallow yield is limited to avoid drawing in saline from below. Salinity exceeds 1500 mg/l.
Exposed in Moresby east of Geraldton Fault; below Greenough Alluvium, Spearwood, and Quindalup west of Geraldton Fault	Yarragadee Formation	Jurassic	Fresh water inland, but saline nearer the coast. Best aquifer in the Geraldton Region.
Below all systems except Northampton	Cattamarra Coal Measures	Jurassic	Mostly unsaturated or low yielding
Below all systems except Casuarina and Northampton	Kockatea Shale	Triassic	Bore yields very low and mostly saline

The first major work on the geology and mineral resources of the Northampton Mineral Field was completed by Gibb Maitland (1903). Woodward (1903), in an appendix to this work, gave details of all six named mines that have been identified during the present work on HOWATHARRA.

Talbot (1914) gives a detailed account of the surface and subsurface workings at Narra Tarra, and notes that production was recommencing at the site following initial development and production between 1874 and 1880. Talbot (1914) states that there are two mines at this centre; the Narra Tarra lead mine to the north and the Narra Tarra copper mine to the south. According to Talbot (1914), this was worked for copper 'in the early days of the colony', but was being worked for lead at the time of his visit. This mine is now known as Narra Tarra East (Marston, 1979). Wilson (1926) details the state of operations in the Northampton Mineral Field, and the geology of many of the mines and prospects. The only mine operating on HOWATHARRA at the time of his report was the Narra Tarra lead mine.

The most recent work to provide details of the mineralization and mining history of the area is provided in Ferguson (1999), which classifies mineralization in the Northampton Complex as hydrothermal vein-type deposits. The only mine on HOWATHARRA for which Ferguson (1999) provides details is the abandoned Narra Tarra lead mine. Ferguson (1999) notes that the Narra Tarra deposit, which lies on a 030° trending shear, was worked between 1874 and 1880, and again between 1913 and 1928. The galena-rich veins cut granulite country rock, and in the southwestern part of the shear these veins contain significant quantities of chalcopyrite.

Hydrogeology

Gozzard et al. (1988) provided the most recent account of the hydrogeology of HOWATHARRA, summarized in Table 14.

Acknowlegements

The assistance provided by engineers and planners in the City of Geraldton, and the Shires of Greenough and Chapman Valley is acknowledged. Thanks are extended to the City of Geraldton Library for access to archived records and photographs.

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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;
- field photographs;
- rock and regolith descriptions;
- structural information;
- field sketch locations.

Linear features are presented as separate layers or line themes:

- faults;
- dunecrests;
- swales;
- cliffs or scarps;
- seabed ridges.

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

Mineral occurrences (WAMIN) and quarry locations

The mineral occurrence dataset on the CD-ROM is extracted from GSWA's Western Australian Mineral Occurrence database (WAMIN) and 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.

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 HOWATHARRA from 23 August 1992, with the onshore and offshore regions being enhanced separately and pieced together as a mosaic. 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 came 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	*Northing*
11 Mile Old Well	268800	6830500
Bella Vista Nature Reserve	272600	6841200
Bluff Point Camp School	267600	6817900
Bluff Point Primary School	267800	6818400
Bluff Point	267400	6817700
Bluff Point Suburb	269500	6818800
Bowes	263800	6844000
Bugara Park	268900	6818300
Buller River	265900	6830000
Carney Hill	279600	6836500
Champion Bay	266100	6818200
Chapman	269000	6819400
Chapman River	275100	6829200
Coronation Beach	261700	6839200
Crowtherton	267400	6819400
Dolby’s Gully	269100	6826600
Drummond Cove	265600	6826700
Drummond Cove Suburb	266700	6826000
East Chapman	280100	6827200
Eastough Park	270000	6824800
Ego Creek	276600	6820700
Fig Tree Crossing Bridge	278900	6832500
Forrester Park	270100	6820800
Geraldton Water Supply(a)	267800	6814200
Glenfield	269900	6823800
Glenfield Beach	266200	6825000
Glenfield Suburb	266600	6823800
Howatharra	268600	6841600
Howatharra Nature Reserve	271200	6840700
Howatharra Well	270200	6841600
Kadewa Well	267600	6844400
Minyanogo Spring	268700	6832300
Moresby	272600	6819200
Moresby Flat Topped Range	272200	6823200
Mumbemarra Hill	277000	6828800
Nabawa(b)	283700	6845400
Narra Tarra(b)	280100	6830900
Narra Tarra Estate	277100	6825200
Nilligarri	267100	6845100
Nilligarri Nature Reserve	266700	6845100
Norm Brand Park	268700	6820600
Oakabella Creek	260800	6841300
Oakabella Homestead	265000	6845000
Oakajee	268600	6837900
Oakajee Nature Reserve	270300	6837200
Oakajee River	263400	6836000
Oakajee Well	267000	6836000
Protheroe	278300	6843600
Protheroe Nature Reserve	279100	6844400
Spalding Suburb	269100	6819200
St Lawrence’s School	267800	6818100
Strathalbyn Suburb	270100	6817900
Sunset Beach Suburb	267600	6821700
Una Brook	278300	6818100
Waggrakine Primary School	269200	6820900
Waggrakine Suburb	267400	6819400
Webberton Suburb	268600	6817800
White Peak	268800	6830500
Witherwarra	273700	6826900
Wokarena	268900	6826800
Wokatherra Nature Reserve	270600	6828400
Yarra Homestead	262800	6843600
Yarrack Creek	260800	6841300
Yellow Gully	260800	6841300
Yetna	276600	6833400

