GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

MINERAL RESOURCES BULLETIN 10

HEAVY MINERAL SAND DEPOSITS OF WESTERN AUSTRALIA

1977

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HEAVY MINERAL SAND DEPOSITS OF WESTERN AUSTRALIA

by

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Issued under the authority of the Hon. A. Mensaros, M.L.A., Minister for Mines

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PREFATORY NOTE

From 1957 until the end of 1974 heavy mineral sands, chiefly ilmenite, some zircon and latterly rutile, have contributed $104 million to the value of mineral production in this State, the value for 1974 alone being nearly $20 million. These figures indicate the importance of this industry which has a further growth potential.

The industry is only young; continuous production commenced as recently as 1957, since which time it has quietly and confidently expanded. Initially all the mines were in the Bunbury-Capel-Busselton area but now the Eneabba-Jurien Bay area has commenced production, which is expected to expand rapidly.

The author has investigated the industry by visiting all established mines, proposed mines, prospects and reported mineral occurrences. He presents the results of his field investigations and literature search in this bulletin. It contains basic information on the minerals concerned, mode of occurrence, description of known occurrences and prospects, notes on exploratory methods used and an extensive bibliography.

This bulletin should become a necessary reference and guide for anyone interested in heavy mineral sands in this State.

2nd February, 1976.

J. H. LORD,
Director.

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CHAPTER 1

Introduction

Deposits of sand containing ilmenite, rutile, zircon, kyanite, monazite and xenotime have been mined continuously in Western Australia since 1956. These minerals are referred to collectively as "heavy minerals" and the sediment carrying them as "heavy mineral sand", or "mineral sand" for brevity in this bulletin. Production from the State up to 31 December 1974 was 7 560 706·83 t of heavy mineral concentrate which earned $104 043 650·97. A breakdown of production by deposit is given in Table 1.

The purpose of this bulletin is to provide information on heavy mineral sand deposits discovered in Western Australia prior to December 1974, and in so doing up-date an earlier summary by Low (1960). To assist present description and future prospecting, the deposits are grouped into areas based on their geographic and geological situations and relative importance (Fig. 1). A review of the geological and geomorphological features which are common to and may control the location of the deposits is presented to assist identification of potential areas of mineralization. Geomorphological terms used in this bulletin follow the definitions presented in Fairbridge (1968). A brief summary of the techniques of exploration is given, together with comments on their usefulness.

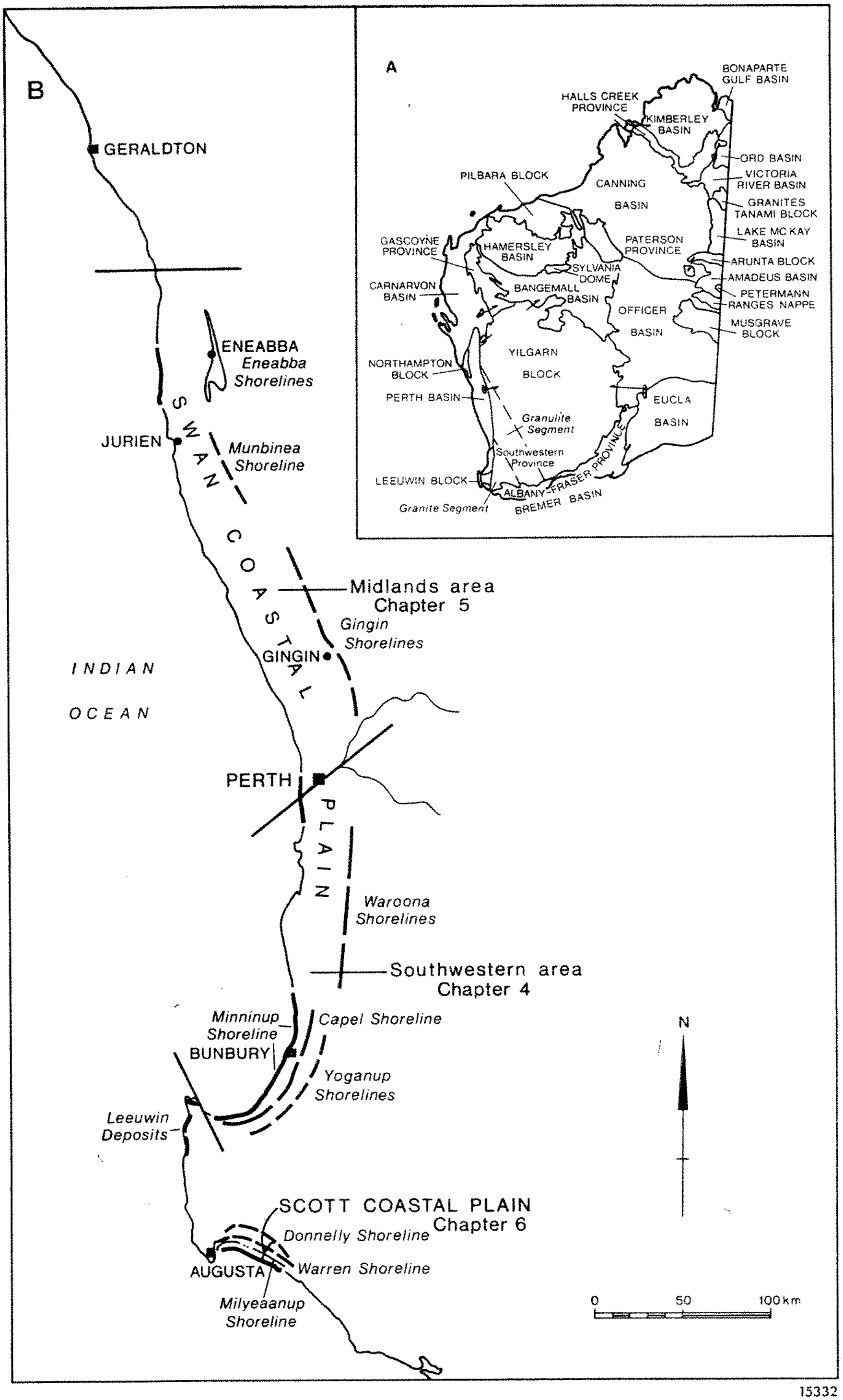
Studies of the sedimentology of heavy mineral sand deposits are considered to be outside the scope of this bulletin as at this time insufficient regional data are available.

HISTORY OF EXPLORATION AND PRODUCTION

Black sands on the coast of Western Australia have been known since the early 1940's, but prior to 1947 there was little interest in the deposits. In 1947 the Commonwealth Government initiated a nationwide survey of deposits containing radioactive minerals and the Geological Survey undertook to investigate the beaches and rivers of the State in a search for monazite concentrations. This investigation was completed in 1948. The results were not published but are held on Geological Survey of Western Australia files 12/1947, 17/1947 and 58/1948.

Early exploration for heavy minerals was restricted to the south coast and the southern part of the Swan Coastal Plain. High grade concentrations on the shore of Cheyne Bay, on the south coast, were first reported by Mr. F. Pinchin in 1947 and the deposit was brought into production by Rare Metals Pty Ltd in 1949 when 73·1 t of heavy mineral concentrate were produced. This, the first

Figure 1. A. Map of Western Australia showing main tectonic units. B. Map of Southwestern portions of Western Australia showing heavy mineral bearing shorelines described in Chapters 4, 5 and 6.



A
BONAPARTE GULF BASIN
HALLS CREEK PROVINCE
KIMBERLEY BASIN
ORD BASIN
VICTORIA RIVER BASIN
PILBARA BLOCK
CANNING BASIN
GRANITES TANAMI BLOCK
LAKE MC KAY BASIN
GASCOYNE PROVINCE
HAMERSLEY BASIN
PATERSON PROVINCE
ARUNTA BLOCK
SYLVANIA DOME
AMADEUS BASIN
CARNARVON BASIN
BANGEMALL BASIN
PETERMANN RANGES NAPPE
OFFICER BASIN
MUSGRAVE BLOCK
YILGARN BLOCK
NORTHAMPTON BLOCK
PERTH BASIN
EUCLA BASIN
Granulite Segment
Southwestern Province
ALBANY-FRASER PROVINCE
LEEUWIN BLOCK
BREMER BASIN
Granite Segment
B
GERALDTON
ENEABBA
Eneabba Shorelines
JURIEN
Munbinea Shoreline
SWAN COASTAL PLAIN
Midlands area Chapter 5
Gingin Shorelines
GINGIN
INDIAN OCEAN
PERTH
Waroona Shorelines
Southwestern area Chapter 4
Minninup Shoreline
Capel Shoreline
BUNBURY
Yoganup Shorelines
Leeuwin Deposits
N
SCOTT COASTAL PLAIN Chapter 6
Donnelly Shoreline
AUGUSTA
Warren Shoreline
Milyeaanup Shoreline
0 50 100 km
15332

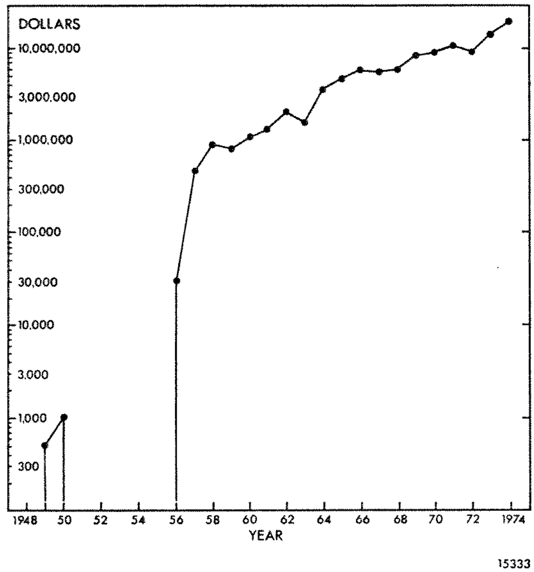


Figure 2. Realized value of annual heavy mineral production in Western Australia.

mineral sand mining in Western Australia, was short lived, terminating in 1950. From the latter part of the 1940's, prospecting activity in the south of the Swan Coastal Plain intensified and by 1959 there were mines at Koombana Bay, Capel, Yoganup and Wonnerup in the Bunbury-Capel area producing ilmenite, leucoxene, rutile, zircon, and monazite. In 1949 Mr. H. J. Thorley pegged the Koombana Bay deposit which was brought into production by Perron Bros Pty Ltd and Cable (1956) Ltd in 1956. In 1954, Mr. H. B. Giddens pegged the Capel South deposit and following further pegging by Mr. J. M. Joice and Mr. F. G. Foreman, Western Titanium N.L. was formed and brought the deposit into production in 1957. Westralian Oil N.L. (later Westralian Sands Ltd) began testing heavy mineral concentrations in the vicinity of the Yoganup Central and Capel North deposits in 1954 and commenced mining in 1959 and 1964 respectively. In 1959 Ilmenite Minerals Pty Ltd began mining the Wonnerup Beach deposit and early in the 1960's they opened a pit on the Wonnerup deposit. In 1966 Cabel (1956) Ltd (now Cable Sands Pty Ltd) took over Ilmenite Minerals Pty Ltd and mining of the Stratham South and Wonnerup deposits was started on a large scale. The mines at Koombana Bay and Wonnerup Beach closed in 1966 and 1967 respectively, and mining at Yoganup Central will cease in the near future.

Exploration for heavy mineral deposits north of Perth during 1969 and 1970 led to the pegging of the core of the Eneabba deposit by Mr. J. R. Adamson in September, 1970. News of this find led to extensive exploration north of Perth and to the discovery of the Jurien deposit by West Coast Rutile Pty Ltd (subsequently Black Sands Ltd, now owned by W. M. C. Mineral Sands Pty Ltd), and the Regans Ford and Gingin deposits by Westralian Sands Lennard Explorations. Mines have been established on the Eneabba deposits by Allied Eneabba Pty Ltd, and Jennings Mining (Australia) Pty Ltd. Western Titanium Ltd are planning to begin mining in the near future. The Jurien deposits are being evaluated by W.M.C. Mineral Sands Pty Ltd; Westralian Sands Lennard Explorations are currently conducting feasibility studies on the Gingin deposits.

Figure 2 shows the realized earnings of the total production of heavy mineral sands from Western Australia.

MINERALOGY

The mineral names currently employed in the mineral sands industry are "commercial names", controlled as much by the specifications of physically produced products as by their mineralogy. Individual mineralogical descriptions are given below. The specific gravity (S.G.) is given first, followed by the hardness on Moh's scale (H.), and a general description.

ILMENITE

S.G. 4·5–5 H. 5–6

Ilmenite, the commonest heavy mineral in the Western Australian mineral sand deposits, is an oxide of iron and titanium with the general chemical formula $(Fe,Ti)_2O_3$, containing between 44 and 60 per cent by weight of TiO_2.

In reflected light ilmenite is isotropic and usually has a moderate bireflectance. Where seen in igneous rocks, it commonly has lamellae of hematite, but these are rare in ilmenite in heavy mineral sands. Ilmenite is distinguished from magnetite by its magnetic properties and unlike hematite, it has a black streak.

ALTERED ILMENITE

Altered ilmenite (Temple, 1966) is produced where some iron is removed from ilmenite by solution to form a mixture of ilmenite and amorphous iron-titanium oxide. Bayley and others (1956) describe this process and show that it forms a continuous chemical series by the alteration of ilmenite to leucoxene. The alteration is caused by groundwater percolating through the enclosing sediments, dissolving some ferrous iron and oxidizing the remainder to ferric iron; excess titanium is deposited as rutile crystallites. This process occurs above the water table and is effectively a form of supergene enrichment (Ziv, 1956). Temple's summary of the alteration process is illustrated in Figure 3, to which are added analyses of Western Australian ilmenites and altered ilmenites. Figure 4 shows microphotographs in reflected light of ilmenite, altered ilmenite and leucoxene, and serves to illustrate the alteration process.

Altered ilmenite is a complex mixture of amorphous and crystalline components and generally has a lower reflectivity than ilmenite It is isotropic. Examples of the mineral from the Capel area contain intergrowths of ilmenite-rutile, ilmenite-hematite, and ilmenite-spinel (MacDonald, 1964). In commercial practice the term "altered ilmenite" refers to a product transitional between ilmenite and leucoxene, having between 65 and 87 per cent by weight of TiO_2. In general this product has a moderate to high solubility in sulphuric acid—an important factor in the sulphate route (see p. 17 footnote). Deposits on the Yoganup line and in the Midlands area contain a high proportion of altered ilmenite in the heavy mineral fraction.

LEUCOXENE

S.G. 3·5–4·5 H. 4–5·5

Leucoxene is not a distinct mineral species, but is the stage in ilmenite alteration before crystallization of rutile. Various authors have described leucoxene as a mixture of minerals including arizonite, pseudorutile and pseudoanatase, but the validity of these mineral species is still in dispute. As

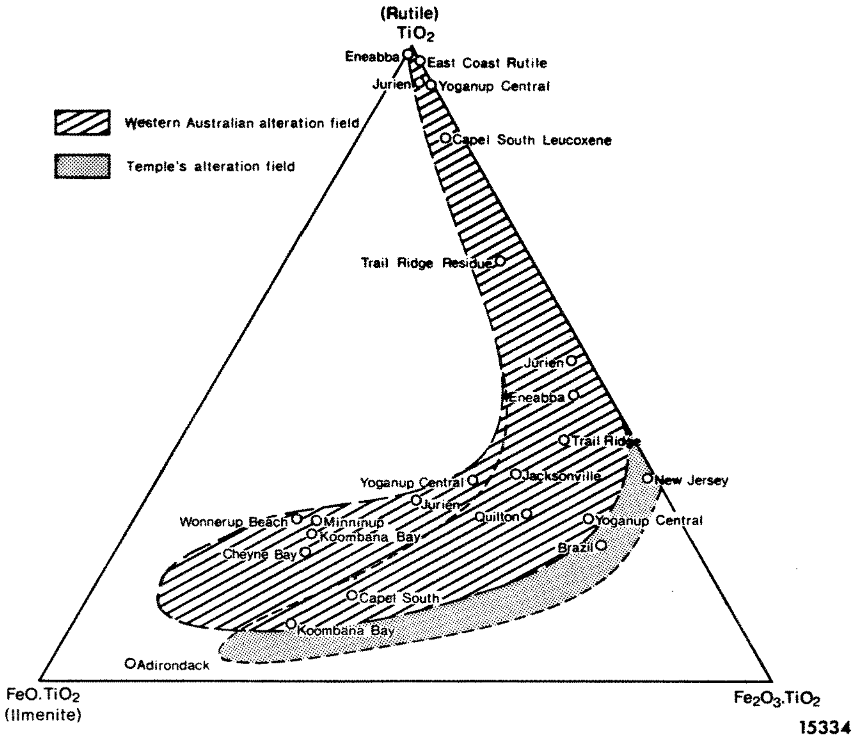


Figure 3. Diagram showing variations in chemical compositions of ilmenite altering through leucoxene to rutile.

leucoxene is a distinctive material with a relatively consistent chemical composition, it is convenient to refer to it as a mineral possessing its own properties.

The mineral is a white to yellow-brown amorphous iron-titanium oxide mixture. In thin section it is highly reflective with low to moderate relief and has patchy bireflectance. It contains between 88 and 94 per cent by weight TiO_2.

RUTILE

S.G. 4·2 H. 6–6·5

Rutile is a translucent to opaque oxide of titanium; its TiO_2 content is generally higher than 94 per cent by weight. When translucent it is seen to exhibit parallel extinction and has a high refractive index with extremely high birefringence; in some sections the mineral is pleochroic. In reflected light rutile is usually greyish-white and anisotropic. It is characterized by strong internal reflection and moderate reflectivity.

ZIRCON

S.G. 4·2–4·9 H. 7·5

Zircon is a zirconium silicate with the general chemical composition $ZrSiO_4$, but small amounts of hafnium commonly replace the zirconium. It usually occurs as stumpy to prismatic grains and varies from colourless to yellow, brown or pink. It is translucent to transparent, with parallel extinction, moderately high refractive index and a uniaxial positive optic sign.

A

B

C

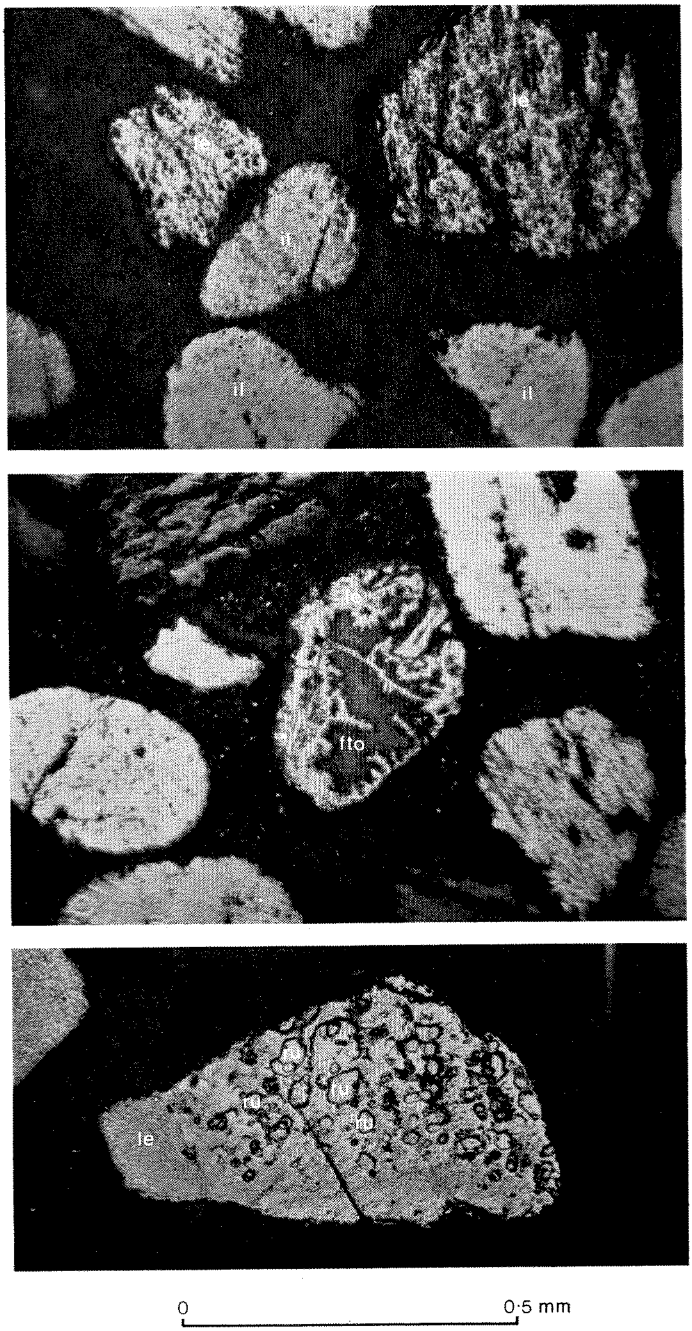


Figure 4. Photomicrographs showing alteration of ilmenite to rutile by supergene enrichment. A. Ilmenite (il) and leucoxene (le). B. Leucoxene (le) forming from amorphous iron-titanium oxide (fto). C. Rutile (ru) crystallites forming from leucoxene (le).

KYANITE

S.G. 3·5–3·6 H. 4–8 (varies with crystallographic direction)

Kyanite is an aluminium silicate with the general chemical composition Al_2SiO_5. It is particularly common in mineral sands in the Midlands area. The mineral is transparent. Characteristic microscopic properties are: a perfect basal cleavage which commonly controls the position of the grain in grain mounts, its white to pale blue colour, an extinction angle of about 30 degrees and a biaxial negative optic sign. In mineral sands it commonly occurs as large, moderately rounded grains.

MONAZITE

S.G. 4·9–5·4 H. 5–5·5

Monazite is a phosphate salt of rare earth elements with the general composition (CeLaYt) PO_4 but often contains a little thorium in the crystal lattice. Monazite from Capel contains inclusions of iron oxide and occasionally of liquid (Baker, 1959). The mineral is translucent, usually yellow to brown but may be a reddish-brown to black colour if inclusions are common. Monazite usually occurs as rounded to ellipsoidal grains. The grains often have a slightly oblique extinction between 2 and 10 degrees, a refractive index between 1·78 and 1·85 and strong birefringence. They have a biaxial positive optic sign.