NOTES: (a) On GERALDTON (1:50 000)
(b) On NANSON

Appendix 3

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 4

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

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

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

Appendix 5

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 HOWATHARRA 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 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

Table 5.1. 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)
Speciality 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 5.2. Modifications made to the Mining Journal Ltd (1997) commodity classification

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

Table 5.3. 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 5.1

more than prospecting purposes (bold, italic, sans serif numbers, e.g. ***181***);

- operating mine — workings that are operating, including on a care-and-maintenance basis, or that are in development leading to production (bold, sans serif numbers, e.g. **37**).

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

Commodity group

The WAMIN database includes a broad grouping based on potential or typical end-use of the principal commodities constituting a mineral occurrence. The commodity group as given in Table 5.1 determines the colours of the mineral occurrence symbols on the map. The commodity groupings are based on those published by the Mining Journal Ltd (1997), and are modified as shown in Table 5.2 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 5.3).

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

Table 5.4. Minimum intersections for mineral occurrences in drillholes or trenches

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

NOTE: na: not applicable

Mineral occurrence determination limits

The lower cutoff limit for a mineral occurrence is more reliably based on 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 5.4.

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.

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Appendix 6

Classification of rock material strength

Strength	*Test method*				
	Hand	*Thumbnail*	*Pocket knife*	*Geological pick*	*Hand specimen*
Extremely weak	easily crumbled	indented deeply	–	–	–
Very weak	crumbled with difficulty	scratched easily	peeled	–	–
Weak	broken into pieces	scratched	peeled	deep indentations (<5 mm)	broken by single light hammer blow
Moderately weak	broken with difficulty	scratched with difficulty	difficult to peel but easily scratched	shallow indentations easily made	usually broken by single light hammer blow
Moderately strong	–	–	scratched	shallow indentations with firm blow	usually broken by single firm hammer blow
Strong	–	–	–	superficial surface damage with firm blow	more than one firm hammer blow to break
Very strong	–	–	–	–	many hammer blows required to break
Extremely strong	–	–	–	–	only chipped by hammer blows

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

Further details of geological publications and maps produced by the Geological Survey of Western Australia can be obtained by contacting:

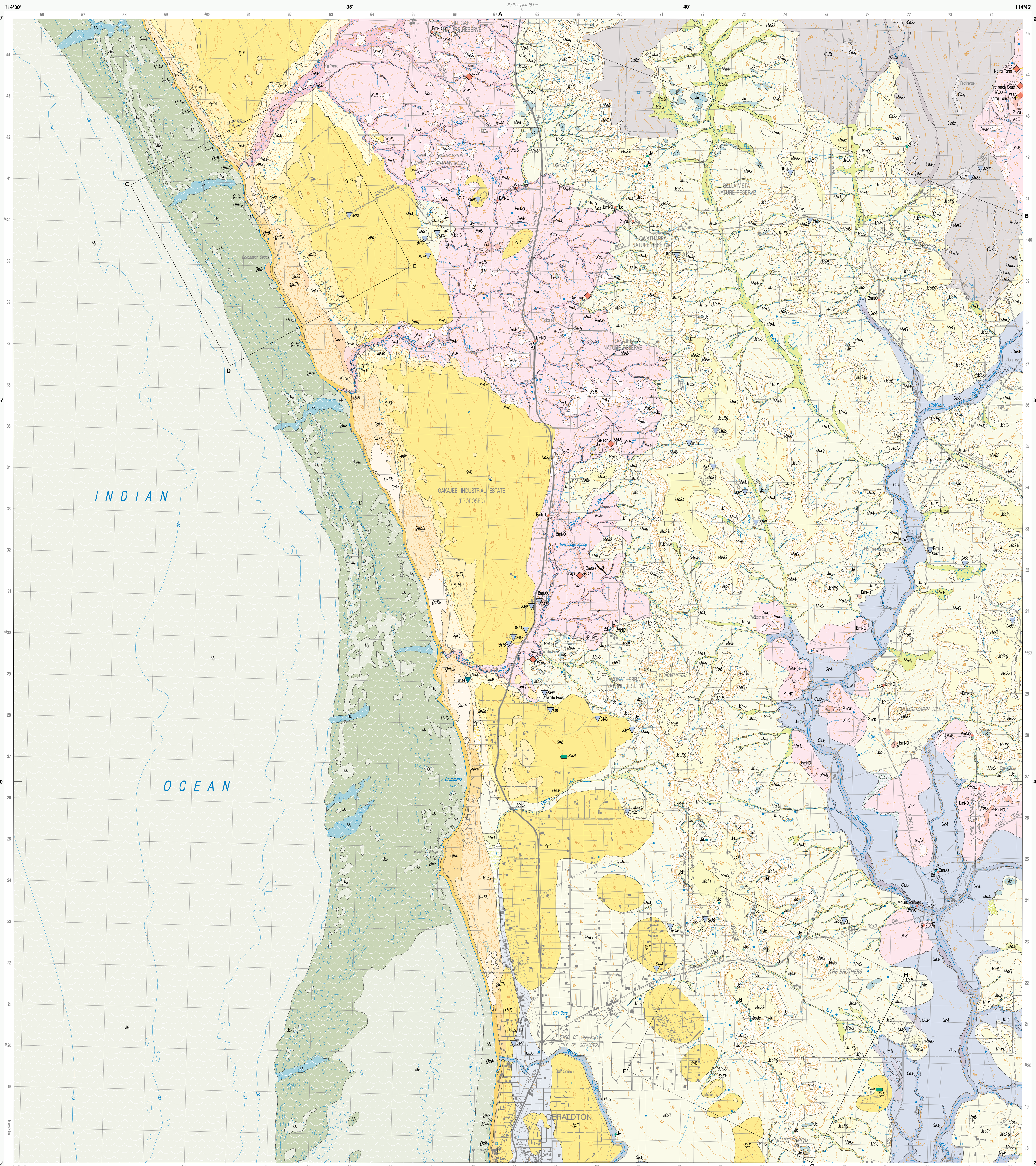
Information Centre
Department of Minerals and Energy
100 Plain Street
East Perth WA 6004
Phone: (08) 9222 3459   Fax: (08) 9222 3444
www.dme.wa.gov.au

HOWATHARRA

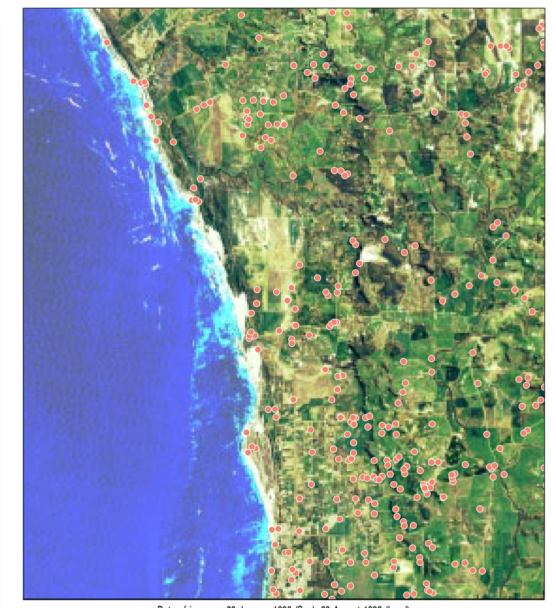
WESTERN AUSTRALIA 1:50 000 REGOLITH–LANDFORM RESOURCES SERIES

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SHEET 1840-IV FIRST EDITION 2001