XENOTIME

S.G. 4·59 H. 4–5

Xenotime is essentially a phosphate salt of yttrium but usually has varying amounts of erbium, cerium and thorium in the crystal lattice. The generalized chemical composition is YPO_4. Foster (1949) and Hutton (1947) present detailed studies of the variations of xenotime and its relationship to similar minerals. The mineral is usually translucent, brown to yellow and occurs as rounded to prismatic grains. It has parallel extinction and a high refractive index between 1·72 and 1·82, with strong birefringence. The mineral has a uniaxial positive optic sign and is sometimes weakly pleochroic.

OTHER MINERALS

Descriptions of other minerals found in mineral sand deposits appear in Hutton (1952) and Baker (1962). In general they are grouped as "others" in heavy mineral estimations made by the mining industry. They include garnet, tourmaline, spinel, staurolite, pyroxene, hornblende, chromite, magnetite, hematite, limonite and apatite. All have been recorded from Western Australian deposits but not in economic quantities.

MINING METHODS

Extraction and treatment methods were reviewed by Blaskett and Hudson (1965). Heavy mineral deposits usually consist of unconsolidated clayey sands for which the most economic method of mining is dredging. The Stratham South, Capel North and some Eneabba mines are dredged at the present time and the Wonnerup Beach and Koombana Bay deposits have been dredged in the past. Where the sand has a ferruginous cement, forming coffee-rock (p. 36), or where it has an irregular base, it is impracticable to dredge, and sluicing or methods using backhoes, draglines, rubber-tyred front-end loaders, bulldozers or scrapers in conjunction with trucks are employed.

Coffee-rock often contains up to 90 per cent heavy minerals and various attempts to recover them have been made. Use of explosives and chemical scrubbing after crushing has generally proved uneconomical, but the application of acid, if readily and cheaply available, can disintegrate coffee-rock with moderate success. Nevertheless coffee-rock is seldom treated because recovery of

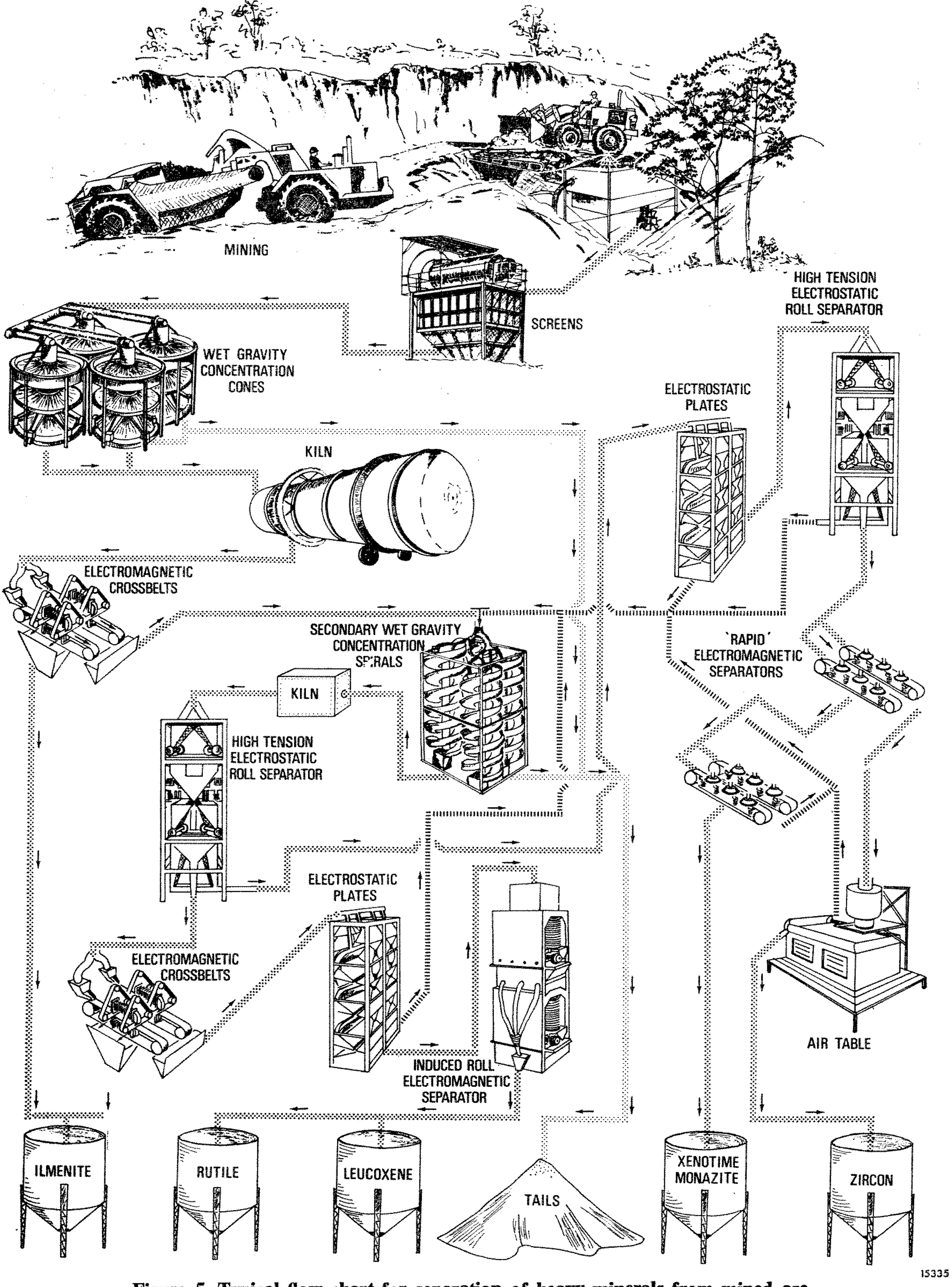


Figure 5. Typical flow chart for separation of heavy minerals from mined ore.

heavy minerals is poor and when recovered, grains are commonly thickly coated with iron oxide.

The treatment of heavy mineral sand is relatively simple since individual species are separated by physical means. The heavy mineral fraction is first obtained by gravity separation using various combinations of cones, spirals and sluice traps. Middling products are usually recycled. The various minerals are then separated by magnetic and electrical methods, and zircon is cleaned up on air tables. A flow sheet of a typical heavy mineral separation plant is shown in Figure 5.

USES OF THE MAIN PRODUCTS

ILMENITE

The main use of ilmenite is in the manufacture of titanium dioxide pigment by the sulphate route*. This pigment is white with high opacity; it is non-toxic and is used extensively in the paint industry. The pigment is also required in the manufacture of ceramics, rubber, ink, coated textiles, paper fillers, transducers and gems. A little ilmenite is used as a metallurgical feedstock for the manufacture of ferro-titanium, aluminium alloys and as electrode coating.

RUTILE

Rutile contains little iron and is a richer source of titanium than ilmenite. It is the main raw material used in the chloride route† for manufacture of titanium dioxide pigment. Rutile is used extensively as a flux coating for welding rods, and raw material for the titanium metallurgical and chemical industries.

LEUCOXENE AND ALTERED ILMENITE

Altered ilmenite contains more titanium than its parent, and providing it is soluble in sulphuric acid, can be used as feedstock for the sulphate route for manufacturing titanium pigment. In general altered ilmenite can be mixed with ilmenite as feedstock for synthetic rutile plants such as that operated by Western Titanium Ltd at Capel.

Leucoxene may be substituted for rutile for some purposes, and is used to coat welding rods, for chloride route pigment manufacture and as feedstock for synthetic rutile or titanium sponge.

ZIRCON

Zircon is a high-refractory mineral used extensively in foundry industries, zircon refractories, high grade castings and in the aluminium and glass industries. It is employed in opacifying ceramics. Zirconium compounds derived from zircon are used as high temperature refractories in rocket technology as polishers and tanning agents, and small quantities of zircon are reduced to zirconium metal for use in sophisticated products such as atomic reactors.

MONAZITE AND XENOTIME

Monazite and xenotime are the major sources of rare earth elements and thorium. The rare earth oxides market is expanding

* In the sulphate process, ground ilmenite is reacted with sulphuric acid and the product dissolved in water or recycled acid. After adjusting the oxidation state and level of iron in solution, titanium dioxide of the desired physical form is precipitated under controlled conditions and a pigment-grade product prepared by careful washing and calcination.

† In the chloride process, rutile is reacted with gaseous chlorine in the presence of carbon to produce impure titanium tetrachloride, which is purified by fractional distillation and oxidized under controlled conditions to form pigment of the required properties. Rutile is the preferred feed because its low iron content lessens chlorine consumption and the problem of ferric chloride waste disposal.

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owing to their use in colour television and exhaust scrubbers. The principal consumption of rare earth oxides is as additives in glass manufacture, carbon arcs and metal alloys (Callow, 1966).

KYANITE

Kyanite, like zircon, is a refractory mineral, used in the manufacture of high quality refractory bricks. It is also a source of alumina in metallurgical processes. Other applications are in glass manufacture, boiler and furnace lining, and in the foundry industry.

ACKNOWLEDGEMENTS

I wish to acknowledge the assistance given by members of the Government Chemical Laboratories, and the Drafting and Statistics branches of the Department of Mines in the presentation and collection of information used in some sections of this bulletin.

The assistance of all operating companies and many exploration companies who have kindly permitted the publication of data from their private records has enhanced the bulletin content. Each report referred to is acknowledged in the text.

ABBREVIATIONS AND STATISTICS

All heavy mineral and other per cent values are WEIGHT per CENT, unless otherwise stated.

t	:	tonnes
M	:	million, 10^6
LTO	:	Lands Title Office
M.C.	:	Mineral Claim
D.C.	:	Dredging Claim
h.m.	:	heavy mineral
m.s.l.	:	mean sea level

CHAPTER 2

Production, Reserves and Resources

PRODUCTION

Production figures are derived from company reports and returns to the Department of Mines. Between 1949 and 1974 heavy mineral sand mining in Western Australia produced a total of 7 560 706·83 t of ilmenite, leucoxene, rutile, zircon, monazite, xenotime and crude concentrates. The realized value of sales up to December, 1974 was $104 043 650·97. The tonneages and values of the individual minerals sold, taken from the Mines Department Annual Reports, are given in Table 1. The average f.o.b. price received from sales of heavy minerals in 1974 is given in Table 2.

TABLE 1. TOTAL PRODUCTION OF HEAVY MINERAL PRODUCTS REPORTED TO THE WESTERN AUSTRALIAN MINES DEPARTMENT BETWEEN 1949 AND 1974 INCLUSIVELY

Mineral	Realized Production*	
	Tonnes	Value ($)
Ilmenite†	6 919 276·75	74 761 102·10
Leucoxene	82 637·37	5 648 281·96
Rutile	26 440·59	2 800 949·87
Zircon	502 331·40	17 055 685·46
Monazite	29 659·96	3 563 188·71
Xenotime	202·31	212 889·87
Crude Concentrates	158·45	1 553·00

* Realized production is that sold.

† In addition 54 930·2 t of upgraded and reduced ilmenite has been produced.

TABLE 2. AVERAGE F.O.B. PRICE PER TONNE FOR HEAVY MINERAL PRODUCTS IN 1974

Mineral Product	Average Price ($)
Ilmenite	13·16
Leucoxene	104·41
Rutile	134·39
Zircon	68·16
Monazite	145·20
Xenotime	809·10

The status of the Western Australian mineral sands industry, within both the Australian and world marketing scene, is discussed by Bambrick (1971), Ward (1973), Industrial Minerals (1974), and Alfredson and others (1974). Production of individual heavy minerals is listed in Table 3 and commented on below.

Ilmenite is the principal heavy mineral obtained from Western Australian deposits. Up to 1969 only ilmenite suitable for sulphate route production of titanium dioxide pigment was marketed, but the commissioning of an ilmenite up-grading plant at Capel, in 1969, opened up the market for altered ilmenite. In the period between 1969 and 1974, 54 930·20 t of up-graded and reduced ilmenite were produced. When the Eneabba mines come into production, ilmenite, containing higher vanadium and chromium than that in deposits of the Southwestern area,

TABLE 3. TOTAL PRODUCTION* OF HEAVY MINERAL PRODUCTS FROM INDIVIDUAL DEPOSITS IN WESTERN AUSTRALIA TO 31 DECEMBER 1974

Deposit	Company	Production in Tonnes							
		Ilmenite	Leucoxene	Rutile	Zircon	Monazite	Xeno-time	Crude Concen-trate	Total Individual Deposit
Southwestern area									
Capel South	Western Titanium Ltd	2 721 266·01 (*a*)	10 511·95	18 017·60	238 339·87	16 463·00	202·31		3 004 800·74
Capel North	Western Mineral Sands Pty Ltd	1 562 393·64			57 687·22 (*b*)	4 937·26 (*b*)			1 625 018·12
Stratham South	Cable (1956) Pty Ltd	694 290·87	25 292·26		42 934·53	2 140·02			764 657·66
Wonnerup	Cable (1956) Pty Ltd	183 502·26	12 558·58		21 199·66	711·04			217 971·54
Yoganup Central and Extended	Westralian Sands Ltd	1 305 588·79	33 949·58	1 172·82	136 853·83 (*c*)	5 309·20 (*c*)			1 482 874·22
Koombana Bay	Cable (1956) Pty Ltd	227 550·39			3 481·12	99·44			231 130·95
Wonnerup Beach	Cable (1956) Pty Ltd	194 693·38							194 693·38
Cheyne Bay	Rare Metals Pty Ltd....							158·45	158·45
Total		6 889 285·34	82 312·37	19 190·42	500 496·23	29 659·96	202	158·45	7 521 305·06
Midlands area									
O'Connor	Jennings Mining Ltd (d)	27 041·00	325·00	7 125·00	4 627·00				39 118·00
Adamson	Allied Eneabba Pty Ltd (d)	3 137·55		337·02	207·78				3 682·35
Total		30 178·55	325·00	7 462·02	4 834·78				42 800·35
State Total		6 919 646·89	82 637·37	26 652·44	505 331·01	29 659·96	202	158·45	7 565 106·41

* Figures based on those from Department of Mines (Statistics Branch) and supplemented by company information.
(a) 54 930·20 t of upgraded and reduced ilmenite produced from this mine.
(b) Up to 1972.
(c) Includes Capel North production 1973 and 1974.
(d) First production from new mines in 1974.

Table 4. Total Identified Heavy Minerals in Ground in Western Australian Deposits as Reported to the Mines Department in March 1973

Area	Demonstrated Reserves of Heavy Minerals						Inferred Heavy Minerals *Tonnes*
	Measured *Tonnes*	Indicated *Tonnes*	Grade of Ore *Wt. Per Cent*	Composition of Heavy Mineral Fraction *Weight Per Cent*			
				Ilmenite	Rutile	Zircon	
Scott Coastal Plain, Bremer Basin, Leeuwin Block....	....	7 563 300	9·9	65·9	3·4	6·1	2 461 000
Southwest (Busselton, Capel etc.)	16 420 000	13 120 700	14·4	77·2	1·0	7·3	3 161 000
Midlands (Eneabba, Jurien etc.)	24 849 000	8 907 800	9·34	56·8	8·48	21·3	3 158 300
Miscellaneous (excludes Onslow and Lockyer prospects)	....	2 021 000	....	....	....	....	26 100 000
State Totals	41 269 000	31 612 800	....	....	....	....	34 880 300

Table 5. Published Reserves (including possible ore) of Heavy Minerals in Western Australia, December 1974

Deposit	Average Grade *Weight Per Cent*	Proved*	Probable*	Possible*	Ilmenite	Rutile	Zircon
			Tonnes			*Weight Per Cent*	
Capel South (a)	....	6 600 000	1 300 000	....	....	....	....
Adamson deposit (a)	9·7	5 226 600	12 615 000	....	....	7·8	....
O'Connor and Dobney deposit (c)	....	....	9 550 000	....	....	....	....
Boodanoo (b)	....	....	....	1 000 000	55	....	....
Cheyne Bay (b)	50	....	304 800	....	73·5	2·6	19·7
Bremer Bay (b)	....	....	371 870	....	69·0	11·0	20
Minninup (b)	20	116 200	....	....	77	....	5
Wonnerup Beach (d)	....	130 443	....	....	85	2	6
Jurien (a)	9	1 178 000	710 000	1 158 000	55–60	10	10
Jurien (c)	7·4	2 032 000	477 520	609 600	....	....	....
Gingin (c)	10	1 500 000	....	....	....	....	....
Busselton (c, e)	....	+1000000	....	....	....	....	....
Totals	....	17 783 243	25 329 190	2 767 600	....	....	....

* These terms are approximately equivalent to measured, indicated and inferred.

NOTES: (a) Company report. (b) G.S.W.A. report. (c) Newspaper report. (d) Gardner (1951) less subsequent production. (e) Includes several deposits on Capel line and on Leeuwin Block.

will be produced. This ilmenite is not suitable for sulphate route pigment production, but may be converted to upgraded ilmenite for use in the chloride route.

Zircon is the major by-product recovered in the Southwestern area where it forms between 4 and 15 per cent by weight of the heavy mineral fraction. At Eneabba, anticipated zircon production will almost equal rutile production.

Leucoxene is a minor by-product in the Southwestern area. The market for leucoxene has been unstable but commissioning of the ilmenite up-grading plant which uses some leucoxene as feedstock may ensure a more uniform sale.

Monazite is a minor constituent of the heavy mineral deposits of Western Australia, with sales amounting to only 29 659·96 t to the end of 1974.

Until now *rutile* has been a minor by-product but larger tonneages will be produced as mines come into production at Eneabba where the heavy mineral fraction contains between 10 and 20 per cent by weight of this mineral.

Xenotime is a minor by-product at the Capel South mine. The recorded production between 1968 and 1974 is 202·31 t; sales realized $212 889·87.

RESERVES AND RESOURCES

Reserves are defined as deposits of heavy mineral bearing sediment from which heavy minerals can be extracted profitably under present economic conditions. In general, reserves are associated with mining operations and have been the subject of feasibility studies. Resources include heavy mineral deposits which may become commercial propositions but are not economic to mine at the present time, and are unlikely to be mined unless there is a substantial improvement in the prices of heavy minerals. Classification of reserves follows the system recommended by the Joint Committee on Ore Reserves of the Australasian Institute of Mining and Metallurgy, and the Australian Mining Industry Council (1972). The terms employed to qualify reserves and ore are respectively, measured, indicated, and inferred. These terms are used also to describe resources.

By March, 1973 heavy minerals in discoveries reported to the Mines Department amounted to 41·269 Mt of measured reserves, 31·612 Mt of indicated reserves and 34·9 Mt of inferred mineral. This information is expanded in Table 4. Published reserves and tonnes of inferred minerals are compiled in Table 5. The total measured and indicated reserves of 72·9 Mt (Table 4) considerably exceeds the publicly available figure of 43·1 Mt of the two corresponding categories in Table 5.

Reserves and resources of Western Australian heavy minerals are given in Table 6 (the figures are based on those of Table 4). Measured and indicated reserves amount to 61·5 Mt while reserves and resources together total 107·8 Mt (March, 1973).

TABLE 6. RESERVES AND RESOURCES OF HEAVY MINERALS IN WESTERN AUSTRALIA, MARCH 1973

	Measured	Indicated	Inferred
	Million Tonnes		
Reserves	39·506	22·0	....
Resources	1·763	9·6	34·9
Total Resources	41·269	31·6	34·9

CHAPTER 3

Geomorphological and Geological Setting

Ancient and modern shoreline sediments containing anomalous concentrations of heavy minerals occur in lacustrine, estuarine and marine environments, which often cannot be separated. However, a number of empirical observations may be made on what constitutes favourable geological and geomorphological conditions for accumulation of economic heavy mineral concentrations. The geomorphic controls appear to be a moderately mature drainage system with a nearby settling environment, such as a swale behind a foredune system, or an estuary; and a gently sloping beach with a strongly developed foredune system. Geological controls include the rock types in the source area (which determine the composition of the heavy mineral fraction); a periodic inflow of sediment into the settling system; and a persistent sorting medium such as wind, or swell waves on a microtidal coast. Co-existence of these controls, over a relatively short period only, is necessary for the formation of a heavy mineral deposit. For example, the discovery of the wreck of a whaler, thought to be the "North America" dating from either 1840 or 1843 (G. Henderson, pers. comm., 1973) in the Koombana Bay mine indicates that favourable conditions need not exist for more than 200 years for a heavy mineral deposit to accumulate. In Koombana Bay there appears to be no deposition of heavy minerals on the coast adjacent to the mine at present, but concentrations are forming on the beach north of Pelican Point, 2·5 km to the northeast along the coast. This could be a result of the construction of the breakwater on Casuarina Point and dredging in Koombana Bay and Leschenault Inlet.

EUSTASY

The different heights above sea level at which heavy mineral deposits have been discovered in Western Australia are commonly attributed to eustatic changes in sea level (world-wide variations in respective elevation of the land and sea). Changes in sea level are ascribed to various phenomena such as ice ages, major earth flexures, rate of rotation of the earth or the release of juvenile water. Application of the concept of eustasy has led to world-wide correlation of events and a time scale has been proposed based on melting curves and elevations of wave-cut terraces. Figure 6 illustrates this information for Western Australia.

Fairbridge (1947, 1948, 1958 and 1961) reviewed correlations based on eustatic phenomena. Most of the data is derived from elevations of wave-cut platforms along the modern coast where variation in sea level between —90 and +3 m are referred to the past 11 000 to 17 000 years. Evidence from Western Australia of variation in relative sea levels is summarized in Table 7. There is evidence of still stands of the shoreline at elevations ranging from 230 m above to 110 m below present sea level. The best preserved platform in Western Australia is that at +3 m. This can be traced from the Abrolhos Islands to Israelite Bay.

The presence of buried shoreline deposits on the Swan and Scott Coastal Plains, at varying distances from the modern coast, may reflect eustatic changes in sea level. The shoreline deposits are usually more complex than predicted from Figure 6, consisting of several wave-cut benches and associated beach deposits indicating that transgression (as at Yoganup Extended), regression and progradation (as at Minninup and Wonnerup Beach) have strongly modified predictable effects of eustatic changes of sea level.

Variations in shoreline position are related to eustasy, and are important in preserving beach deposits. Preservation of heavy mineral accumulations depends on the rate of transgression or regression of the shoreline after deposition, and the volume of sediment deposited at the time of sea-level fluctuation. In conditions of low sediment inflow, transgression will usually cause beaches to be preserved and sand dunes to be eroded while regression usually results in dunes being preserved and beaches eroded. With high sediment inflow at the time of transgression beach deposits are preserved though dunes may be redistributed, and during regression, both beach and dune sands may be preserved.

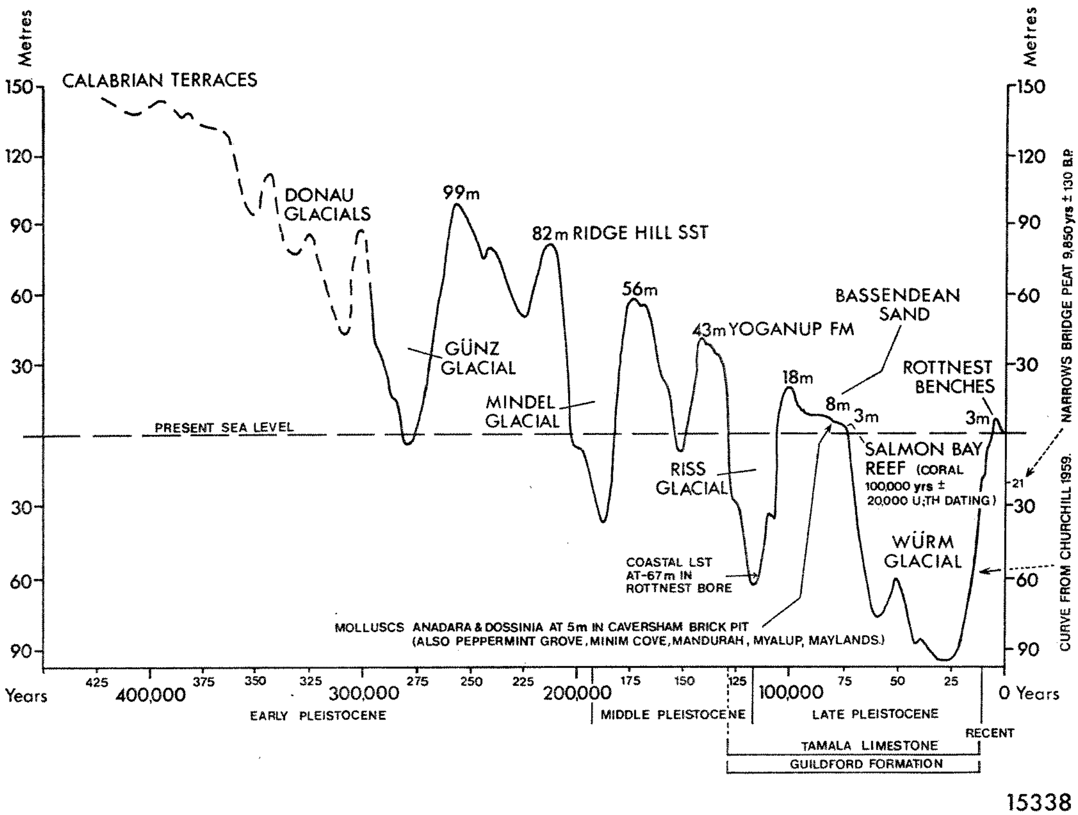

Figure 6. Diagram showing correlations between eustatic changes in sea level and Western Australian Quaternary deposits and sea stands.

TABLE 7. REPORTED ELEVATIONS OF SEA LEVEL STANDS IN WESTERN AUSTRALIA AND INTERNATIONALLY

Elevation above sea level (*metres*)	Locality	Evidence	Reference
230	South Coast areas	Sea caves, erosion notches	Clarke and Phillips (1953)
152	South Coast areas	Wave-cut bench, notches	Clarke and Phillips (1953)
137	Helena Valley	Wave-cut platform	Clarke and Williams (1926)
115	Eneabba	Beach deposits	Lissiman and Oxenford (1973)
103	Eneabba	Beach deposits	Lissiman and Oxenford (1973)
100	International	Pliocene	Fairbridge (1961)
97	Eneabba	Beach deposit	Lissiman and Oxenford (1973)
91	Eneabba	Beach deposit	Lissiman and Oxenford (1973)
76	Ridge Hill .... Helena Valley .... Swanview .... North Boyanup .... Gingin	Wave platform .... Wave platform .... Wave platform .... Beach deposit .... Beach deposit	Woolnough (1920) Clarke and Williams (1926) Fletcher and Hobson (1932) Sofoulis (1973) This bulletin p. 80
61–76	South Coast areas .... Yoganup Extended	Notches .... Beach deposit	Clarke and Phillips (1953) This bulletin p. 77
68	Parry Inlet .... Regans Ford .... North Boyanup	Beach or estuarine deposit .... Beach deposit .... Beach deposit	This bulletin p. 90 This bulletin p. 80 Sofoulis (1973)
60	International	Günz-Mindel high	Fairbridge (1961)
55–60	Waroona	Beach deposit	This bulletin p. 49
45–50	Yoganup Central	Sea cliff (46 m)	This bulletin p. 42
40–45	Mundijong .... Yoganup Extended	Beach deposit .... Sea cliff (43 m)	This bulletin p. 48 This bulletin p. 45
40	North Boyanup	Beach deposit	This bulletin p. 46
37	Yoganup Extended	Beach deposit	This bulletin p. 45
33–37	Bullsbrook	Beach deposit	This bulletin p. 80
35	Jurien prospect	Beach deposit	This bulletin p. 75

TABLE 7. REPORTED ELEVATIONS OF SEA LEVEL STANDS IN WESTERN AUSTRALIA AND INTERNATIONALLY—*continued*

Elevation above sea level (*metres*)	Locality	Evidence	Reference
30	South Coast areas .... Wagerup .... International	Notches .... Beach deposit .... Mindel-Riss high	Clarke and Phillips (1953) This bulletin p. 50 Fairbridge (1961)
27	Yoganup Central .... North Boyanup	Beach deposit .... Beach deposit	This bulletin p. 42 Sofoulis (1973)
25	Yarloop prospect	Sea cliff	This bulletin p. 50
20	Hamel prospect .... North Boyanup	Beach and estuarine deposits .... Beach deposit (21 m)	This bulletin p. 49 Sofoulis (1973)
15	Stoate 1000N .... International	Beach deposit .... Riss-Würm high	This bulletin p. 55 Fairbridge (1961)
14	Gosnells	Flat plain	Fairbridge (1947)
12–15	South Coast areas .... Israelite Bay .... Stoate 7000N	Notches .... Wave-cut platform .... Beach deposit	Clarke and Phillips (1953) Clarke and Phillips (1953) This bulletin p. 55
10	Stratham South .... Stoate 4000N	Beach deposit .... Beach deposit	This bulletin p. 53 This bulletin p. 55
8	Stoate 8000N .... Swan Coastal Plain	Beach deposit .... Series of lakes	This bulletin p. 55 Fairbridge (1947, 1948)
6	International .... Israelite Bay .... Capel South	Mid-Recent .... Wave-cut platform .... Beach deposit	Fairbridge (1961) Clarke and Phillips (1953) Fitzgerald (1975)
3	Rottnest .... Peppermint Grove .... Dillon Bay .... Cheyne Bay	Wave-cut platform .... Wave-cut platform .... Wave-cut platform .... Wave-cut platform	Teichert (1950) Fairbridge (1947, 1948) Clarke and Phillips (1953) Wilson (1927)
2	West Coast	Wave-cut platform	Fairbridge (1948, 1954)
1·5	Rottnest	Notch	Teichert (1950)
0·6	Rottnest	Notch	Teichert (1950) Fairbridge (1948, 1954)

SEA LEVEL

TABLE 7. REPORTED ELEVATIONS OF SEA LEVEL STANDS IN WESTERN AUSTRALIA AND INTERNATIONALLY—*continued*

Depth below sea level (*metres*)	Locality	Evidence	Reference
1	Bunker Bay	Beach deposit	This bulletin p. 83
2–3	West Coast	....	Fairbridge (1954)
3	Minninup	Beach deposit	This bulletin p. 57
6	Admiralty Chart .... Brockman	Ridge .... Beach deposit	Fairbridge (1947) This bulletin p. 98
9	West Coast	Association	Teichert (1950)
20	International	Günz low	Fairbridge (1961)
20–30	International	....	Fairbridge (1961)
45	West Coast	Admiralty Chart Ridge	Fairbridge (1950)
90	International	Mindel low	Fairbridge (1961)
95	International	Würm low	Fairbridge (1961)
110	International	Riss low	Fairbridge (1961)

Estimates of the age of heavy mineral deposits on the Swan Coastal Plain are commonly attempted by eustatic correlation by comparison with the international model. This method has recently had to be reconsidered, particularly since the likelihood of Cainozoic tectonism has been recognized (Cope, 1972). Any age determined by eustatic correlation therefore should be treated with caution. On the Swan Coastal Plain wave-cut platforms of different elevations are correlated by their geomorphic associations. Their varying elevations may be due to folding about east-west axes or differential compaction of underlying sediments.

Past fluctuations of sea level up to 10 m can be identified both on modern and fossil coastlines and these sometimes have led to preservation of individual beach deposits, particularly where progradation has taken place. One result of progradation is to separate beach deposits by bodies of mixed sands. For example, at the Adamson deposit the shorelines are separated by up to 50 m laterally. Where progradation did not take place, as on the less protected coast at the Dobney prospect north of Eneabba, the shorelines tend to be intermingled.

COASTAL ENVIRONMENT

Fairbridge (1968) described the features commonly associated with modern and ancient shoreline environments. Analyses of the modern coast provide some information on the nature of sedimentation and geomorphic processes leading to formation of heavy mineral deposits on shorelines of the past. For a heavy mineral deposit of economic importance to form it appears there should be a settling environment adjacent to a shoreline fed by drainage from heavy mineral bearing terrain; a moderately consistent current and wave pattern; an immature beach; and a protected shoreline.

SETTLING ENVIRONMENT

Drowning of modern rivers resulting in the large estuaries and inlets along the coast of Western Australia is attributed to the transgression of the sea during the past 10 000 to 20 000 years. Leschenault, Wonnerup and Gordon Inlets are examples of such estuaries. In these situations where there is periodic flow from major rivers into closed or sheltered water prior to entering the ocean, efficient separation of silt and sand occurs, the separated materials being flushed onto the coast during floods. Features that indicate a settling environment are identifiable in fossil shorelines, but obviously are less well preserved than along modern coasts.

The association of estuarine sediments with heavy mineral deposits is a common feature. In the Capel South mine a fossil estuary into which flowed the Ludlow and Capel Rivers, lies parallel to the ancient shoreline for about 1 km, on the east of the deposit. This "estuary" is a moderately prominent feature on aerial photographs. Shoreline deposits at the base of the Whicher, Darling and Gingin Scarps commonly have swamp, lacustrine, fluvial and marine sediments intimately intermixed.

CURRENTS AND WAVES

Currents, storm waves and swell are more efficient sorting agents on a microtidal rather than a macrotidal coast (Zenkovich, 1968); deposition of well-sorted sediments, including mineral sand, in the macrotidal environments is uncommon.

Long-shore currents transport significant amounts of shoreline sediments parallel to the beach. Along the west coast of Western Australia currents oscillate in direction, the southerly drift in winter being slightly stronger than the northerly drift in summer. Long-shore current on the west coast does not appear to be an important sorting agent. However, the south coast has a persistent westerly current which flows parallel to the coast and is the main sorting agent.

Swell and waves generated in the westerly wind system known as the "roaring forties" are the main agencies of sorting on the west and southwest coasts. Storm waves from the northwest impinge on the west coast and are generally destructive. Beach sediments are periodically removed by storm waves and deposited in the littoral zone adjacent to the coastline, such as on the exposed coast at Minninup. Destruction of a beach is followed by redeposition by swell and it is during this process that most of the sorting of the sediment occurs. This type of reworking of the beach deposits appears to have taken place on the fossil beach at the Capel South mine. While swell is the principal sorting medium, storms may be essential for the formation of larger heavy mineral deposits as these ensure complete reworking of the sand.

The relationship between currents, swell and waves appears to have been consistent since the formation of the earliest Cainozoic fossil beach deposits. The result is that beach deposits on the west coast tend to have sorting tails which point to the north and along the south coast, tails pointing to the east. There appear to be two main exceptions: in the Capel South and Eneabba mines, tails of the beach deposits point south. These may be due to local diffraction of predominantly southwest swell by reefs, offshore islands or bars in the vicinity of these deposits causing swell to impinge on the coast from a northwesterly direction.

COASTLINE SHAPE

Shape of a coast is controlled by the rock types exposed, the presence of reefs or islands offshore,and the direction of tides, storms and currents.

Coasts in these areas of apparent tectonic stability with gentle to moderate seaward slopes are commonly composed of sandy reaches between rocky headlands. Most beaches flanking the Scott and Swan Coastal Plains are straight, although interrupted by rocky headlands up to 20 km apart. Along the coast adjacent to the Naturaliste Region and the Albany-Fraser Province, where resistant igneous and metamorphic rocks are exposed on the coast, zeta (ζ) and omega (Ω) shaped bays are common with headlands 10 to 12 km apart.

Progradation of beach sediment on the coastline in Western Australia is common where a headland or promontory occurs which deflects the direction of the swell pattern. Progradation appears to be favourable for the preservation of mineral sands. At Eneabba on the 97 m level, two heavy mineral deposits have formed at the same elevation during different stages of progradation of a shoreline. Progradation has been reported from Busselton (Saint-Smith, 1912), Duke of Orleans Bay (Clarke and Phillips, 1953) and Koombana Bay.

BEACH MATURITY

A mature beach profile tends to be convex in shape. Most mineral sand deposits show moderately linear base profiles with a slight seaward dip thus indicating immaturity. The eastern shoreline at the Yoganup Central heavy mineral deposit is, exceptionally, a mature beach, though this deposit appears to be formed by erosion and redeposition of an earlier boulder and pebble beach. Most other beach deposits rich in heavy minerals, including the western shoreline at Yoganup Central, have distinctly immature base profiles.

Protection of some beaches by offshore features is common on all coasts. It is particularly well demonstrated along the Perth metropolitan coast where beaches like Sorrento, Kwinana and Rockingham, protected from storms by a chain of islands and reefs, are sandy and stable, whereas unprotected beaches like Scarborough and Triggs are exposed to erosion in stormy weather. The discontinuous nature of heavy mineral deposits on most shorelines suggests that mineral sands on flat open beaches require protection by off-shore features if they are to be preserved.

DUNES

Dunes are formed along coastlines by wind movement of local sand and consequently dunes containing heavy mineral deposits are likely to develop on the shoreward side of beach concentrations of heavy minerals. In general the dune sands are fine to very fine grained, moderately well sorted, and have slightly fine skewed grain-size distribution.

Modern dunes along the Western Australian coast are composed essentially of carbonate fragments. Some lithification occurs. In most dunes on the Minninup and Capel lines and in the Coastal Belt, bedding is preserved. Dips of bedding range from 10 to 15 degrees landward, to 15 to 25 degrees seaward. In general the base of a dune deposit is nearly horizontal but may dip seawards between 2 and 10 degrees, as at Minninup Beach, or be slightly arched, as at the Wonnerup mine. Bedding is delineated by orientation of platy minerals in inland dunes and carbonate fragments in the coastal dunes.

Heavy mineral concentrations commonly occur in the foredunes or in the first main line of dunes. All known dune deposits in Western Australia are found in transverse dunes, lying parallel to the coastline. Concentrations of heavy minerals up to 50 per cent by weight are commonly found on the face of the first main line of dunes and may be as much as 70 per cent by weight on faces of foredunes.

Lowry (1965) suggested that the fossil dune systems were originally calcareous, but are now completely leached of carbonate leaving quartz and heavy minerals. Reviewing the geology of heavy mineral deposits on fossil shorelines, such features as well-preserved delicate cross-bedding, paucity of limestone remnants in the deposits, and supergene enrichment of ilmenite (this takes place in acid conditions) indicate that the dunes were predominantly quartz sand at the time of deposition.

Shape and maturity of a beach, currents and waves, and tidal environment do not have any effect on the formation of dune heavy mineral deposits. It appears that, providing the wind transports sand from beaches to dunes and sorting occurs, heavy mineral deposits may form regardless of other coastal features. At Onslow a dune heavy mineral deposit has formed inland from a macrotidal coast, and at Hassels Beach a heavy mineral concentration occurs in dunes inland from minor heavy mineral concentrations on the beach. Heavy mineral bearing dunes may develop considerable distances from the shoreline and on precipitous coasts if onshore winds are sufficiently strong. For example, at Eneabba, dune deposits are up to 3 km inland from the fossil shoreline, and at Yallingup, dunes are blown up to 60 m above sea level along the coast.

Dune deposits are more likely to be preserved than beach deposits, as they are not subject to erosion by storm waves. Reworking of dunes is common, particularly following marine transgression. Modification of fossil dunes by wind and sheet erosion produces near-horizontal, wide sheets of slightly re-sorted dune sands which may in places contain sufficient heavy minerals to be mined, as at Yoganup Central.

PROVENANCE

The rock types present in the headwaters of rivers contributing sediment to the coast determine the composition of the heavy mineral fraction in a deposit. The main heavy mineral source is rock of the Precambrian nuclei, the geology of which is described in Western Australia Geological Survey Memoir No. 2. Heavy minerals appear to have been concentrated in some members of Mesozoic formations and eroded and redeposited in the Cainozoic heavy mineral deposits in the Perth Basin. The stratigraphy of the basin is described by Playford and others (1976), but Figure 7 summarizes the Mesozoic and Cainozoic units.

Heavy mineral deposits in Western Australia contain principally ilmenite, zircon, rutile and kyanite, the relative proportions of each species being dependent on rocks in the area of provenance. Ilmenite is commonly derived from mafic igneous rocks, being a common constituent of gabbro and basalt. Zircon is associated with felsic igneous and sedimentary rocks, and is a common accessory mineral in metamorphosed sediments and granitic rocks. Rutile is widely distributed as an accessory mineral and is commonly a minor constituent of metamorphosed rocks; it may also occur as a diagenetic mineral in sediments. Kyanite, unknown in igneous rocks, is common in sedimentary and metamorphic rocks.

Erosion of rocks in the primary source area is effected by abrasion usually associated with creeks. For most of the heavy mineral

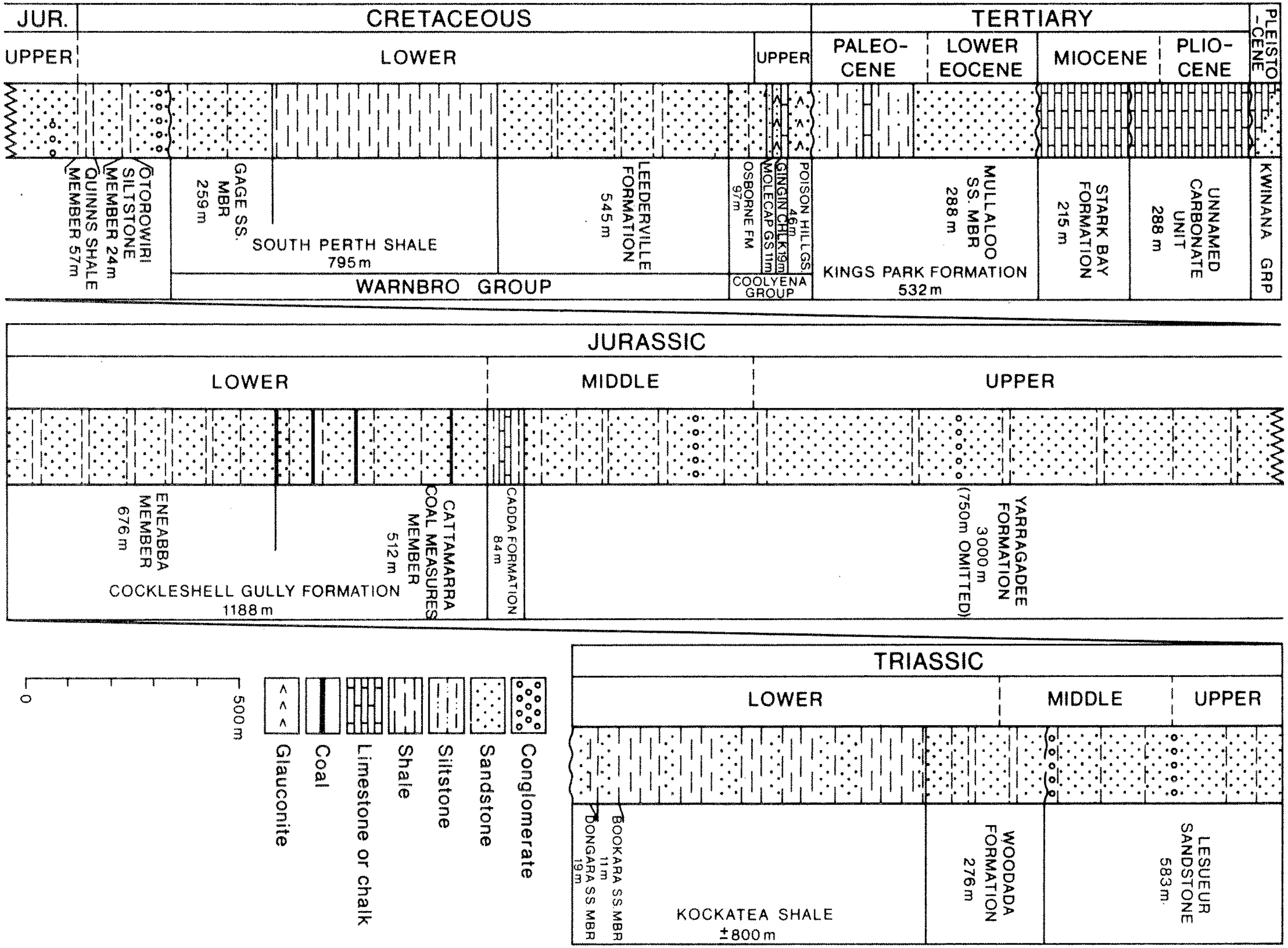

Figure 7. Stratigraphic column of the Mesozoic and Cainozoic rocks in the Perth Basin.