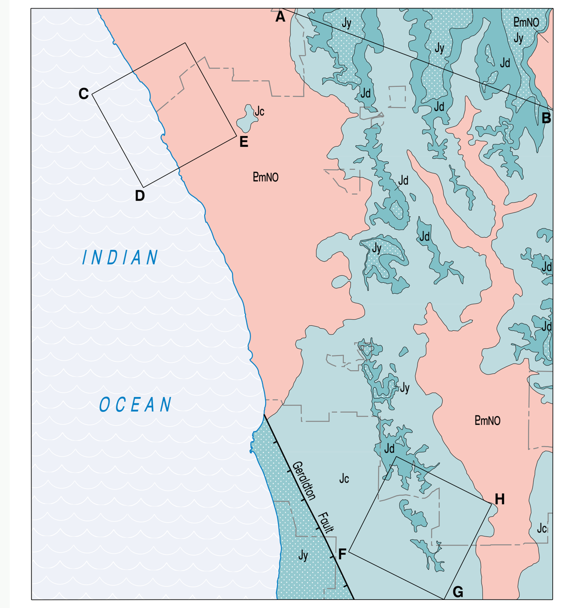


LANDSAT TM IMAGE WITH FIELD SITE LOCATIONS

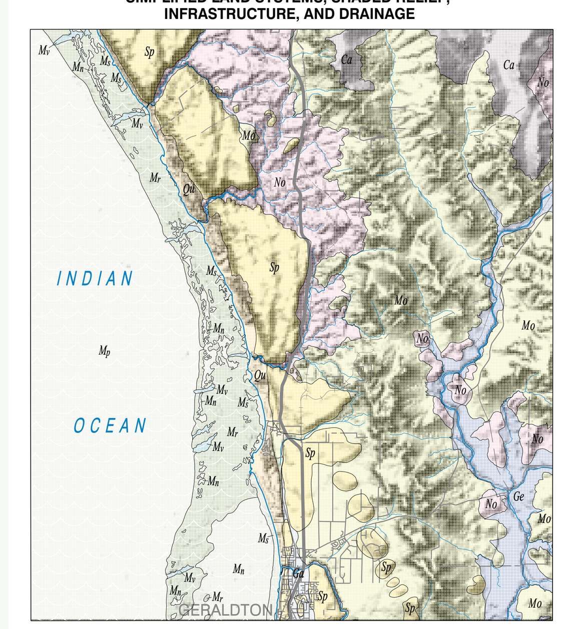


Date of imagery: 20 January 1996 (Sea), 23 August 1992 (Land)

INTERPRETED ONSHORE BEDROCK GEOLOGY



SIMPLIFIED LAND SYSTEMS, SHADED RELIEF, INFRASTRUCTURE, AND DRAINAGE



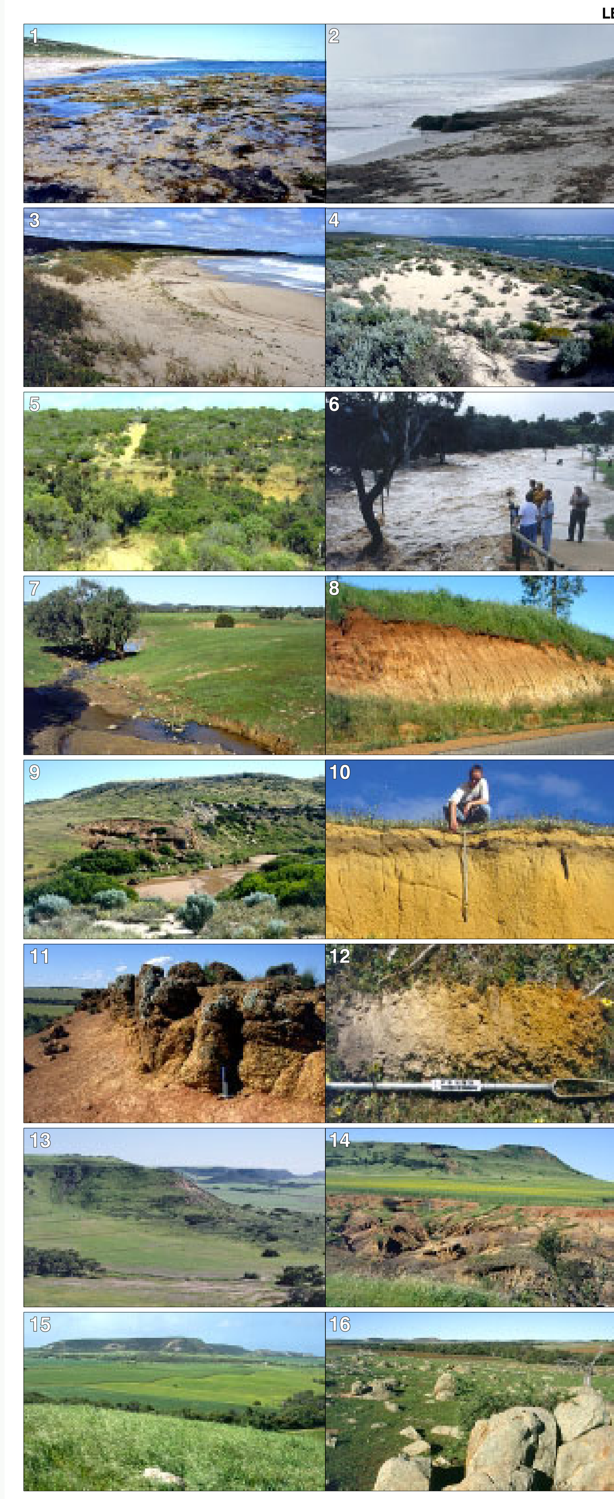
The Howatharra Regolith–Landform Resources map provides information on the regolith (soils) and underlying rocks, on the landforms (landscape), topography, infrastructure, and on the mineral and construction material resources of Howatharra. This map will be of value in landuse planning, the sustainable 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.