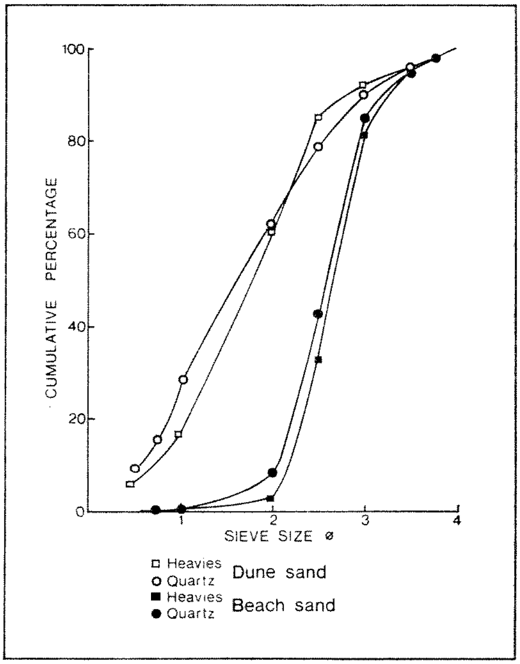

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Figure 8. Cumulative frequency diagram showing distribution of grain sizes of heavy minerals and quartz in beach and dune sands at Eneabba (after Lissiman and Oxenford, 1973).

deposits, the drainage contributing sediment to the coastal environment is a major river with a moderately mature valley in the lower reaches. The riverine transport of heavy mineral bearing sediments depends on the hydraulic and hydrodynamic properties of the sediment. Briggs (1965), Hand (1967) and Lowright and others (1972) have reported the hydrodynamic properties of light and heavy fractions of sediments and have generally concluded that the light and heavy fractions are not in hydraulic equivalence. This anomaly is usually explained as being due to varying types of transport such as saltation, rolling and suspension, or the difference in original grain size in the source area. Hand (1967) reported that grain sizes of heavy mineral fractions in beach and dune sediments are finer than predicted from hydraulic equivalent theory. The usual relationship between light and heavy fractions of beach and dune deposits is shown in Figure 8.

The influence of differing provenance is exemplified by the Midlands area (Chapter 5) which differs from the Southwestern area (Chapter 4) and the Scott Coastal Plain (Chapter 6) as the deposits contain a greater proportion of rutile and kyanite. The difference in provenance is due to variations in the geology of the Yilgarn Block. The source areas for Mesozoic and Cainozoic sediments in the Perth Basin are two segments, one granulitic and the second granitic, of the

TABLE 8. PROVENANCE OF HEAVY MINERAL DEPOSITS IN WESTERN AUSTRALIA

Deposits	Major Provenance	Minor Provenance
Adjacent to the Leeuwin Block	Leeuwin Block	....
Bremer Basin	Albany–Fraser Province	Yilgarn Block
Scott Coastal Plain	Granite segment of Southwestern Province	Leeuwin Block
Yoganup line		
Waroona line	Granite segment of Southwestern Province	
Capel line		
Minninup line		Leeuwin Block
Eneabba	Perth Basin: Yarragadee Formation	
Jurien	Lesueur Sandstone Yarragadee Formation	Granulite segment of Southwestern Province
Gingin		
Coastal	Yarragadee formation	
Midlands		
Perth Basin	Southwestern Province	....
Onslow prospect	Hamersley Basin	....
Hutt Lagoon prospect	....	Northampton Block
James Price Point		
Broome	Kimberley Block	Halls Creek Province
Gibbings Island		
Lake Boodanoo	Yilgarn Block (Boodanoo gabbro)	....

Southwestern Province of the Yilgarn Block (Gee, 1975). The granulite segment contributes rutile, kyanite and ilmenite (characteristically high in chromium) to the northern Perth Basin, while the granite segment is the source for ilmenite, with low chromium content and zircon, forming the usual mineral suite in the Southwestern area and Scott Coastal Plain. Ilmenite concentrations are recorded from lake shores at Lake Boodanoo and Lake Dumbleyung on rocks of the Yilgarn Block. Table 8 summarizes the provenances of most of the heavy mineral deposits in Western Australia.

55531—[3]

On the Swan and Scott Coastal Plains an immediate provenance for heavy mineral deposits can be a particular formation within the adjacent sedimentary rocks. It is likely that the Leederville Formation in the South-western area and Scott Coastal Plain, and the Yarragadee Formation in the Midlands area were major contributors of material to the shoreline deposits. These sediments probably had provenances comparable to the modern sediments now being derived primarily from the Yilgarn Block.

LITHOLOGIES OF HEAVY MINERAL DEPOSITS AND ASSOCIATED ROCKS

BEACHES, DUNES AND ASSOCIATED DEPOSITS

The composition and grain size of sediments in heavy mineral deposits are controlled directly by the nature of the rocks in the immediate provenance. For example, on the Swan Coastal Plain most of the sand-sized material is derived from reworking of Mesozoic rocks in the Perth Basin, while boulders, cobbles and pebbles in the base of beach deposits on the Yoganup and Waroona line are mainly derived from the "Kirup Conglomerate" (Taylor, 1971).

Bi-modal grain-size distribution of sediments in heavy mineral deposits is common in Western Australia. The basal sediment in most heavy mineral deposits is either conglomerate, grit or coarse-grained sandstone, the heavy mineral fraction often being in a medium to fine-grained interstitial sand. The bi-modal grain size can be seen best in the Yoganup line where there is a conglomerate with a matrix of fine to medium-grained heavy mineral bearing sand, and is demonstrated by sieve analyses of the sand in the deposits of the Minninup line as shown in Figure 9. These beach deposits are considered to have formed initially in moderate to high energy conditions, followed by a period of accretion and progradation during lower energy conditions when finer-grained sands were laid over earlier deposits. A modern analogy is seen in Cowaramup Bay on the west coast of the Naturaliste Region.

In Western Australia, ilmenite in heavy mineral deposits, at some distance from the source rocks, shows signs of weathering and enrichment in TiO_2 (p. 13). Alteration of feldspar in the original sediments has resulted in small rounded fragments of kaolin (e.g. Yoganup, Eneabba and Capel South) which increase the clay fraction of the heavy mineral sand. Enrichment of TiO_2 in ilmenite grains has been attributed to supergene enrichment by Ziv (1956), and is thought to have occurred in temperate climatic conditions.

ROCKS UNDERLYING HEAVY MINERAL DEPOSITS

In Western Australia beach deposits containing heavy minerals are usually incised into pre-existing consolidated sediments. In general immediately inland from beach deposits there is a small, but sometimes prominent, sea cliff on which berms develop and over which dunes form. These features are rarely exposed along a fossil shoreline but are sometimes identified as subdued modifications of slope on the modern surface.

The Yoganup, Donnelly, Capel and Warren Shorelines (see Fig. 1) overlie the Leederville Formation which consists of sandstone, siltstone and claystone. It is usually deeply weathered in surface exposure but fresh rock may contain feldspar. Heavy mineral slicks are common in sandy members of the formation and have probably been reworked in the younger beach deposits. At Yoganup Extended drilling has located Bunbury Basalt in a small fossil offshore island, and at Capel South boulders of Bunbury Basalt have been found in the base of the deposit.

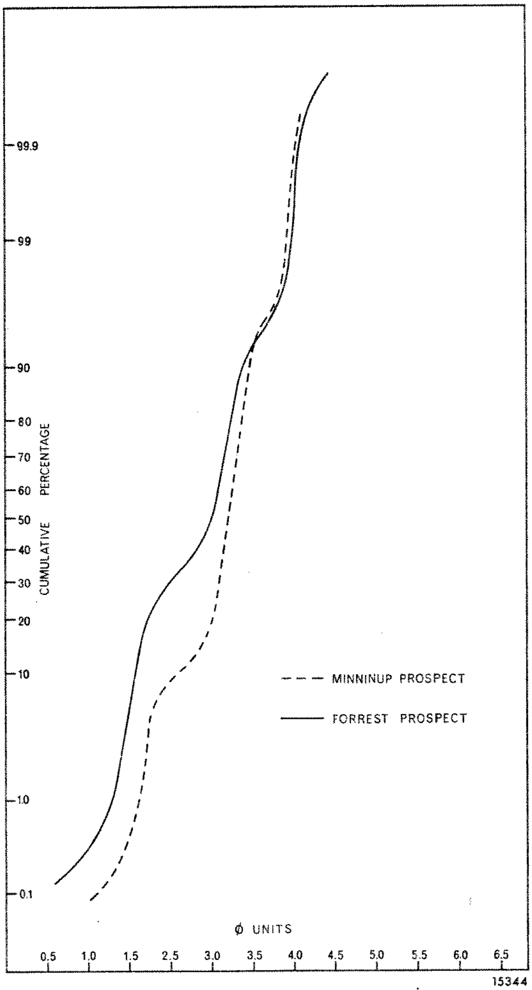

Figure 9. Cumulative frequency diagram showing distribution of grain sizes of beach sands from the Minninup and Forrest deposits.

Lesueur Sandstone and Cockleshell Gully Formation underlie the Munbinea Shoreline, where the main heavy mineral concentration is found on Lesueur Sandstone. This sandstone contains heavy minerals (Balme, 1969) which probably contributed to the beach deposits.

The Gingin and Eneabba Shorelines have beach sediments deposited on a floor of sandstone, siltstone and shale of the Yarragadee Formation. Heavy mineral bearing sediments, common in the formation, are exposed west of Three Springs and Arrino.

The coastal deposits between Onslow and Israelite Bay are adjacent to or overlie Tamala Limestone (formerly referred to as Coastal Limestone). It is a calcareous cemented arenite composed of shell fragments and quartz grains. The coastal deposits north of Broome overlie the Broome Sandstone.

OVERBURDEN

Heavy mineral deposits in Western Australia are generally at the surface, or carry only thin colluvial overburden derived from nearby higher areas. In some cases these thin covers are less than 10 cm thick (e.g. Eneabba, Capel North) but more often they are about 1 m thick.

Heavy mineral deposits at the foot of the Whicher, Darling and Gingin Scarps may be buried by up to 20 m of sand and clay deposited as alluvial fans. These fans may coalesce and cover the shoreline deposits entirely, as at Burekup.

The Tamala Limestone extends up to 20 km inland in some places on the Swan Coastal Plain and conceals ancient shoreline sediments in several places, such as those of the Munbinea and Capel Shorelines, at Jurien and Stratham North respectively. This limestone may have a hard siliceous or calcareous cap rock but is usually moderately friable at depth.

Overlying heavy mineral deposits in some areas are fine-grained sandstone and siltstone which vary in thickness from 1 to 10 m and contain only small amounts of heavy minerals. Associated with these sediments are carbonaceous shale and peat in discontinuous beds which vary between 50 cm and 2 m thick. The sandstone and siltstone appear to be an eolian deposit formed by redistribution of beach and dune sediments, while carbonaceous shale and peat have evidently been deposited in an estuary or swale during progradation of the coast.

COFFEE-ROCK

Terrill (1957) presented criteria for distinguishing between the iron-rich secondary rocks known as laterite and coffee-rock. After reviewing the terminology he concluded that the best definition of laterite is rock formed in place by breakdown and weathering of older rocks. Coffee-rock is developed at or near the water table by deposition of iron as cement. These definitions are accepted by the heavy mineral sand industry and are used in this bulletin.

Lissiman and Oxenford (1973) described three types of coffee-rock: massive, honeycomb and columnar. To this group the writer adds a fourth: pod-form variety. Massive coffee-rock is a hard, limonite-cemented sandstone. Honeycomb coffee-rock is a hard to moderately hard cellular rock with cell walls of limonite-cemented sand and ovoid to pipe-like pores of unconsolidated sand. Columnar coffee-rock is a moderately hard to friable rock composed of generally vertical planar limonite-cemented sand sheets set in an unconsolidated sand matrix. Pod-form coffee-rock consists of pods of cemented sand between 1 and 50 cm in diameter set in near-horizontal layers in a matrix of unconsolidated sand. The texture of the cement in all types of coffee-rock is similar and it is probable that the four classes represent stages in the formation of massive coffee-rock. With the exception of pod-form coffee-rock there are usually vertical linear structures in the cement parallel to the major direction of water percolation. These have been mistaken for root passages, but the phenomena occur in many localities where there are no roots.

The process by which coffee-rock forms has not been studied closely. Limonite appears to form as coats on individual sand grains which merge into pod-form coffee-rock and ultimately into the more structured honeycomb, columnar or massive forms. Limonite cementation in beach sand deposits is often erratic with no obvious control of the shapes of the cemented zones which lie from 10 cm to 1 m apart. It has been reported (J. Oxenford, pers. comm., 1973) that ilmenite from the coffee-rock contains less TiO_2 than that in the remainder of the deposit. This suggests that at least part of the supergene enrichment process occurred later than coffee-rock formation.

Chapter 4

Deposits of the Southwestern Area

The Southwestern area, for the purpose of this bulletin, consists of Swan Coastal Plain between the Swan River and Whicher Scarp (see Fig. 1). The Coastal Plain is made up of swamps, dunes, beaches, and river flats. Many of these features are now "fossil" in the sense that some are buried and others have only minor surface expression. Most of the commercial mineral sands are found in "fossil" beaches and dunes some distance inland from the present coast.

Before 1974, mining of deposits of heavy minerals was restricted entirely to the Southwestern area. Up to December 1974 $104 043 650.97 was earned from ilmenite, zircon, leucoxene, monazite, rutile and xenotime sales. The chief characteristic of deposits in this area is that the heavy mineral fraction is predominantly of high quality ilmenite. Zircon is commonly less than 20 per cent by weight, and the minor minerals are usually less than 5 per cent of the heavy mineral fraction.

In the past the ages of the deposits have been determined by reference to eustatic information, but there may be inaccuracies. There is, for example, evidence that the Capel Shoreline is of Early Pleistocene age and some thought that the easternmost strand lines at Yoganup may be as old as Late Tertiary. While absolute or relative age is of little importance when considering the accumulation of heavy mineral sands, such information, when available, could assist prospecting in view of the possibility of Cainozoic warping in the Perth Basin sediments (Cope, 1972). Heavy mineral deposits in the Southwestern area are grouped on the basis of their geomorphic positions.

PROSPECTING RECOMMENDATIONS

Heavy mineral prospecting along the recognized shorelines has been extensive, and has successfully located deposits along the length of the Yoganup and Waroona Shorelines, and in the southern part of the Capel Shoreline. Along the Yoganup and Waroona Shorelines heavy mineral deposits, large enough to be economic, are currently held by various exploration companies. The generally well preserved Capel Shoreline between Burregenup and Busselton is now well known. North of Burregenup this shoreline has not been recognized and its absence may be due to erosion of the shoreline by rivers such as the Harvey, Murray and Serpentine. As it is likely that the Capel Shoreline is not preserved in this area it follows that prospecting potential is low.

Should the concept of an association of estuaries with heavy mineral deposits be accepted, it is to be assumed there is a fair potential for deposits on the west of such features or their fossil equivalents. The Capel, Murray, and Preston Rivers and Gynudup Brook could have been associated with estuaries; exploration may locate deposits of heavy mineral in these localities.

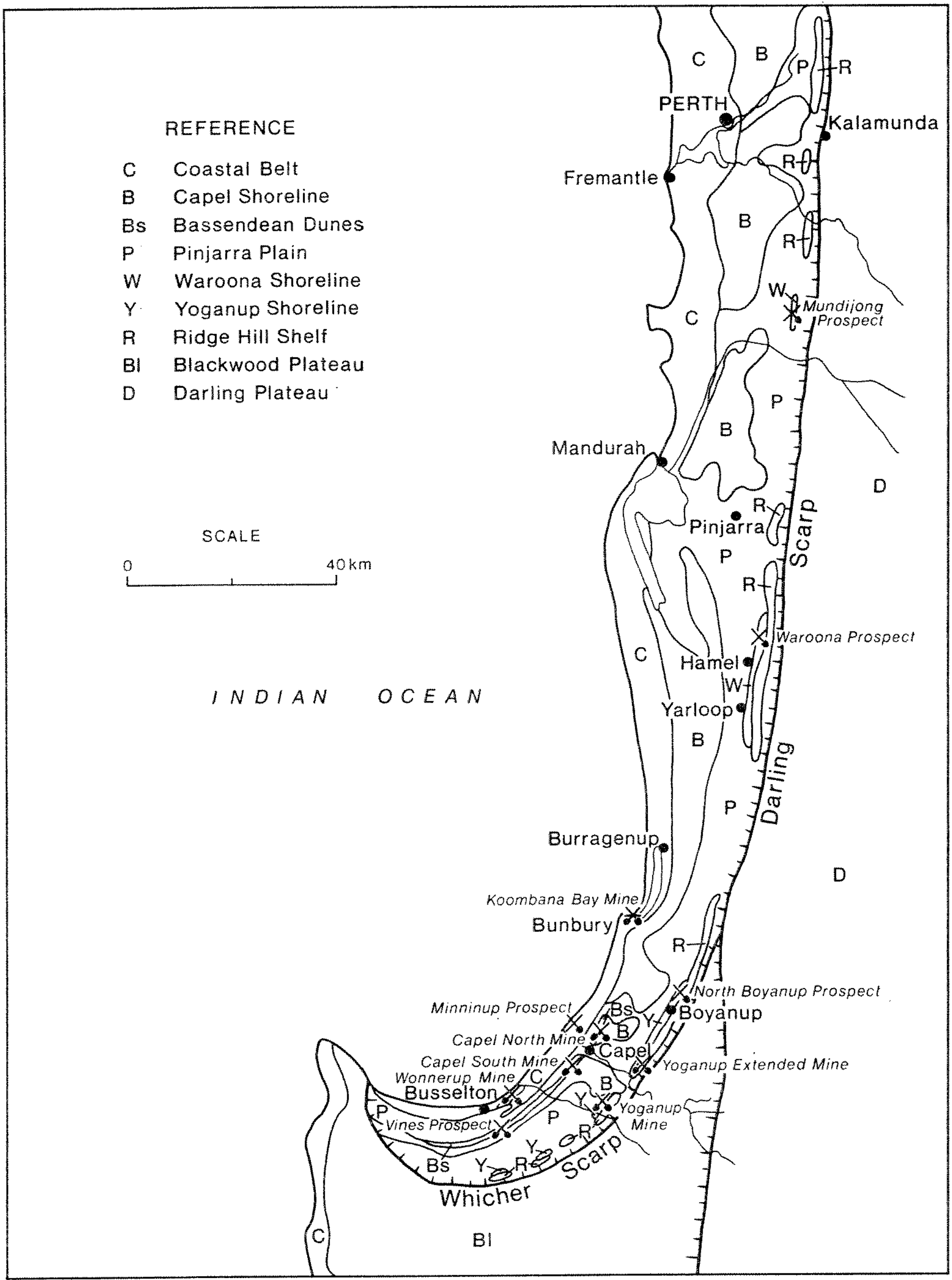

Figure 10. Map showing geomorphic units and heavy mineral deposits in the Southwestern area.

REGIONAL GEOMORPHOLOGY

Saint-Smith (1912) and Jutson (1912a) provide the earliest geomorphological descriptions of the Swan Coastal Plain. They were followed by Woolnough (1920), Prider (1948), McArthur and Bettenay (1960), Welch (1964), Lowry (1965), and Seddon (1972). The data now presented includes information collected by exploration companies and a proposed revision of terminology of published material. It is not exhaustive, but should illustrate adequately the geomorphic framework for the mineral sand prospector. Figure 10 shows the main geomorphic units.

The dissected *Darling Scarp* marks the eastern limit of the Swan Coastal Plain. The west-facing scarp has a maximum elevation of 300 m with relief up to 200 m. The term Darling Fault Scarp was introduced by Saint-Smith (1912) and Jutson (1912a), but is now replaced by Darling Scarp in useage.

The *Whicher Scarp* (Fairbridge, 1949) is an arcuate north-facing scarp formed by marine erosion and marks the southern limit of the Swan Coastal Plain. It was originally named the Collie-Naturaliste Scarp by Woodward (1917) and has been referred to as the Whicher Fault Scarp by some workers.

The *Ridge Hill Dune System* (Lowry, 1965), situated on the upper edge of the Ridge Hill Shelf, is a podsolized beach ridge and dune system incised into and overlapping the Whicher and Darling Scarps. The base of the Ridge Hill Dune System is approximately 76 m above sea level and can be traced from south of Busselton to east of Perth

The *Ridge Hill Shelf* (Woolnough, 1920) is a dissected surface up to 3·5 km wide at the foot of the Darling Scarp. The surface slopes gently west and has been deeply dissected by stream erosion. It is an old geomorphic feature and according to Seddon (1972) is restricted to the east side of the Darling Fault. The maximum elevation of the Ridge Hill Shelf is 76 m and it falls to the west, to about 45 m above sea level. The surface is generally composed of ferruginous, cemented detrital laterite.

The *Swan Coastal Plain* was defined by Saint-Smith (1912) as the plain between the Darling Scarp and the ocean. Now the plain is considered to be bounded to the east by the Ridge Hill Shelf. The main references on the Swan Coastal Plain are Woolnough (1920), McArthur and Bettenay (1960), Lowry (1965), and Seddon (1972).

The *Yoganup Dune System* is proposed for podsolized dunes and beach ridges at the foot of the Ridge Hill Shelf. It is a complex system of dunes and beach ridges lying between 25 and 50 m above sea level giving rise to a subdued topography. Good exposures of this system can be found in mineral sand pits on the Yoganup line.

The *Pinjarra Plain* (McArthur and Bettenay, 1960) consists of alluvial surfaces which slope westwards from a maximum of 45 m above sea level to 15 m. It may extend farther westwards beneath dunes. The plain attains its maximum width of about 13 km in the Pinjarra district, but is generally less than 8 km wide. Its alluvial surfaces are formed by coalescing alluvial fans which attain maximum altitudes at the mouths of gorges in the Darling Scarp. Commonly streams and rivers occupy notches in the summits of the alluvial fans but occasionally they have cut a course into lower country nearby. An example of an old stream is the ancestral Gynudup Brook which may have been a major contributor of material to the Pinjarra Plain (W. McArthur, pers. comm. 1973). In some places the Pinjarra Plain overlaps the Ridge Hill Shelf, as at Crooked Brook. Lakes, swamps and estuaries lying between the younger dune systems (Bassendean and Spearwood) on the seaward side of the Pinjarra Plain, are included in the unit. These features are usually flat bottomed.