M_s	M_n	M_p	M_v	M_r

- M_s Marine shore face
- M_n Marine nearshore
- M_p Marine offshore
- M_v Marine channel
- M_r Marine reef
- *Qu* Quindalup System — beach and dunefields
- *Ga* Greenough Alluvium System — alluvial plain
- *Ge* Greenough System — alluvial terraces and channels
- *Sp* Spearwood System — deflated dunes
- *Ca* Casuarina System — undulating plateau
- *Mo* Moresby System — plateau and footslopes underlain by Jurassic rocks
- *No* Northampton System — low hills and rises underlain by Proterozoic rocks

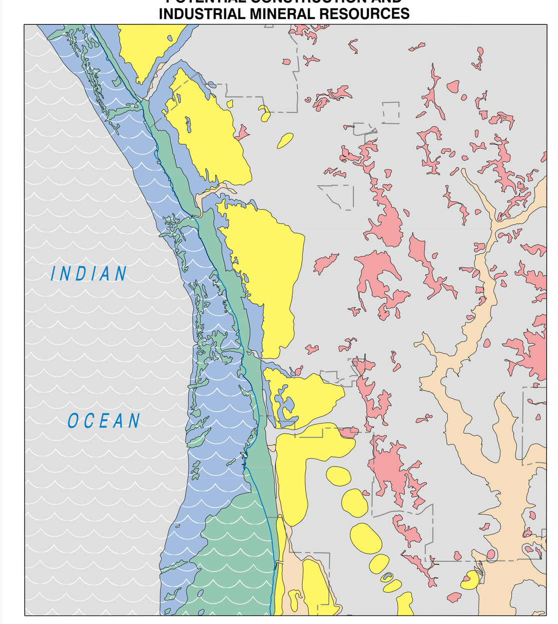
LEGEND



REFERENCE

SYMBOLS

POTENTIAL CONSTRUCTION AND INDUSTRIAL MINERAL RESOURCES



Ferruginous gravel — *MoRc, MoRz, MoRfp*

Cemented ferruginous pisolitic duricrust gravel cappings on low hills and plateaus, sometimes concealed by residual quartz sand. Potential source of aggregate for road building.

Red and yellow sand — *SpE*

Quartz-rich sand of eolian origin formed as a weathered residuum over limestone. Potential source of sand for building platforms and construction.

Limestone — *Mr, QuE2, QuBp, SpAk, SpBk, SpEk, SpCf*

Calcrete and calcarenite (limestone) formed by weathering of carbonate-rich sand dunes. Rock varies in strength from moderately weak to very strong, and may be excavated as aggregate or boulders. Overlain by varying thicknesses of yellow and red sand. Limestone may be used for road base, large-scale fill and harbour installations, and sand for building.

Limesand — *Ms, Mn, Mv, QuBb, QuBr, QuE1a, QuE1b,*

Mostly unlithified shell-rich sand of eolian and marine origin, with carbonate contents up to 75%. May be suitable for agricultural applications.