The *Bassendean Dune System* (McArthur and Bettenay, 1960) is a group of low sand hills of siliceous and calcareous sand interspersed with swales. The dunes overlie the Pinjarra Plain, being formed along a former shoreline. Lowry (1965) considers that a beach line along the western margin of the Bassendean Dune System cannot be separated geomorphologically from the dunes. The western margin of the dunes lies approximately 5 m above sea level and their relief is rarely greater than 18 m. Sand-bottomed swamps are common in interdunal swales.

The *Spearwood Dune System* (McArthur and Bettenay, 1960) consists of a group of high dunes up to 8 km wide on the western side of the Swan Coastal Plain. The dunes have altitudes of up to 76 m. Lowlands east of the dunes separate them from the Bassendean Dune System which is thought to be older.

The *Quindalup Dune System* (McArthur and Bettenay, 1960) consists of lines of dune and beach ridges, parallel and adjacent to the present coastline, with swampy lakes or inlets on the landward side separating them from the Spearwood Dune System. It is usually less than 1·5 km wide. The dunes are usually partly fixed. In the Busselton area a prograding coastline (Saint-Smith, 1912, p. 74) forms part of the Quindalup Dune System. In places the dune system rests on the Spearwood surface.

The *drainage systems* of the Swan Coastal Plain are mainly consequent water courses draining from the Darling Scarp, though they are commonly the subject of marked northerly or southerly diversions where they enter the Pinjarra Plain. There are only five natural drainage exits from the Coastal Plain between Perth and Busselton, namely Fremantle, Bunbury, Mandurah, Peppermint Grove and Busselton. River capture is evident on the Coastal Plain, most notably in the Joshua and Crooked Brooks which have been beheaded by the Preston River. McArthur and Bettenay (1960) claim that the Swan, Collie and Dandalup Rivers, which have flood plains, existed in the late to middle Pleistocene, whereas other rivers with straighter channels are post-Pleistocene. Evidence presented in the descriptions of heavy mineral deposits suggests that the Capel, Ludlow and possibly the Preston and Ferguson Rivers pre-date the mineral sands.

REGIONAL GEOLOGY

The regional geology of the Southwestern and adjacent areas of the State is described by Geological Survey of Western Australia (1975), Playford and others (1976), Williams (1975) and Gee (1975).

The Yilgarn Block, Leeuwin Block and the Perth Basin are regional structural units influencing the geology of heavy mineral deposits in the Southwestern area. The Yilgarn Block is the primary source area for sediment in the southern part of the Perth Basin and is considered to be the provenance of heavy minerals concentrated in the Cainozoic shorelines. The Leeuwin Block, which includes rocks of high metamorphic grade, contributes material to the modern shorelines but does not appear to have contributed greatly to the older shorelines where the majority of the heavy mineral orebodies occur.

PRECAMBRIAN ROCKS

The provenance of heavy minerals in the Southwestern area is the granite segment of the Southwestern Province (Gee, 1975). This segment is composed of foliated granitic gneiss and migmatite with discrete intrusive bodies of granodiorite, adamellite and porphyritic microcline granite. In the Donnybrook-Greenbushes district, north-striking belts of garnet-hornblende rock, mica schist, quartzite, metaperidotite and quartz-feldspar-biotite gneiss are present. Williams (1975) reports large layered gabbros, mafic volcanic and sedimentary rocks, banded iron-formation and quartzite in the segment.

PHANEROZOIC ROCKS

Phanerozoic conglomerates overlie Archaean rocks of the Southwestern Province at Harvey, Roleystone, Mundijong, Gosnells and between Bridgetown and Yoganup (Taylor, 1971; Baxter and Doepel, 1973; and Churchward and Bettenay, 1973). They are polymictic pebble and cobble conglomerates with a sandy clay matrix. The unit exposed in the Bridgetown area is called the "Kirup Conglomerate" by Taylor and possibly correlates with the Nakina Formation of the Collie Basin (Lord, 1952; Playford and others, 1975).

Playford and others (1976) describe the sedimentary units of the Perth Basin. Cockbain and Playford (1973) discuss the Warnbro Group which overlies Bunbury Basalt and includes the South Perth Shale and Leederville Formation. The name South Perth Formation is superseded; rocks formerly assigned to this formation are now included in the Leederville Formation. The latter, exposed in the face of the Whicher Scarp, forms the platform on which Cainozoic shorelines were deposited. It is a sequence of sandstone (frequently feldspathic and occasionally glauconitic) and conglomerate with siltstone and claystone. The formation is usually of continental facies. Water bores in the Perth Basin between Mundijong and Yarloop have intersected Jurassic rocks of the Yarragadee and Cockleshell Gully Formations.

The Mesozoic rocks of the Perth Basin are overlain by marine and continental sediments which may be of Tertiary or Quaternary age. The Yoganup Formation (Low, 1971a) is a shoreline deposit consisting of beach and dune sediments. It is exposed along the base of the Whicher and Darling Scarps and includes sand, conglomerate and silt with concentrations of heavy minerals in places. The Yoganup Formation includes the deposits of the Yoganup and Waroona lines of this bulletin. Mines for heavy mineral have been established at Yoganup Central and Yoganup Extended (Fig. 10). Overlying and interfingering the Yoganup Formation is the Guildford Formation formed by the coalescence of alluvial fans associated with rivers and creeks draining the Darling and Whicher Scarps (Low, 1971a). It may be up to 20 m thick, being usually composed of sandy clay and silt. Overlying the Guildford Formation is a sequence of dune sands and related sediments termed the Bassendean Sand (Lowry, 1965; Playford and Low, 1972a). They are mainly quartz sand dunes but may contain calcarenite in places. Heavy mineral ore bodies are mined within the Bassendean Sand at Wonnerup, Capel South, Capel North and Stratham South, the ore occurring in fossil foredunes and beaches. Overlying the Bassendean Sand and Guildford Formations are dunes composed of calcareous fragments commonly cemented by carbonate, which have been referred to the Tamala Limestone (Playford and others, 1976) but were formerly known as the Coastal Limestone. There is no significant deposit of heavy minerals in the Tamala Limestone. Seaward of the Tamala Limestone is a sequence of swamp, dune and beach sediments which contain mineral sands at Koombana Bay, Wonnerup Beach and Minninup. This unit is termed the Safety Bay Sand (Playford and others, 1976) and is approximately equivalent to the Quindalup Dune System. All deposits are dissected, and in places are overlain by alluvial sediments adjacent to the main drainage channels of the Swan Coastal Plain.

DEPOSITS ON THE YOGANUP LINE

Deposits of mineral-sand-bearing marine and continental sediments at the foot of the Whicher Scarp, between Burekup and Dunsborough, are referred to as the Yoganup line. They are situated between 25 and 75 m above sea level.

McArthur and Bettenay (1960) described the line as the Ridge Hill Shelf; Welch (1964) referred to the deposits as "lower escarpment"; and Low (1971a) included sediments within the line in his Yoganup Formation. All major rivers draining the Whicher Scarp dissect the Yoganup line. Southwest of the Abba River smaller streams have also dissected the line, forming a series of small discontinuous mineral sand deposits. The sediments of the Yoganup line at Yoganup Central are assigned to the Pleistocene System by Welch and Low on the basis of eustatic correlation. They formed when sedimentation was taking place at the foot of the Whicher Scarp. At the time of deposition the sea was 27 to 45 m above present day sea level. The deposits originated along an emerged shoreline and coast, and lie unconformably on Mesozoic sediments of the Leederville Formation. The rock types present in the Yoganup line consist of disrupted-framework conglomerate, white clayey sand, siltstone and yellow sand. Rich concentrations of heavy minerals occur in the white clayey sand, and usually some heavy mineral concentrations are present in the overlying yellow sand. Youthful drainage from the Whicher Scarp dissects the Yoganup line in places, for example Tiger Gully, and forms alluvial fans which bury sediments of the line (as at Burekup). Such overburden is usually barren of heavy minerals.

Westralian Sands Ltd and Ilmenite Pty Ltd hold Mineral Claims covering the main heavy mineral concentrations on the line. Rivers separate the main groups of deposits. The best exposures of the mineral sands are at Yoganup Central and Yoganup Extended. Table 9 summarizes the composition of the heavy mineral fraction on the line.

YOGANUP CENTRAL MINE
(Lat. 33°37′S, long. 115°36′E)

General information

The mine is 13 km by road from Capel, which is 26 km south of the port of Bunbury. It is situated between the Ludlow and Capel Rivers; the richest concentration was closer to the Ludlow River. It was known also as the Yoganup mine.

Yoganup Central is mined by Westralian Sands Ltd; mining began in 1959 and is nearing completion.

Mining method: The ore is mined using a combination of bulldozers, rubber-tyred front-end loaders, and steel track mechanical diggers operating from the top of the bench. The ore is taken to a wet gravity concentrator on site. Concentrates are then transported by road to a mineral separation plant at Capel. Ilmenite is shipped from Bunbury in bulk; zircon, monazite and xenotime are bagged prior to shipping.

Production: Between 1959 and 1972, 6 651 581 t of sand had been treated yielding 1 476 950 t of heavy mineral concentrate. Production, recorded by the Department of Mines Statistics Branch, groups Yoganup Central and Yoganup Extended mines (Table 3.)

Geological information

The heavy mineral bearing sediments at Yoganup Central extend over a length of about 5 km and are up to 200 m wide. The deposits occur along the foot of the Whicher Scarp and form a line which is slightly concave to the west.

Medium-grained sandstone, siltstone, clayey sandstone, sandstone and claystone of the Leederville Formation underlie the mineral sands. Lateral and vertical facies variations in the rocks are common, with heavy mineral seams up to 3 cm thick predominantly restricted to the sandy members. Quartz, muscovite and kaolin are the major minerals identified in these sediments.

The general distribution of beds within Yoganup Central is shown in Figure 11. Two white clayey sand beds, the eastern and western, are separated by clay and siltstone and overlain by yellow sand.

TABLE 9. COMPOSITIONS OF HEAVY MINERAL FRACTIONS FROM DEPOSITS ON THE YOGANUP LINE

Area	Tutunup	Yoganup			Yoganup Extended					North Boyanup		
Strand Line *metres above m.s.l.*	Main 46–49	Eastern 66	Main 43–46	Lower 37	Eastern 66	Main 43–46	Intermed 36	Lower 28	West 26–28	Eastern 77	Main 40	Lower 22–28
Av. grade h.m.	14·57	12·27	25·0	15·0	17·68	12·17	13·15	13·39	26·12	11·98	24·49	14·52
Av. slime content	25·00	21·03	25·0	31·0	18·19	21·18	23·06	18·11	20·9	16·62	32·15	25·89
Ratio av. m^3 overb. per tonne of h.m.	0·45:1	0	0	2·46:1	0	0	0·34:1	1·80:1	1·77:1	0	1·4:1	3·4:1
Av. TiO_2 per cent of ilmenite	57·5	59·0	57·0	60·0	58·0	55·0	59·0	59·0	60·0	57·0	55·0	55·0
Mineral Assemblage of Heavy Mineral Concentrate												
Ilmenite	68·0	56·0	57·0	....	76·0	75·0	65·5	73·5	82·0	80·0	83·0	86·0
Altered Ilmenite	8·0	5·0	4·5	....	9·0	4·5	10·0	2·6	2·6	4·6	0·8	1·2
Leucoxene	11·0	18·0	6·0	....	7·6	7·0	14·0	10·4	3·5	3·0	1·1	1·1
Rutile	0·5	1·5	1·0	....	0·7	0·7	0·6	1·2	1·3	1·1	0·4	0·5
Zircon	10·5	18·0	12·0	....	5·3	12·0	8·7	11·0	9·5	10·5	14·0	10·0
Monazite	1·0	0·5	0·3	....	0·2	0·2	1·1	0·5	0·2	0·1	0·05	0·04
Others (mainly alumino-silicates)	1·0	1·0	1·2	....	0·6	0·6	1·1	0·8	0·9	0·7	0·65	1·16
Total	100·0	100·0	100·0	....	100·0	100·0	100·0	100·0	100·0	100·0	100·0	100·0
Ilmenite .... / Altered Ilmenite .... / Leucoxene .... }	87·0	79·0	85·5	....	92·6	87·0	89·5	86·5	88·1	87·6	84·9	88·3

After Fitzgerald and others (1975).

NOTES: All figures are per cent, except where indicated otherwise. Av. = average. h.m. = heavy minerals. overb. = overburden. m.s.l. = mean sea level.

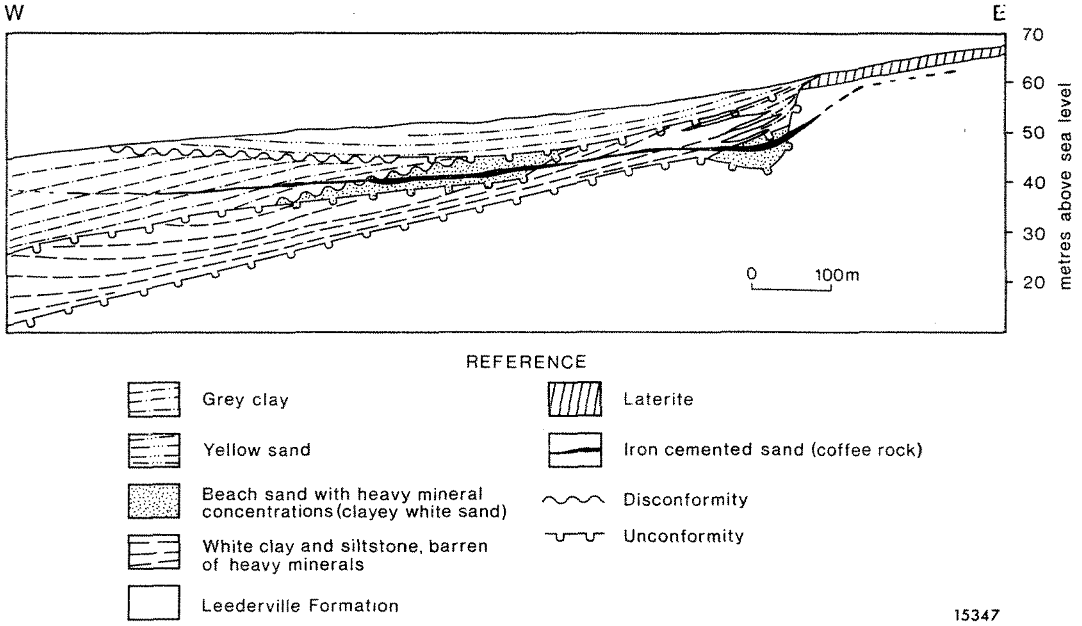

Figure 11. Diagrammatic cross section of the northern end of the Yoganup Central deposit.

In the Yoganup line sediments, disrupted-framework conglomerate of variable thickness commonly occurs at the base of the white clayey sand units. It is composed of clasts of quartz, quartzite, sandstone, granitic rock and a pink felsic rock set in a matrix of white clayey sand. The matrix contains up to 60 per cent by weight of heavy minerals. Clast sizes in the conglomerate tend to a bimodal grouping. The quartz clasts have a range of 5 to 15 cm in diameter; other rock fragments may be up to twenty times this size. There is a predominance of rock fragments in the northern end of the western basal bed and of quartz in the southern end of the eastern bed. Some sandstone clasts are similar in texture and composition to Leederville Formation sandstones exposed in the floor of the mine, but most are similar to rocks present in the "Kirup Conglomerate".

The eastern basal white clayey sand contains up to 90 per cent heavy minerals. The bed is composed of moderately well-sorted, fine to medium-grained quartz grains which are moderately well rounded to subangular, with well rounded grains of ilmenite, zircon and monazite (Table 9). Sofoulis reports higher monazite and zircon concentrations on the eastern (former landward) side of the unit. Clay minerals are present in the matrix and as fine sand-sized pellets. There is local penetration of heavy minerals into the Leederville Formation.

A siltstone bed containing mainly silt and clay with small amounts of very fine-grained heavy minerals, minor granule gravel and sand overlies the eastern basal bed. The heavy minerals in this bed are difficult to recover by wet separators as the silt and clay tend to ball when wet. The bed is lensoid and is absent in many parts of the Yoganup Central mine.

The western white clayey sand bed is deposited unconformably on both the eastern white clayey sand bed and the siltstone bed. The sand is usually medium to fine grained, contains heavy minerals and is set in a clay matrix. Clay occurs both as matrix and as fine pellets. Moderately well rounded quartz and well rounded ilmenite and zircon grains are present. The bed usually contains less zircon and monazite than the eastern white clayey sand unit. There is a small amount of well rounded sand, with grain size ranging from coarse to granule size, in this bed. The unit is generally more poorly sorted than the eastern basal bed.

Yellow medium-grained quartz sand (most of the quartz grains are coated with yellow iron oxide) with minor matrix clay unconformably overlies the white clayey sand bed. On the contact between this unit and the underlying sediments are rounded to subrounded fragments of clayey white sand. Charcoal fragments, between 1 and 10 cm in diameter, occur on, and for up to 1 m above the contact. They are thought to indicate that the contact surface was exposed to the air. Throughout the units, particularly towards the base there are layers of partly rounded granule size ferruginous fragments. Minor irregularities on the contact may be due to compaction of the underlying white clayey sand and siltstone. Economic heavy mineral concentrations occur only in the yellow sand adjacent to mineralized white clayey sand.

Massive, columnar and honeycomb types of coffee-rock are common at Yoganup Central in the basal white clayey sand units, and pod-form coffee-rock occurs in the yellow quartz sand. Large areas of the eastern basal clayey sand contain massive and columnar coffee-rock. Incipient development of all types of coffee-rock occurs throughout the deposit. Pod-form coffee-rock occurs as rounded granules of fine-grained sand cemented by limonite, and as friable cylindrical structures reminiscent of the grain in wood.

References: Morgan (1964a,b), Welch (1964), Lowry (1965), Baxter (1970), Low (1971a), Sofoulis (1972), Fitzgerald and others (1975).

YOGANUP EXTENDED MINE

(Lat. 33°25′S, long. 115°41′E)

General information

The deposit is 11 km southwest of Capel and is accessible by sealed roads from the Bussell Highway, along Gavins Road for 8 km, and then about 4 km south to the mine. It is worked by Westralian Sands Ltd.

Mining method: The ore is mined using rubber-tyred scrapers and bulldozers, and concentrated on site by wet gravity separation. Concentrates are transported to Capel by road for mineral separation. All products are shipped from Bunbury; ilmenite in bulk, zircon and monazite in bags.

Production: Westralian Sands Ltd has been mining at Yoganup Extended since March 1972. To April 1973, 147 236 t of heavy minerals were produced from 1 254 000 t of ore mined. The average grade of ore treated was 11·7 per cent heavy minerals. Production from this mine is recorded with Yoganup Central by the Statistics Branch of the Department of Mines (Table 3).

Geological information

The Yoganup Extended mine has two principal shorelines commonly lying near to one another, but in places separated laterally by up to 100 m. East of the main group of fossil shorelines and parallel to it, lies a third large deposit which contains heavy minerals not chemically suitable for the current market. Associated with these deposits are numerous smaller sub-parallel heavy mineral bearing horizons which are generally discontinuous. The base levels of these deposits are given in Table 9.

The beach and dune deposits are known to extend for at least 7 km along the base of the Whicher Scarp between the Ludlow and Preston Rivers and are up to 500 m wide. The eastern edge of the deposit is slightly concave to the west.

In most places sediments of the Leederville Formation occur at the base of the deposit. An outlier of Bunbury Basalt has modified the shape of the western shoreline in the southern end of the mine area. The Leederville Formation at the mine is a sequence of deeply weathered flat-lying claystone, siltstone, arkose and sandstone. The sandstone members contain up to 20 per cent heavy minerals.

The shoreline deposits at Yoganup Extended are considered to be the northward extension of those in the Yoganup Central mine. The differences in base elevations are believed to reflect an upward movement to the south of an east-west axis of uplift (Cope, 1972). The deposits have been correlated with part of the Yoganup Formation (Low, 1971a).

At the time of inspection (1972) the 46 m shoreline was being mined. The section in the pit comprised a basal disrupted polymictic conglomerate, overlain by a grey heavy mineral bearing clayey sand and yellow sand. Information from drilling indicates that the deposit is younger than the 44 m western shoreline. Both these shorelines are part of the main strand line (Table 9).

The basal conglomerate has clasts of quartz, pink sandstone, white sandstone, granitic rock and quartzite in a clayey sand matrix. Fragments of sandstone with similar texture to that in the underlying Leederville Formation occur in the base of the unit. The matrix generally makes up more than 60 per cent of the conglomerate and contains up to 40 per cent heavy minerals. The conglomerate, rarely more than 2 m thick is more commonly 0·5 to 1 m thick.

The overlying grey clayey sand bed contains up to 50 per cent heavy minerals and up to 25 per cent of clay. The clay minerals occur both as unstructured matrix and discrete sand-sized grains. Quartz grains are moderately to poorly rounded; the heavy mineral fraction is generally well rounded, consisting principally of ilmenite with zircon and minor monazite (Table 9).

The youngest unit exposed in the pit on the middle shoreline is a yellow sand composed of moderately rounded quartz grains coated with yellow iron oxide. The unit contains concentrations with up to 50 per cent of heavy minerals. Its base commonly contains a layer of granules and pebbles of pod-form coffee-rock which may be detrital material, or possibly, represents a stage in the development of coffee-rock. In most places this layer is overlain by sand containing between 3 and 5 per cent by volume carbonaceous fragments in a bed less than 10 cm thick. Similar beds occur throughout the basal 5 m of the unit. Where it overlies mineralization in the grey clayey sand, this sand is also mined for heavy minerals.

Massive and columnar coffee-rock occur within the conglomerate, clayey sand beds and the Leederville Formation, with maximum development in the ilmenite rich, grey clayey sand beds. There is some development of bedded pod-form coffee-rock in the yellow sand unit.

No detailed information has been obtained on the western and eastern shoreline deposits for this description.

Reference: Sofoulis (1972).

NORTH BOYANUP PROSPECT

(Lat. 36°26′S, long. 115°46′E)

General information

The North Boyanup prospect lies at the foot of the Whicher Scarp, north-northwest of Boyanup townsite. The deposit is situated between the Ferguson and Preston Rivers and is approximately 20 km from Bunbury and 22 km from Capel.

Westralian Sands Ltd and Ilmenite Pty Ltd investigated the deposits as part of a joint venture.

Geological information

The heavy mineral deposits are situated within a northward extension of the Yoganup Shoreline beyond the Yoganup Extended mine. There were no accessible exposures of sediments when the deposit was visited in 1972, but drill cuttings suggest conglomerate and grey clayey sand are overlain by yellow sand. The shoreline is complex, though somewhat similar to that at Yoganup Extended mine, with bases between 21 and 76 m above sea level. Washouts and distortions of the mineralized sediments are common.

Alluvial outwash fans cover the deposit with up to 20 m of barren brown clay and sand in places. One fan is formed where Crooked Brook breaks through the Whicher Scarp.

The deposits discovered so far are currently the subject of a feasibility study. In some places the thickness of overburden will prevent mining. North Boyanup lies in an intensive agricultural belt but restoration after mining should not be difficult.

References: Sofoulis (1972, 1973), Fitzgerald and others (1975).

TUTUNUP PROSPECT

(Lat. 33°41′S, long. 115°34′E)

General information

The prospect is situated at the foot of the Whicher Scarp between the Ludlow and Abba Rivers. It is approximately 19 km from Capel by road and is on the western border of the State Forest. The railway from Jarrahwood to Busselton follows the Ludlow River, passing just north of the prospect.

Heavy mineral deposits here were explored by the Geological Survey of Western Australia and Westralian Sands Ltd.

Geological information

There are no signs of the deposit on the surface. Yellow sand, common above heavy mineral deposits on the Yoganup line, is ubiquitous along the foot of the Whicher Scarp at the Tutunup prospect, but mineralization in this unit is rare at the surface.

Drilling shows several discrete zones of heavy minerals in conglomerate and white clayey sand covered by up to 20 m of unconsolidated mineralized yellow sand. The conglomerate has a disrupted framework with a high heavy mineral content in the matrix. Overlying the conglomerate is white clayey sand with up to 50 per cent of heavy minerals. The yellow sand is similar to that at Yoganup Central mine and is mineralized at depth where high-grade sections were encountered when drilling the underlying units. The contact between the underlying Leederville Formation and the mineral sand is between 45 and 56 m above sea level.

References: Rowston (1966), Low (1966), Sofoulis (1972), Fitzgerald and others (1975).

MINOR OCCURRENCES

Vasse

(Lat. 33°44′S, long. 115°30′E)

The prospect is situated at the foot of the Whicher Scarp between the Abba and Sabina Rivers and is about 8 km southeast of Busselton, lying on both sides of the Vasse Highway.

Westralian Sands Ltd conducted a small-scale scout drilling programme and minor surface sampling on the prospect. The results of drilling indicate there are two concentrations of heavy minerals at approximately 27 and 49 m above sea level. The higher deposit occupies a notch in the face of the Whicher Scarp, while the lower deposit lies at the foot of the scarp. The sedimentary succession in both deposits is reported to be similar to that in the Yoganup Central mine.

Reference: Sofoulis (1972).

Happy Valley

(Lat. 33°41′S, long. 115°37′E)

The Happy Valley prospect is situated along the face of the Whicher Scarp, northeast and southwest from Yoganup Siding. It is approximately parallel to, and about 2 km inland from, the Yoganup Central mine and the Tutunup prospect. Yoganup Siding, on the Jarrahwood-Busselton railway, is 18 km by road from Capel.

The deposits have been drilled by Ilmenite Pty Ltd and the Geological Survey of Western Australia. They have a high clay content with erratically distributed concentrations of heavy minerals. Massive and honeycomb coffee-rock occur in association with mineralized beach and dune deposits. North of the Ludlow River, yellow sand containing heavy mineral concentrations occurs in a zone parallel to the northward projection of the beach deposits. This sand is reported to contain little coffee-rock. Rowston has described magnetic and scintillometer surveys made south of the Ludlow River and concludes that no significant mineralization occurs in that area.

References: Low (1966), Rowston (1966).

Burekup

(Lat. 33°20′S, long. 115°50′E)

The Burekup prospect is situated at the foot of the northernmost part of the Whicher Scarp, between the Ferguson and Collie Rivers. Burekup, at the northern end of the deposit, is about 20 km by road from Bunbury.

The deposits are currently being prospected by Cable (1956) Ltd and Westralian Sands Ltd. Their stratigraphy is similar to that at Yoganup Extended mine. In some places they are dissected by drainage channels and in others are buried by up to 10 m of unmineralized clayey alluvium. The average thickness of the deposits is reported to be 4 m, with an average grade of about 8 per cent heavy minerals. The heavy mineral fraction is chiefly ilmenite, with leucoxene and zircon as minor constituents.

DEPOSITS ON THE WAROONA LINE

Deposits of sand, silt and clay formed in lacustrine, fluviatile, eolian and marine environments along the foot of the Darling Scarp between Armadale and Burekup are grouped as the Waroona line. They are distinguished from deposits on the Yoganup line in that they are best developed between buried rocky headlines; individual deposits do not fall on a straight line.

Most of the mineralized deposits on the line overlie weathered Archaean granitic rocks east of the Darling Fault although the deposits north of Waroona overlie weathered siltstone and shale correlated with the Cardup Group. South of Waroona the western side of the line overlies Mesozoic sediments of the Cockleshell Gully and the Leederville Formations. Information on lithology of the underlying rocks is scanty, as most drilling programmes have employed continuous auger methods and no heavy mineral separations or lithological studies have been done on the cuttings.

The deposits consist of a basal disrupted-framework conglomerate and overlying clayey sand, siltstone and peat. They contain up to 60 per cent of heavy minerals. Yellow, moderately well sorted sand overlies most of the enriched sediments and where mineralized, adjacent to the underlying high grade zones, its average grade is less than 15 per cent heavy minerals. The yellow sand overlies all the western deposits on the line, and extends up the face of the Darling Scarp.

The elevation of the bases of these deposits varies from 25 to 120 m above sea level. The deposits on the western side of the line commonly occur on a bench between 25 and 30 m above sea level, and are correlated with the Yoganup Dune System. Beach deposits, recorded from between 75 and 77 m above sea level, are correlated with the Ridge Hill Dune System. The elevation of the base of the yellow sand bears no relation to buried shorelines and is irregular in shape and relief.

MUNDIJONG PROSPECT

(Lat. 32°16′S, long. 116°00′E)

General information

The prospect is situated east of Mundijong along the foot of the Darling Scarp between the South Western Highway and the railway line. The main concentrations of heavy minerals lie north of Manjedal Brook, with a minor extension on the eastern side of the highway. Mundijong is about 25 km by road from Kwinana and is connected to it by a railway approximately 27 km long.

The deposit has been prospected by Westralian Sands—Lennard Explorations Ltd and Cable (1956) Ltd.

Geological information

The deposit has an irregular west-dipping base 115 m above sea level on the eastern side and slopes down to approximately 42 to 45 m on the western side. A buried beach on the western margin contains up to 45 per cent heavy minerals. Irregular low sand hills to the east, with low heavy mineral content, are considered to be dunes. The deposit has been eroded by creeks draining the Darling Scarp and apart from a small occurrence at Byford is not found further north. The southern area between Medulla Brook and Manjedal Brook was drilled but no concentrations of heavy minerals were reported.

At the base of the deposit is hard quartz-bearing kaolin, thought to represent weathered rock of the Proterozoic Cardup Group which is exposed east of the heavy mineral deposit.

TABLE 10. COMPOSITIONS OF HEAVY MINERAL FRACTIONS FROM DEPOSITS ON THE WAROONA LINE

Mineral	Mundijong Prospect		Byford	Waroona Prospect	Wagerup Prospect
	Beach	Dunes			
		Weight Per Cent			
Ilmenite	73	15–60	35–40	80–82	89·5
Leucoxene	5·6	10–50	25–30	1–3	....
Rutile	....	5–15	5–10	....	....
Zircon	5	5–15	10–15	4–5	3·8
Others	....	10–20*	10–15*	....	....
Ilmenite Composition					
TiO_2	59	....	....	56·2–57·1	53·7

* Kyanite, magnetite, staurolite, tourmaline, spinel, garnet.

The economics of this deposit depend on two factors other than its heavy mineral content. The first is the problem of conflicting land use; the spread of the Perth metropolitan area southwards has tended to raise the price of rural land and make mining rights expensive to acquire. The second factor is the distance (about 120 km) from the separation plant at Bunbury and the consequent high costs of transport; this may be overcome if ilmenite is separated at the mine and only the secondary minerals (leucoxene, zircon and monazite) transported to Bunbury. Compositions of two heavy mineral fractions are shown in Table 10 which also gives a breakdown of a heavy mineral fraction from the small deposit at Byford.

References: Simpson (1952), Newstead (1972).

WAROONA PROSPECT

(Lat. 32°50′S, long. 115°15′E)

General information

The prospect is situated immediately east of Waroona townsite and extends north along the foot of the Darling Scarp for approximately 8 km. It lies east of and almost parallel to the South Western Highway. The deposit was drilled by Norseman Titanium N.L. and Cable (1956) Ltd, and most of the information in this description has been obtained from their work.

Geological information

Two kilometres northeast of Waroona the heavy mineral deposit is bisected by a creek which has eroded the shoreline. North of the creek the base of the main concentration lies between 56 and 59·5 m above sea level with dunes up to 65 m above sea level. South of the creek the base is between 60 and 65 m above sea level.

Deeply weathered clayey material, which may represent weathered granitic rock, underlies the deposit. Minor conglomerate has been reported from its base on the western margin. The deposit dips to the west at about 5 degrees.

The thickness of mineralization is greater along the eastern side where dunes are developed. The mineral sand is up to 9 m thick and consists of up to 60 per cent of heavy minerals. The composition of the heavy fraction is given in Table 10. In some areas heavy mineral concentrations occur in clay and laterite beneath the deposit.

A dune containing about 20 per cent heavy minerals is currently being quarried by the Waroona Shire Council for sand; the resulting pit is used for sanitary waste disposal. This dune is dissected by Drakes Brook in the south and by a creek in the north.

HAMEL PROSPECT

(Lat. 32°53′S, long. 115°54′E)

General information

The Hamel prospect is situated between Sampson and Yalup Brooks along the foot of the Darling Scarp. The deposit is exposed 2 km east of Hamel townsite, north of Waterous Road. It has been known also as Location 10 and Yalup North and was tested by Cable (1956) Ltd and Norseman Titanium N.L.

Geological information

The deposit is about 4 km long and up to 1 km wide. It lies west of a buried granitic headland, and comprises two lines of heavy mineral concen trations covered by yellow sand.

The base of the western line is approximately 18 to 21 m above sea level. This strand is dissected by creeks, and dunes are developed on its eastern side.

The eastern line lies up to 100 m east of the western strand and stands between 19 and 23 m above sea level. This strand slopes westward and rests on clay. The deposit contains between 20 and 25 per cent of clay. The heavy mineral fraction contains approximately 86 per cent ilmenite averag- 55·0 per cent TiO_2. No zircon is reported.

McKnoe Brook and Black Tom Brook dissect the deposit but have not removed much of the sand. Yellow sand, redistributed over the area by wind, merges with the shorelines to form a further low-grade deposit.

MINOR OCCURRENCES

Coolup

(Lat. 32°42′S, long. 115°54′E)

Coolup deposit, situated at the foot of the Darling Scarp, lies on the northern side of the Murray River, approximately 5 km east of Coolup. It extends southwards from Meelon Siding for about 10 km.

Coolup was investigated by Norseman Titanium N.L. The richest concentration of heavy minerals occurs on the south side of creeks which drain into the Murray River and cut the deposit. The sediments have angular grains and are considered to be directly derived by erosion of the hinterland. Very little evaluation drilling has been done.

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Wagerup

(Lat. 32°54′S, long. 115°53′E)

Reconnaissance drilling by Norseman Titanium N.L. and Cable (1956) Ltd indicated a dissected southern extension of the Hamel prospect in the Wagerup area.

Wagerup is 10 km south of Waroona on the South Western Highway. The deposits are situated east of Wagerup townsite and extend northward to Yalup Brook.

The occurrence is also known as Yalup South. It is situated at the base of the Darling Scarp with buried granitic "headlands" immediately to the east. Yellow mineralized sand is common between small creeks at the base of the scarp. Bancell Brook and other streams dissect the deposit, and northeast of Wagerup a swamp covers the western limit of the mineralization.

Yarloop

(Lat. 32°58′S, long. 115°54′E)

The Yarloop prospect lies on both sides of the South Western Highway, north and south of the junction with Black Rock Road. It is approximately 2 km southwest of Yarloop and situated east of the railway line. The deposits have been investigated by Cable (1956) Ltd and Busselton Minerals N.L. who located two bodies of heavy minerals.

East of the South Western Highway, on both sides of Black Rock Road, scattered zones with heavy mineral concentrations occur from about 25 m to 66 m above sea level on the face of the Darling Scarp. The eastern part of the deposit is about 1·5 m thick and contains an average of 7 to 9 per cent heavy minerals while the western side, up to 5 m thick, contains as much as 50 per cent heavy minerals. Youthful streams dissect the deposit along Black Rock Road. Underlying the deposit is a coarse-grained quartz sand with a clay matrix.

On the west side of the South Western Highway is a deposit of yellow to brown sand containing up to 8 per cent heavy minerals and between 7 and 25 per cent clay. Its base is about 40 m above sea level.

DEPOSITS ON THE CAPEL LINE

Heavy mineral concentrations formed in a discontinuous body of marine and continental sediments between Burragenup and Dunsborough are referred to as the Capel line. Orebodies are found in beach and dune sand and are commonly associated with swamp, lacustrine and outwash sediments. Units adjacent to the beach and dune sand are commonly mineralized due to reworking and mixing of material during and after deposition. G. W. Kendrick (pers. comm. 1971) using fossil remains in the Capel South mine estimated the youngest age for the deposits as Early Pleistocene (200 000 to 300 000 years). Eustatic correlation with the Monastirian Terraces (Fairbridge, 1961) indicates an age of less than 100 000 years. The disparity between these ages emphasises the need for caution when using eustatic methods.

High-grade deposits of heavy minerals on the Capel line between Stratham and the Vasse River yielded, from four mines, more than 5·6 Mt of heavy mineral concentrates between 1956 and 1974. The major product is ilmenite with zircon, leucoxene, monazite and rutile as by-products.

The line, approximately parallel to and some 7 km inland from the coast, is slightly arcuate in form, being concave to the northwest. Swamps lying between the Bassendean Dune System and the Spearwood Dune System often cover the seaward margin of the line south of the Capel River.

Beach deposits occuring on the west side of the line, between 4·6 and 5 m above sea level, contain up to 90 per cent heavy minerals. This ancient beach has been traced for 20 km south of the Capel River. North of Capel River the beach is eroded by Gynudup Brook. West of the Vasse River vestiges of the beach deposits have been located though no large orebodies have been identified. The beach deposit is currently mined by Western Titanium Ltd at Capel South.

Dune deposits, containing up to 40 per cent heavy minerals, occur along the length of the line except where it is eroded by major rivers. The dunes are mined at Capel North, Stratham and Wonnerup. Economic deposits are confined to the foredune of the line. Commonly the adjacent inland dune is barren of heavy minerals, and in one locality east of Capel, contains moderately high-grade silica sand. Heavy mineral concentration is uniform throughout the foredune at about 10 to 15 per cent. Erratic enrichment of the west face of the dune occurs in many places. Present sheet erosion of the dune sand often results in redistribution of sand over the old beach in a layer up to 1 m thick with generally little heavy mineral content.

CAPEL SOUTH MINE

(Lat. 33°36′S, long. 115°30′E)

General information

The Capel South mine is 3·8 km southwest of Capel, on the Bussell Highway; Capel is 26 km from the port of Bunbury. The mine lies between the Ludlow and Capel Rivers and has also been known as the Capel mine.

The Capel South deposit is mined by Western Titanium Ltd, a wholly owned subsidiary of Consolidated Gold Fields (Aust.) Ltd. Mining began in 1956.

Mining Method: Prior to 1971 the ore was sluiced from the mine face by hydraulic cannons (monitors) and pumped to a concentrator and mineral separator adjacent to the pit. Since 1971 dry mining has been introduced with rubber-tyred tractors and bulldozers delivering ore to a bin plate feeder for pumping to a wet gravity concentrator. Concentrates are then pumped to a mineral separation plant. Ilmenite, zircon, monazite, leucoxene and rutile are sold either in bulk or in bags. Some ilmenite and all altered ilmenite are processed at the mine site in an ilmenite up-grading plant, producing synthetic rutile.

Production: There are three distinct ore bodies within the Capel South mine. Up to the 31st December 1972 the northern orebody yielded 1 368 071 t of heavy mineral concentrates, from 7 859 267 t of ore. The yield of the southern orebody was 27 608 t of heavy minerals from 354 018 t of ore and that of the buried orebody was 160 490 t of heavy minerals from 582 619 t of ore. Total production for the deposit up to 1974 is shown in Table 3.

Geological information

The Capel South deposits are exposed over a length of 14·5 km and a width of 310 m. They lie unconformably, commonly on a fossil sea cliff between 3 and 6 m high, over the Leederville Formation. The Leederville Formation in the Capel South mine consists mainly of dark lagoonal clay containing organic material with local lenses of subangular, poorly sorted, white to grey sand. They are predominantly unlithified. Boulders of Bunbury Basalt occur at the base of the deposit at the northern end of the northern orebody. The Mesozoic sediments are deeply weathered.

The buried orebody is the oldest unit overlying the Leederville Formation. It is a sequence of lenticular fine and medium-grained sands which appear to be shoreline deposits, with a base 5·8 m above sea level. Individual lenses are up to 1 km long, 4·5 m thick and 100 m wide. Heavy minerals appear to be more concentrated in the fine-grained sands of each lens.

Separating the buried orebody and the northern orebody is a bed composed of green-grey to white clayey sand and sandy clay about 2 to 5 m thick which usually has low heavy mineral content. When freshly broken, the sediments have, characteristically, a musty smell.

The northern orebody, composed of well-rounded and moderately well-sorted quartz sand containing up to 80 per cent of heavy minerals (Table 11), occurs along the base of the sea cliff, The palaeogeomorphic feature in which the bed is deposited extends beneath the Ludlow River to the Abba River. The base of the bed is commonly marked by a disrupted-framework conglomerate composed of shell fragments, boulders of basalt, and fragments of underlying sandstone. G. W. Kendrick (pers. comm., 1971) identified a bivalve mollusc, which resembles *Anodontia sphericula* (Basedow), and *Chlamys* (*Equichlamys*) *bifrons* (Lamark) in the basal part of the deposit. This bed is overlain by up to 7 m of sand with rich heavy mineral concentrations. Fitzgerald and others point out that the concentrations tend to produce tails which indicate periodic movement of sediment both northward and southward along the shore. The grade of the northern orebody is up to 80 per cent heavy minerals in the northeast, and up to 60 per cent in the southwest. The orebody as a whole dips west, lying between 5·8 and 9·2 m above sea level.

A yellow sand commonly overlies the northern orebody. It is rarely greater than 2 m thick and

TABLE 11. COMPOSITION OF HEAVY MINERAL FRACTIONS FROM DEPOSITS ON THE CAPEL LINE

Mineral	Capel South Mine 1	Capel South Mine 2	Capel North Mine	Stoate Prospect	Vine Prospect	Prowse Prospect
	Weight Per Cent					
Ilmenite	78·3	73·5	94·6	79·4	63·5	77·6
Altered Ilmenite	7·0	9·4	....	2·1	2·7	12·5
Leucoxene	3·2	5·5	....	2·3	13·2	....
Rutile	0·4	0·4	0·7	....	....	1·3
Zircon	8·0	6·8	3·9	7·5	17·1	6·2
Monazite	....		0·3	0·6	0·3	....
Xenotime	....		....	0·1	0·1	....
Kyanite	....		....	....	0·08	....
Garnet	....		....	2·1	0·12	....
Others	....		0·5	0·4*	....	....
Ilmenite Composition						
TiO_2	....		53·6–54·0	55·3	56·0	....

* Hornblende, spinel.
NOTES: 1. North orebody.
2. South orebody.

contains fragments of sandstone similar to those found in the northern orebody along its base.

The southern orebody is a yellow to white sand with a westerly dipping base between 15 and 18 m above sea level. At its base is a white sand which interfingers with overlying yellow sand and may be a leached derivative of the latter. Heavy minerals are distributed evenly through the sands and the deposit contains less clay than the northern orebody. Within this deposit are indurated fragments of ferruginous clayey sand. In the upper 3 m fragments of charcoal and humic material appear to have been deposited in layers contemporaneously with the sands.

Massive and columnar coffee-rock are present in the northern orebody. The massive coffee-rock is found at the top of the bed and the columnar type towards the base. This cementation has not affected the composition of the heavy minerals. There is a little pod-form coffee-rock in the southern orebody, but the buried orebody lying at or below the modern water table contains no coffee-rock.

References: Hudson (1955, 1958, 1959c), Baker and Edwards (1956a, 1956b), Thomas and Tasker (1957), Baker (1959, 1962), Low (1960a, 1972a), Macdonald (1964), Welch (1964), Lowry (1965), Baxter (1970), Ljung (1973), Fitzgerald and others (1975).

CAPEL NORTH MINE

(Lat. 33°31′S, long. 115°35′E)

General information

The Capel North mine is 8·4 km by road northwest of Capel, and 25·6 km south of Bunbury. It lies north of the Capel River, and east of both Gynudup Brook and the Bussell Highway. It has also been known as the Capel mine and is currently operated by Western Mineral Sands Pty Ltd, representing a joint venture between Australian Titan Products Pty Ltd and Westralian Sands Ltd.

Mining Method: Ilmenite is the only mineral extracted. Residues were sold to Cable (1956) Ltd between 1964 and 1969, but are now bought by Westralian Sands Ltd.

Mining is carried out with rubber-tyred front-end loaders and bulldozers. Until 1972 ore was concentrated at the mine face and then pumped to an ilmenite separation plant. In 1973 a dredge was brought into operation on the deposit. Ilmenite is carted to Bunbury by road trains and shipped to Burnie, Tasmania. Residual heavy mineral concentrates are taken to the Westralian Sands Ltd mineral separation plant at Capel.