Sand and gravel — *GaAc, GaAa, GeAc, GeAe, GeAt, MoAf, NoAt*

Fluvial sediments ranging from silty clay to sandy gravel. Potential source of aggregate-quality sand or gravel for building and fill.

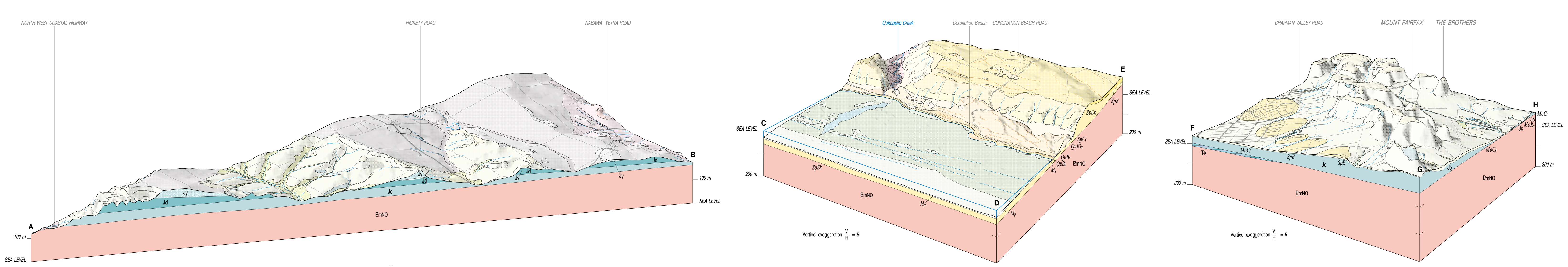
Mp, QuE1w, GaAw, GeAw, GeAd, SpEw, CaAd, CaRz, CaRc, MoAc, MoAw, MoAd, MoCf, MoCt, NoAc, NoAe, NoAd, NoC, NoCt, NoRc

Colluvial or fluvial sand, gravel, and clay, with some weathered rock, or offshore deep water sand plain; limited potential.

SCALE 1:250 000

0 5 10 Kilometres

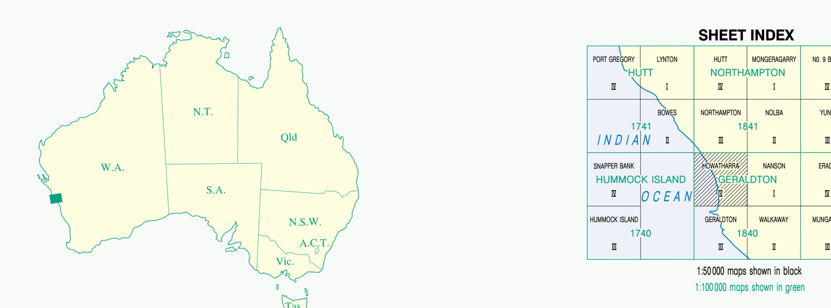
BLOCK DIAGRAMS



HOWATHARRA — MINERAL OCCURENCES

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.

SHEET INDEX



Geology by R. L. Langford 1998–99

Edited by D. Ferdinando and G. Loan

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

Topography from the Department of Land Administration Sheet SH 50-1, 1840, 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 Department of Land Administration and the Water and Rivers Commission

Published by the Geological Survey of Western Australia. Digital and hard copies of this map are available from the Information Centre, Department of Minerals and Energy, 100 PlainStreet, East Perth, WA, 6004. Phone (08) 9222 3459, Fax (08) 9222 3444

Plotted by the Geological Survey of Western Australia

The recommended reference for this map is:
LANGFORD, R. L., 2001, Howatharra, W.A. Sheet 1840-IV:
Western Australia Geological Survey, 1:50 000 Regolith–Landform Resources Series.

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

GOVERNMENT OF WESTERN AUSTRALIA
CLIVE BROWN, M.L.A.
MINISTER FOR STATE DEVELOPMENT; TOURISM; SMALL BUSINESS; GOLDFIELDS–ESPERANCE

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
TIM GRIFFIN, DIRECTOR

SCALE 1:50 000

1000 500 0 Metres — 1 2 3 4 5 Kilometres

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

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

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

WESTERN AUSTRALIA 1:50 000 REGOLITH–LANDFORM RESOURCES SERIES

HOWATHARRA

SHEET 1840-IV FIRST EDITION 2001