Production: To the 31st December 1972 production from the deposit was 1 293 484 t of ilmenite, 128 485 t of altered ilmenite, 16 646 t of leucoxene, 15 270 t of rutile, 61 000 t of zircon and 5 157 t of monazite. The Department of Mines Statistics Branch incorporates production of all minerals other than ilmenite from Capel North with figures for Westralian Sands Ltd and Cable (1956) Ltd. Total production up to 1974 is given in Table 3.

Geological information

The Capel North deposit, a sand hill, extends over a length of 4 km and is up to 150 m wide; it stands some 15 m above the surrounding plain. Heavy mineral grades of up to 50 per cent by weight occur on the western side of the deposit.

The unconformity with the Leederville Formation is relatively planar with a slight dip (usually less than 5 degrees) to the west. The Mesozoic sediments in the base of the pit are deeply weathered grey sandy clay and white clayey sand in which small quantities of heavy minerals have been reported.

The basal sand is white, generally friable and moderately sorted with bedding that dips between 10 and 30 degrees to the west. The sediments penetrate the underlying Mesozoic sands in places. No conglomerate is recorded. B. K. Welch (pers, comm., 1973) reports pinnacles of lime-cemented sand at the top of this unit. Fossil fragments of calcareous algae, bryozoa and foraminifera have been recovered from these pinnacles.

Overlying the white sand and in places interfingering with it, is a grey sand composed of a moderately homogeneous mixture of quartz and heavy minerals. This unit is best developed on the western side of the deposit. Weakly developed planes in the sand suggest near-horizontal bedding. The sand is friable, though slightly more consolidated than the underlying white sand. It is of variable thickness, ranging between 2 and 10 m, and its contact with the underlying white sand is nearly horizontal. Fragments of white sand, between 1 and 2 cm in diameter occur in the grey sand and may be derived from the underlying bed.

Overlying unconformably both white ana grey sands is a yellow sand. The contact is near horizontal. The upper unit extends further to the east than either of the white or grey sands. The heavy mineral content of the yellow sand is consistently 10 to 15 per cent by weight, where it is adjacent to the grey sand, though there is a marked decrease in the tenor of the ore toward the east. The composition of the heavy mineral fraction is given in Table 11.

West of the main deposit drilling has identified a linear feature with a base between 1·8 and 3·1 m above sea level, in which are sands containing up to 50 per cent heavy minerals. The deposit is irregular in strike continuation but may be up to 30 m wide. It may be an ancient creek bed or perhaps represents remnants of a marine beach behind which the dune was formed.

Columnar coffee-rock is found along the base of the deposit in a near-horizontal layer, closely following the contact between the Leederville Formation and the overlying sands. In the mine generally, coffee-rock is unimportant and is not a mining problem.

References: Hudson (1959a, 1966, 1969), Low (1960), Welch (1964), Lowry (1965), Baxter (1970), Grey (1973), Fitzgerald and others (1975).

STRATHAM SOUTH MINE

(Lat. 33°30′S, long. 115°35′E)

General information

The Stratham South mine lies on the northerly extension of the Capel North orebody. It is situated 7·6 km north of Capel, east of Bussell Highway and is 23·7 km south of Bunbury. It is bounded to the north by Gynudup Brook. The mine has also been known as the Stratham mine. The mine is owned and operated by Cable (1956) Ltd, a subsidiary of Kathleen Investments (Aust.) Ltd. The first production was in 1966.

Mining method: The deposit is mined by dredge and floating gravity concentrator. Heavy mineral concentrates are trucked to a separation plant at Bunbury. Ilmenite is shipped in bulk, while zircon and leucoxene are shipped either in bulk ore in bags, minor quantities of monazite and xenotime are also shipped in bags.

Up to the 31st December 1974, 694 291 t of ilmenite, 42 935 t of zircon, 25 292 t of leucoxene and 2 140 t of monazite were produced.

Geological information

The Stratham South deposit, a northerly trending sand hill up to 12 m above the plain, is terminated northwards by Gynudup Brook. The underlying Leederville Formation is sandy clay and clayey sand, but very little information is available on these sediments as the floor of the deposit is not exposed during mining.

The base of the deposit is nearly horizontal on the east side but dips at approximately 5 degrees westwards on the western margin. Controlled levelling has not been carried out though a barometric observation on the base indicates it is about 10·7 m above sea level on the eastern side.

The deposit is composed of fine to medium-grained quartz sand with heavy minerals. It is relatively uniform in texture and mineral content over the ore width but has minor colour variations due to iron staining. In the western side up to 45 per cent heavy minerals are reported, but in the east grades are generally lower than 20 per cent.

In one part of the mine a swamp encroaches upon the eastern side of the deposit and massive coffee-rock is developed at the same level as the water table. This material is mined by blasting and sluicing.

WONNERUP MINE

(Lat. 33°40′S, long. 115°25′E)

General information

The mine site is on Sussex Location 7, 2·5 km south of Wonnerup Siding on the Busselton to Bunbury railway line. It is situated approximately 10 km east of Busselton and is accessible from the Bussell Highway. The deposit lies southeast of the highway and is situated between the Sabina and Abba Rivers. Since 1966 the leases, formerly held by Ilmenite Minerals Pty Ltd, have been operated by Cable (1956) Ltd.

Prior to 1971 the deposit was mined with a dredge which delivered ore to a land based gravity concentrator. The southern end of the deposit, which has a sloping floor, is now mined with rubber-tyred front-end loaders. Ore is concentrated in gravity cones and concentrates are taken 50 km to Bunbury for further separation. Ilmenite is shipped in bulk; zircon and leucoxene are shipped either in bulk or in bags, and monazite is shipped in bags.

Production: In the period 1966 to 1974, 183 502 t of ilmenite, 12 559 t of leucoxene, 21 200 t of zircon, and 711 t of monazite were produced. Prior to 1966 some production from this mine may have been included with that from the Wonnerup Beach mine.

Geological information

The deposits, which form a southerly extension of the Capel South mine orebody, are approximately 1·7 km long and 180 m wide. As at Capel South the seaward deposit appears to be a buried beach and the landward deposit a dune. The extremities of the deposits have been truncated by the Abba and Sabina Rivers.

The mineral sands unconformably overlie the Leederville Formation, represented here by clayey sands and sandy clays. The intervening unconformity, horizontal on the eastern side, dips at up to 10 degrees in the western part of the deposit.

The eastern deposit, currently mined, is a low sand dune with up to 15 per cent heavy minerals. The sediment is a fine to medium-grained quartz sand with fine-grained heavy minerals. Quartz grains are coated with various amounts of hydrated iron oxides. No bedding can be seen in the sands though the floor of the deposit dips seaward.

South of the Abba River the seaward deposit (not yet mined) is separated from the low sand hil by a swamp. It was drilled by continuous auger methods and consequently no detailed information is available, but concentrations of heavy minerals of up to 20 per cent are known. There are no data on absolute levels, but it seems likely that this deposit is at the same level as the Capel South mine.

Incipient pod-form coffee-rock is developed in the seaward side of the dune deposit.

STRATHAM NORTH PROSPECT

(Lat. 33°28′S, long. 115°36′E)

General information

The Stratham North prospect is approximately 14 km south-southwest of Bunbury on the eastern side of Bussell Highway, lying east of Cokelup Swamp and north of the Stratham-Boyanup Road. It is located on Boyanup A.A. Locations 166, 186, 187 and Wellington Locations 923, 1348 and 2630.

Geological information

Western Titanium Ltd own the tenements. The description given here was derived from drill logs and assay information provided by that company.

Two parallel deposits of mineral sands were outlined during exploration of the prospect. They run approximately north and lie up to 35 m apart.

Below the deposits brown, medium to coarse-grained sand and sandy clay, of the Leederville Formation, has between 10 and 60 per cent clay and minor heavy mineral concentrations. One drill-hole intersected 2·5 per cent heavy minerals made up mainly of ilmenite and zircon.

The western deposit is a sand containing up to 25 per cent heavy minerals and appears to be composed of two interfingering lenticular beds suggesting a complicated history of deposition. The eastern deposit is composed of quartz sand with up to 10 per cent heavy minerals. It is 0·8 km long and approximately 60 m wide, while the western body is 2 km long and up to 90 m wide. The bases of the two deposits are between 1·8 and 4·6 m (western), and 6·0 and 9·2 m (eastern) above sea level.

Lime and quartz sands, correlated with the Spearwood Dune System, cover the deposit. They are up to 4 m thick on the east, and between 9 and 15 m thick on the western side. The sands contain less than 3 per cent heavy minerals, and are classed as overburden. There is very little consolidated limestone in this accumulation.

STOATE PROSPECT

(Lat. 33°40′S, long. 115°23′E)

General information

The Stoate Prospect, situated approximately 4·5 km southeast of Busselton, is on L.T.O. Lots 11, 12 and 18 of Sussex Location 1.

Geological information

Exploration by Busselton Minerals N.L. revealed four sub-parallel deposits of heavy mineral bearing sand. The three northernmost deposits are considered to be waterlain (possibly beach) sediments while the southern is believed to be dunal.

The sediment below the three northern strands is a yellow to brown sand which may be Leederville Formation, but could be of Cainozoic age.

The most northern of the three beach deposits is composed of brown sand and contains up to 35 per cent heavy minerals and up to 30 per cent clay. The base of the deposit, containing intercalated minor yellow sand, is nearly horizontal and 8·5 m above sea level. A swamp divides the deposit into two parts, each having slightly different heavy mineral suites. The southern part has the higher grade; the heavy mineral composition is given in Table 11.

The middle one of the three waterlaid deposits is composed of brown and yellow sand. Its base, which dips gently northwest, is at an average of 12 m above sea level. The deposit is between 2 and 3 m thick and contains up to 10 per cent heavy minerals. No data are available on the composition of the heavy mineral fraction.

The southernmost waterlaid deposit has a lower base than the middle deposit, at approximately 10 m above sea level, dipping gently to the south. It contains up to 9 per cent heavy minerals and 15 to 30 per cent clay.

The dunal deposit to the south overlies a gently sloping unconformity cut into brown sand and ferruginous conglomerate. The deposit is composed of brown and yellow sand with minor clay, which increases towards the base. The base dips north from 22 to 17 m above sea level.

VINE PROSPECT

(Lat. 33°41′S, long. 115°22′E)

General information

The Vine prospect is 5 km south-southeast of Busselton, lying west of the Vasse Highway on both sides of the Vasse River. Access to the deposit is obtained from Vasse Highway or from a sealed road south of Busselton. It is located on L.T.O. Lot 5 of Sussex Location 5.

Geological information

Three distinct lenses of heavy mineral bearing sediments were located during exploration by Busselton Minerals N.L. Two are situated west of the Vasse River and the third to the east of the river.

The southern deposit, on the west of the river, is composed of yellow sand with grey sand at the base where there is an irregular development of columnar and massive coffee-rock. The floor of the deposit dips gently north at an average of 29 m above sea level. Minerals in the heavy mineral fraction are shown in Table 11.

The northern deposit on the west of the river is composed of brown sand on the seaward (north) side and yellow sand on the landward (south) side. This deposit rests unconformably on a sequence of sand and clay. It contains up to 8 per cent heavy minerals and between 5 and 15 per cent clay.

The deposit east of the Vasse River consists of brown and yellow sand unconformably overlying a poorly consolidated siltstone. Its base lies approximately 15 m above sea level. The deposit contains up to 18 per cent heavy minerals and between 6 and 10 per cent clay. The heavy mineral content varies from east to west along the trend of the deposit.

PROWSE PROSPECT

(Lat. 33°34′S, long. 115°32′E)

The Prowse prospect is located on L.T.O. Lot 2 of Leschenault Location 46, 1·5 km west of Capel.

This prospect is a northern extension of the Capel South deposit on the western side of Bussell Highway. It was drilled by Norseman Titanium N.L. and sufficient ore reserves were established to justify feasibility studies for mining. In conjunction with the Australian Industries Development Corporation the company began construction of a mine plant but the project was abandoned before operations began.

The heavy mineral deposit is linear in form and is similar to the northern orebody at the Capel South mine. Grades of up to 40 per cent heavy minerals occur within the ore zone which is up to 50 m wide and 6 m thick, and may be up to 5 km in length. The deposit is covered by 1 to 5 m of mineralized (4 to 6 per cent heavy minerals) overburden. No geological information is available.

MINOR OCCURRENCES

Numerous small deposits along the Capel line have been drilled but most of the information is not available. (Land tenure on part of the mineralized zone is under Imperial Grant which entails no reporting obligation on the owner)

Ambergate

(Lat. 33°42′S, long. 115°20′E)

The Ambergate deposit is 5·5 km south of Busselton townsite. It is on Sussex Locations 2323, 2324, 2328 and 2329 and is accessible by road.

Very little geological information is available on this deposit as the drilling, carried out by Cable (1956) Ltd, was for reconnaissance purposes only. The surface of the deposit is a yellow sand which appears to be of dunal origin. Heavy mineral grades are reported to range up to 40 per cent by weight. From its geographic position it is inferred that this deposit can be correlated with the dune deposits on the Vine prospect.

Dunkley

(Lat. 33°31′S, long. 115°34′E)

The Dunkley deposit is situated 4·5 km north of Capel on L.T.O. Lots 12 and 13 of Wellington Location 47. It lies on the west side of Bussell Highway, south of Mangles Road. It is small with an average grade of about 10 per cent heavy minerals. The deposit was drilled by Noresman Titanium N.L. and was to be developed in conjunction with the Prowse prospect. No geological information is available from the deposit.

Norton

(Lat. 33°32′S, long. 115°33′E)

The Norton deposit is situated 3 km northwest of Capel on L.T.O. Stirling Estate Lot 153. It lies on the west side of Gynudup Brook, adjacent to the confluence of the brook with the Capel River. The deposit is a southward extension of the Dunkley deposit, and was investigated by Norseman Titanium N.L. who located a small quantity of heavy minerals.

Australind

(Lat. 33°14′S, long. 115°45′E)

The Australind prospect is located 14 km northwest of Bunbury, between the Old Coast Road and the Wellesley River. The area has also been known as the West Harvey prospect.

The deposit is a white to grey sand up to 9 m thick and 45 m wide. Its eastern side has been eroded by the Wellesley River north of the confluence with the Collie River. It was tested by widely spaced drilling over a strike length of more than 2·5 km and grades up to 75 per cent heavy minerals have been reported. The deposit is buried by up to 20 m of calcareous sand overburden.

DEPOSITS ON THE MINNINUP LINE

Heavy mineral deposits along the modern coast between Bunbury and Busselton are grouped as the Minninup line. The sediments were laid down in near-shore marine, backwater swale, and terrestrial environments and consist of lime sand, quartz sand, peat and silt disposed in lenticular bands. Western Australia's western coastline is a microtidal swell environment. Long-shore currents impinge on the coast at acute angles, resulting in large volumes of sediment drifting along the coast from south to north. In such an environment the zones adjacent to the north of river outfalls should be favourable sites for concentrations of heavy minerals. However, heavy mineral deposits on the coast are small, a fact attributed to the low rate of discharge of material from rivers and the high influx of carbonate particles generated in the littoral and neritic zones and carried onshore by current and wave actions.

The sands containing heavy mineral deposits lie within the Safety Bay Sand and are included in the Quindalup Dune System. Mines at Koombana Bay and Wonnerup Beach produced a total of 422 243 t of ilmenite before closing in 1966 and 1967 respectively. Mineralization is also reported from the Forrest, Brockman and Minninup deposits. Each of these is associated with a backwater swale and is adjacent to either an existing, or former, drainage outlet. The deposits are small and contain principally ilmenite. With the exception of the Koombana Bay accumulation, the deposits unconformably overlie Tamala Limestone; the Koombana Bay deposit overlies estuarine sediments, Tamala Limestone and Bunbury Basalt.

The deposits, formed on benches cut in the underlying rocks, occur between 3 m above and below sea level. They represent an assortment of beach, dune, berm and swale deposits associated with a prograding beach. Progradation has caused concentrations of heavy minerals to be separated by up to 10 m of unmineralized sand.

Estimates of the age of the deposits by means of eustatic correlations of benches on which the deposits have formed, indicate an age of between 4 000 years b.p. and the present. However, mining at Koombana Bay exposed the wreck of a whaler dating from either 1840 or 1843, demonstrating that this deposit is less than 200 years old.

KOOMBANA BAY MINE

(Lat. 33°19′S, long. 115°39′E)

General information

The Koombana Bay mine was located 1·6 km east of Bunbury Railway Station. It is connected to Bunbury by a road causeway over Leschenault Inlet. The deposit was on the southern shore of Koombana Bay, immediately west of the dredged channel to the new Bunbury wharf.

The mine, operated by Peron Bros Pty Ltd in 1956 and Cable (1956) Ltd between 1957 and 1966, was the first heavy mineral mine in Western Australia, but production ceased due to depletion of reserves.

Mining method: A small dredge was used for mining ore which was then pumped to a land-based mineral concentration and separation plant. The separation plant is now used by Cable (1956) Ltd to treat ore from Stratham South and Wonnerup mines.

Production: The Koombana Bay deposit produced 227 550 t of ilmenite, 348 000 t of zircon and 100 t of monazite earning $2 041 200. Production ceased in 1966.

Geological information

The deposit was situated on the seaward side of a former narrow peninsula between Leschenault Inlet and the sea. The Collie and Preston Rivers discharge into the inlet which opened to the ocean about 1 km west of the deposit. Recent harbour works, involving the dredging of two new connections and closing the original mouth between the ocean and Leschenault Inlet, have apparently interfered with the geomorphologic processes operating when the deposit was formed. The construction of a breakwater north from Casuarina Point disrupted current patterns in the area, and this also probably affects deposition of heavy minerals. It is reported that heavy mineral concentrations are now forming north of the "Cut", north of Pelican Point.

Low reports that mining operations exposed flows of Bunbury Basalt below the deposit. The deposit's base is generally a calcareous sandstone intermingled with alluvial clay. Unconformably overlying these sediments are recent beach and dune deposits containing heavy minerals.

The average thickness of the deposits was about 1·5 m, containing an average of 30 per cent heavy minerals. Ilmenite made up between 75 and 85 per cent of the heavy mineral fraction.

Thomas and Meharry, in a report for H. T. Phillips, recorded 87·2 per cent heavy mineral concentrates of which 5·8 per cent was garnet. A heavy mineral analysis from Koombana Bay is given in Table 12. The deposit contains mainly ilmenite with garnet, zircon, leucoxene, rutile and monazite, and minor epidote, hypersthene, green spinel, staurolite, biotite and tourmaline. A chemical analysis of ilmenite is given in Table 13.

TABLE 12. COMPOSITIONS OF HEAVY MINERAL FRACTIONS FROM DEPOSITS ON THE MINNINUP LINE

Mineral	Koombana Bay Mine	Wonnerup Beach Mine	Minninup Prospect
		Weight Per Cent	
Ilmenite	90·7	85	77
Leucoxene	1·6	....	1
Rutile	0·8	2	....
Zircon	2·3	6	5
Monazite	0·5	....	....
Garnet	3·8	7	....
Others	0·35*	....	....
Ilmenite Composition			
TiO_2	....	52·9–55·1	53·8–55·1
Cr	....	....	0·6

* Epidote, hypersthene.

TABLE 13. CHEMICAL ANALYSES OF ILMENITE SAMPLES FROM THE MINNINUP LINE

Oxide	Koombana Bay	Wonnerup Beach Mine Dune	Wonnerup Beach Mine Interdune Area	Minninup Prospect
		Weight Per Cent		
SiO_2	1·18	1·00	2·66	0·72
TiO_2	54·20	54·3	51·78	54·65
Fe_2O_3	16·9	13·57	16·8	14·84
FeO	24·4	27·7	24·48	27·8
CaO	tr.	tr.	tr.	tr.
MgO	tr.	tr.	tr.	tr.
P_2O_5	0·055	0·073	0·086	0·085
MnO	1·55	1·15	1·25	1·50
Cr_2O_3	0·025	0·03	0·03	0·025
V_2O_5	0·02	0·00	0·0036	n.d.
Insolubles	1·94	2·28	6·06	1·94

n.d. = not detected. tr. = trace.
Analyses: From British Titan Product Co. Ltd (1947).

Baker described a heavy mineral concentrate 137 m from the present Bunbury Beach, 0·8 km north of Bunbury townsite, which contains ilmenite, leucoxene, zircon, and kyanite (pale greenish-blue variety) as common minerals and pale-pink to pale-brown garnet, green to bluish spinel, zoisite, epidote, less commonly monazite and rarely andalusite.

References: Thomas and Meharry (1954), Low (1960a), Baker (1963), Welch (1964), MacDonald (1964), Lowry (1965).

WONNERUP BEACH MINE

(Lat. 33°37′S, long. 115°25′E)

General information

The Wonnerup Beach mine (D.Cs. 13H and 34H) was situated between the Vasse and Wonnerup Estuaries. The site is approximately 8 km north-east of Busselton and can be reached by the Coast Road.

The deposit was worked by Ilmenite Minerals Pty Ltd between 1959 and 1966 before the company was purchased by Cable (1956) Ltd.

Mining method: Mining was done with a small mobile dredge in an erratic pattern owing to the irregularity of the base. Ore was concentrated at the mine site on the east side of the connection between the Vasse and Wonnerup Estuaries.

Production: In the period between 1959 and 1967 a reported 194 693·38 t of ilmenite were produced earning $2 379 807. It is possible that some of this production came from the Wonnerup mine also operated by this company.

Geological information

Deposits of heavy minerals lie within an area bounded by Malbup Creek, Wonnerup Estuary and Wonnerup Inlet with small areas of high-grade concentrates on the modern beach. The mining operation was carried out entirely over inland deposits.

Situated inland from the modern foredunes and extending to the beach the deposits had a length of 3·5 km and width of up to 200 m. Within this area the water table is high and water covers the deposits in the inlet and estuaries. The latter are drowned mouths of the Ludlow, Vasse, Sabina, and Abba Rivers, each of which erodes part of an inland heavy mineral deposit. The Abba, Sabina and Vasse cut the Capel line and the Ludlow cuts the Yoganup line and flows over the Capel line. The rivers are sluggish and sediment is discharged to the sea only in the winter months.

McMath reports that the concentration of heavy minerals is richest at about the level of the water table and that there is an average thickness of 2·7 m of heavy mineral bearing sands in the deposit. Grades of up to 50 per cent have been recorded from the mine area. A heavy mineral analysis is shown in Table 12. Ilmenite produced from the mine assayed between 51·0 and 55·0 per cent TiO_2; complete analyses are given in Table 13.

Gardner reports that there were 325 000 t of heavy minerals containing 85 per cent ilmenite, 6 per cent zircon, 2 per cent rutile, and 7 per cent garnet in the deposit prior to mining.

References: Blaskett (1949, 1953), Gardner (1951) McMath (1951), Miles and Meharry (1955), Low (1960a), Welch (1964), Lowry (1965, 1967).

MINOR OCCURRENCES

Minninup

(Lat. 33°28′S, long. 115°34′E)

The Minninup deposit is approximately 18 km south-southwest of Casuarina Point along the coast. It is on the seaward side of Wellington Locations 497, 492, 637, 394 and L.T.O. Lots 1 and 2 of Location 44. It is accessible along the beach from Peppermint Grove or Doungup Park, or by sand tracks from graded roads serving the farming area to the east.

The Minninup deposit has also been known as Minninup Beach, Scott, Roberts and Brockman. The deposits were tested at various times since 1948 by the Geological Survey of Western Australia, Ilmenite Pty Ltd, Cable (1956) Ltd, and Norseman Titanium N.L. The early work tested the modern beach and later investigation of the foredunes disclosed a buried concentration of heavy minerals.

A sloping planar prograding beach, with a seaward slope of less than 10 degrees between the low water mark and a small berm, contains the main heavy mineral concentration. Above the berm a prominent foredune is developed, and this attains a height of 15 m in some places. Landward of the beach there are marshlands, now drained, with an outfall within the area of the deposit. The outlet of the drain is in approximately the same position as the former mouth of Gynudup Brook.

Heavy mineral concentrations in the shoreline sediments occur between low and high water mark, within the berm, in the foredune and at the base of the foredune on the landward side. Concentrations of up to 50 per cent, from areas between 3 m above and 3 m below sea level, are reported. The floor for all deposits is an indurated calcarenite of the Tamala Limestone.

McMath estimated that there are 116 200 t of ore with an average grade of 20 per cent heavy minerals between high and low water marks. Ilmenite, zircon, garnet, rutile, monazite and leucoxene have been identified in the ore. Feldspar is reported to occur in small quantities. Gardner claims there are 203 200 t of ore averaging 10 per cent ilmenite, 0·5 per cent zircon and 0·1 per cent rutile. The mineral composition of the concentrate is shown in Table 12 and a complete analysis of the ilmenite is given in Table 13.

References: Dunkin and others (1948), McMath (1950b), Gardner (1951), Low (1960a, 1972a), Welch (1964), Lowry (1965), Baxter (1970) Wise (1972).

Forrest

(Lat. 33°35′S. long, 115°27′E)

The Forrest deposit is located along the coast between the Deadwater and Higgins Cut. It is situated on L.T.O. Lots 5, 6 and 7 of Stirling Estate Location 41 and Wellington Locations 11, 52, 53, 81, 86, 90 and 93. The deposit was drilled by exploration companies but no results were reported to the Department of Mines.

The heavy mineral deposits occur in the modern beach, berm and foredune. There is a concentration on the landward side of the foredune which in some places extends into the Deadwater.

Siesta Park

(Lat. 33°39′S, long. 115°16′E)

Siesta Park is some 8 km west of Busselton. It is accessible from Bussell Highway, lying between the highway and the beach line. McMath reports a minor unecomonic concentration in this area principally adjacent to a drain outlet to the sea. Fossil beaches are reported to be exposed in the drain, but no heavy mineral concentrations are known.

Reference: McMath (1951).

CHAPTER 5

Deposits of the Midlands Area

The Midlands area, for the purpose of this bulletin, is that part of the Perth Basin between the Swan and Irwin Rivers; the deposits occupy parts of the Shires of Moora, Mingenew, Three Springs and Carnamah (see Fig. 1). Cainozoic heavy mineral deposits are preserved along the foot of the Gingin Scarp and on the modern coast. The deposits at the foot of the Gingin Scarp are up to 50 km inland from the coast. Deposits along the Gingin Scarp are divided into the Gingin, Munbinea and Eneabba shorelines. Along these, orebodies have been discovered in paralic sequences at Eneabba, Jurien and Gingin. The coastal deposits are restricted to the modern beach, are small in size, and of no economic significance.

The shoreline deposits at the foot of the Gingin Scarp variously overlie unconformably members of the Lesueur Sandstone, and Yarragadee, Cockleshell Gully, Leederville, and Osborne Formations. These units, particularly the Yarragadee Formation, are an immediate source of heavy minerals. Concentrations of heavy minerals have formed in paralic sequences composed of beach, dune, lagoon and estuarine sediments associated with rivers and creeks draining the Arrowsmith Region or the Dandaragan Plateau. The sequences and associated shorelines can be correlated by means of geomorphic position despite the fact that they occur at differing reduced levels. There are common geomorphic characteristics which indicate that heavy mineral concentrations developed where a large amount of terrigenous material was deposited along the coast in complex shoreline environments. The local geomorphology at the time of deposition determined the extent of preservation of the heavy mineral deposits; at Eneabba, where there was a zeta-shaped bay, the paralic sequence is relatively well preserved, whereas at Jurien and Gingin smaller deposits are now found on what was evidently a less protected open coast.

Minor concentrations of heavy mineral occur at Mosman Beach, Green Head and Snag Island. These deposits are found in the Safety Bay Sand, and unconformably overlie the Tamala Limestone (Coastal Limestone). They are formed by reworking of heavy minerals in the Tamala Limestone, but are not extensive and are of no economic importance.

PROSPECTING RECOMMENDATIONS

Apart from a small section near Dandaragan West, the foot of the Gingin Scarp has been prospected along its entire length between Bullsbrook and the Arrowsmith River. Economic heavy mineral deposits have been found at Eneabba, Jurien and Gingin and heavy mineral concentrations are known at Cooljarloo, Regans Ford, Muchea and Bullsbrook. Drilling has been carried out north of Eneabba to the Arrowsmith River, and although fossil beach sediments have been identified, no significant mineralization has been found. Prospecting, with reconnaissance drilling, between Hill River and Cockleshell Gully failed to locate any deposits of heavy minerals. The unexamined portion of the foot of the Gingin Scarp near Dandaragan West, adjacent to Minyul Swamp, is moderately prospective.

In the Southwestern area of the State heavy mineral concentrations occur on the Capel Shoreline between the Whicher Scarp (which is correlated with the Gingin Scarp) and the coast. However no beach sediments or mineralized dunes have been identified in the corresponding position in the Midlands area, but localities where this line of deposits may possibly be found are on the west side of Lake Logue and White Lake; on the west side of the swamp 6 km east of Green Hill (lat. 30°34′S, long. 115°08′E); and other areas adjacent to the west side of swamps and buried swamps on the east side of the Tamala Limestone outcrop. The extensive encroachment of the Tamala Limestone may have buried deposits formed in this geomorphic position, but if the market value of titanium ores increases, such areas could become targets for exploration.

The modern beaches and dunes are unlikely to contain economic deposits of heavy minerals as no major drainage now arrives at the coast of the Midlands area. The Moore River is the main river discharging into the sea and at one point its course follows the Bassendean Sands-Tamala Limestone contact. Should this zone be mineralized, heavy minerals may have been carried to the coast and deposited within the Safety Bay Sand north of the river mouth. Any deposit formed by such a process is likely to be low grade due to dilution by carbonate fragments, which are common on the modern coast.

REGIONAL GEOMORPHOLOGY

Low (1971b, 1972c, 1972d) described the geomorphology of the Midlands and Seddon (1973) summarized this work as it applied to the southern part of the area. Nine geomorphic units have been recognized as shown in Figure 12. These are the Coastal Belt, Bassendean Dunes, Pinjarra Plain, Gingin Scarp, Arrowsmith Region, Dandaragan Scarp, Dandaragan Plateau, Yarra Yarra Region, and Darling Scarp, with the Darling Scarp marking the eastern limit of the Midlands. The Swan Coastal Plain includes the first three units mentioned.

The *Coastal Belt* (Lowry, 1972) is a complex geomorphic unit composed of compound dunes with primitive swamp lands. It consists principally of dunes, corresponding to the Quindalup and Spearwood Dune Systems of the Southwestern area, forming a sequence of mobile and fixed transverse dunes parallel to the coast, with minor longitudinal dunes extending inland. The coast is one of straight sandy beaches between low limestone headlands, some showing evidence of a wave-cut platform approximately 3 m above sea level. Caves found in the Coastal Belt (for example, Namban, Stockyard Gully and Weelawadji Caves) are related to subterranean stream action in lithified dunes; erosion of limestone dunes leaves pinnacles of resistant limestone, as at The Pinnacles and Tombstone Rocks.

Bassendean Dunes (McArthur and Bettenay, 1960), represented by low sandy ridges parallel to the modern coastline and standing between 76 and 91 m above sea level, are well developed in the Midlands area. Interdunal swamp lands are common. The dunes are associated with a beach ridge which has been tentatively dated by fossil evidence at late Early Pleistocene (p. 66). Some authors (Lowry, 1965) claim that these dunes were originally much higher, and that extensive leaching of calcareous material produced a more subdued topography. However, exposures in sand pits in the Perth

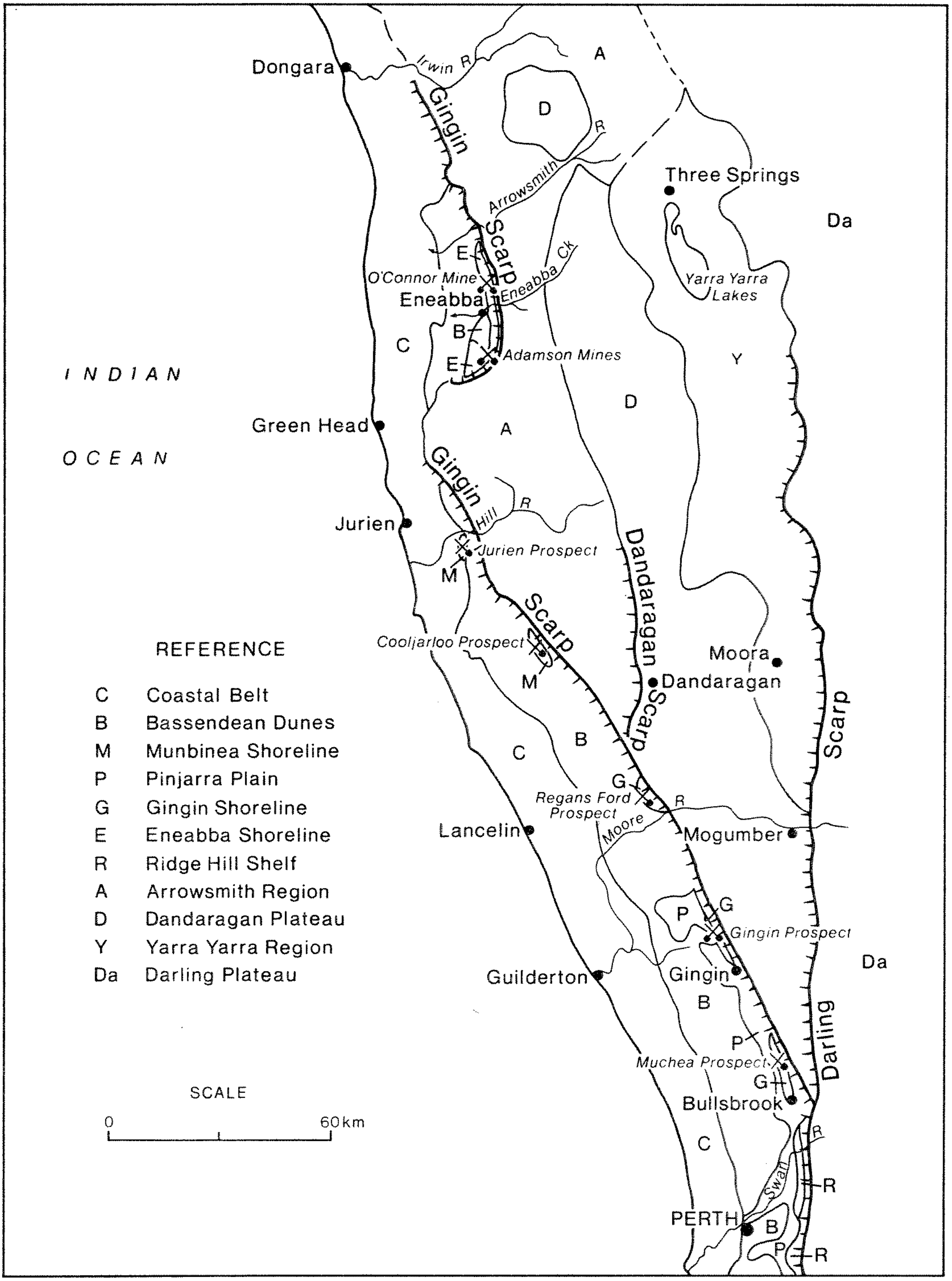

Figure 12. Map showing geomorphic units and heavy mineral deposits in the Midlands area.

area and the Southwestern area indicate that the dunes contained only minor amounts of calcium carbonate. These dunes have encroached across the plain, in some areas as far as the Gingin Scarp, concealing large tracts of the Pinjarra Plain and parts of the Eneabba, Munbinea and Gingin Shorelines.

The *Pinjarra Plain* (McArthur and Bettenay, 1960) equivalent in the Midlands area is less important than in the Southwestern area. It is well developed between the Swan and Moore Rivers. The gently undulating plain is composed of discrete and coalescent alluvial fans.

The *Munbinea Shoreline* is the name proposed for a shoreline system south of the Hill River and now partly buried by dunes of the Coastal Belt and Bassendean Dunes. The shoreline was formed when the sea level was about 36 m above the present level. The system may lie up to 500 m west of the Gingin Scarp. This shoreline is associated with subdued dunes of the Bassendean Dunes and while it may be related to them, its position at the base of the Gingin Scarp suggests that it is older than the dunes.

The *Gingin Shoreline* is the name proposed for beach ridges and dunes at the foot of the southern Gingin Scarp. It forms a discontinuous feature on the Pinjarra Plain running from north of the Moore River to Bullsbrook. It is buried by Bassendean Dunes in some localities.

The *Eneabba Shoreline* is the name proposed for a series of complex fossil coasts in the vicinity of Eneabba where beach ridges occur between 82 and 128 m above sea level, at the base of the Gingin Scarp. Associated with these ridges are dunes, swales and deltaic deposits formerly related to a now buried prograding coast.

The *Gingin Scarp* (Low, 1972d) is a narrow feature with a relief of about 60 m. It marks the eastern limit of the Swan Coastal Plain in the Midlands. The scarp is probably formed by marine erosion.

The *Arrowsmith Region* (Playford and others, 1976) is an area of active erosion with flat-topped hills and alluvial slopes that are being degraded, falling to mature and young river courses. The western side of the region is marked by the Gingin Scarp while the eastern margin is the Dandaragan Scarp in the south; this feature is less distinct to the north. The area is drained by the Arrowsmith, Hill and Irwin Rivers, and Eneabba and Bindoon Creeks as well as numerous other creeks, gullies and brooks.

The *Dandaragan Scarp* (Forman, 1935) is a fairly prominent north-trending feature marking the boundary between the Dandaragan Plateau and the Arrowsmith Region. It is about 70 km long, extends north from Dandaragan, and has less relief than the Gingin Scarp. The feature is probably a marine scarp.

The *Dandaragan Plateau* (McArthur and Bettenay, 1960) is a gently undulating surface which stands between 200 and 300 m above sea level between the Dandaragan Scarp and the Darling Scarp. In general it is a little dissected, drainage being restricted to the western side of the plateau.

The *Yarra Yarra Region* (Playford and others, 1976) stands about 200 m above sea level and is characterized by lakes, swamps and sluggish drainage channels. There is a general slope to the south but water flows only after heavy rain. It is drained in the southern part by occassional connection with the Moore River.

The *Darling Scarp* bounds the Yarra Yarra Region and the Dandaragan Plateau to the east and forms the western boundary of the Darling Plateau. The scarp, an expression of the Darling Fault, is less pronounced northwards.

REGIONAL GEOLOGY

The major structural units in the Midlands area are the Perth Basin and the western margin of the Yilgarn Block. The geology of the Yilgarn Block is described by Gee (1975) and Williams (1975), and that of the Perth Basin by Low (1971b, 1972c, 1972d,), Lowry (1972) and Playford and others (1975). The primary source rocks for heavy minerals are those of the Southwestern Province of the Yilgarn Block. Mesozoic sediments, deposited in continental and marine environments, form the platform on which Cainozoic sedimen's accumulate. Concentrations of heavy minerals in the Mesozoic rocks are known, particularly within the Yarragadee Formation, and these have been reworked to form Cainozoic deposits along the Gingin Scarp. The age of the heavy mineral deposits is unknown, but it is probably within the period Early Pleistocene to Late Tertiary.

PRECAMBRIAN ROCKS

Rivers that drain the granulite segment of the Southwestern Province of the Yilgarn Block provide material to the coastal plain in the Midlands area. This segment is composed of migmatite, gneiss and granitic rocks together with high-grade metamorphic rocks. The latter include metasediments such as sillimanite-kyanite schist, andalusite-quartz-muscovite-biotite schist, cordierite-sillimanite schist, cummingtonite and hornblende schist, talc-silicate schist, quartzite, and magnetite-grunerite banded iron-formation. Mafic metamorphic rocks are represented by plagioclase-hornblende amphibolite and ultra-mafic rocks by olivine-hypersthene assemblages; granulites occur in the central portion of the segment. Cordierite-anthopyllite and garnet-cordierite-hypersthene phlogopite rocks occur in association with some ultramafic granulites. Isotopic ages are between 3·1 to 2·8 b.y. for gneissic rocks and 2·7 to 2·6 b.y. for granitic rocks. Present also are mafic dykes locally containing titaniferous and vanadiferous magnetite, as at Coates Siding. Williams (1975) provides a bibliography of geological reports on the Southwestern Province of the Yilgarn Block.

PHANEROZOIC ROCKS (Fig. 7)

The oldest rocks exposed in the Perth Basin are Triassic sediments of the Lesueur Sandstone, found in the vicinity of Cockleshell Gully. They are a sequence of white to light grey (weathering yellow) coarse-grained feldspathic sandstone with lesser amounts of fine to medium-grained sandstone, conglomerate and siltstone. Cross-bedding is common, and the sediments are considered to be of fluviatile origin. Balme (1969) reports garnet, staurolite and ilmenite from the Lesueur Sandstone.

The Jurassic Cockleshell Gully Formation overlies the Lesueur Sandstone and is divided into two members. The older Eneabba Member is composed of fine to coarse-grained sandstone with interbedded multi-coloured siltstones and claystones. These sediments are considered to have been deposited mainly in a continental environment, but in places they contain paralic and marine sequences. The Cattamarra Coal Measures Member is a sequence of very fine to very coarse-grained sandstone with interbedded grey shale and siltstone carrying beds of coal.

Small outcrops of the Cadda Formation are found in the Hill River area. The formation consists of paralic and marine sequences composed of light-grey to dark-grey shale, siltstone and sandstone, with lenticular limestone and minor calcareous beds.

Overlying the Cadda Formation is a sequence of sandstone and siltstone, with lesser amounts of shale, claystone and conglomerate, termed the Yarragadee Formation. In some works (Lowry, 1972) part of the

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formation is referred to the South Perth Formation. The Yarradagee Formation was deposited in continental conditions.

The sediments of the Warnbro Group described by Cockbain and Playford (1973), overlie the Yarragadee Formation. They are divided, in the Midlands area, into the Leederville Formation and the Dandaragan Sandstone. The Leederville Sandstone is a sequence of sandstone (frequently feldspathic and occasionally glauconitic) and conglomerate with siltstone and claystone in which the relative proportions of the rock types vary considerably. It is considered to have been deposited in alternating marine and continental environments. The Dandaragan Sandstone consists of massive to thickly bedded, ferruginous, feldspathic medium to coarse-grained sandstone, exposed along the base of the Dandaragan Scarp between Gingin and Badgingarra. It is considered to have been deposited in a continental environment.

The Coolyena Group overlies the Warnbro Group and consists of marine glauconite-bearing sandstone, siltstone, shale and claystone of predominantly Late Cretaceous age. It is divided into the Osborne Formation, Molecap Greensand, Gingin Chalk and Poison Hill Greensand.

Unconformably overlying the Mesozoic rocks is a sequence of continental and marine sediments which are tentatively assigned to the Pleistocene, but which may be as old as Tertiary. At the foot of the Gingin Scarp there are fluviatile sediments correlated with the Guildford Formation. Overlying this unit is the Bassendean Sand consisting of quartz sand with patches of calcareous sand. On its western margin are a series of calcarenite dunes formerly referred to as Coastal Limestone, but now termed Tamala Limestone. Along the modern coastline and overlying the Tamala Limestone are a series of usually unconsolidated calcareous and quartz sand dunes, correlated with the Safety Bay Sand.

DEPOSITS ON THE ENEABBA SHORELINES

Discoveries of heavy mineral deposits about 10 km south of Eneabba (250 km north of Perth) in 1970 led to an aggressive pegging rush during 1971, followed by extensive regional exploration in the Midlands area generally. The presence of rutile and ilmenite in heavy mineral concentrates at Eneabba was first reported by Peers (1968) and Rowston (1968) from material between 20 and 25 m below the surface in Eneabba No. 1 water bore. Cable (1965) Ltd, the first exploration company to drill in the area, tested minor heavy mineral concentrations in the shores of Lake Indoon and Lake Logue in 1969. In 1970 Ilmenite Pty Ltd began prospecting for heavy minerals and worked east of Lake Indoon toward the Gingin Scarp. A prospector-farmer, Mr J. Adamson, as a result of intermittent prospecting of creeks draining into Lake Indoon, recognised the deposit south of Eneabba which he pegged in September, 1970. At this time Mr Adamson, in company with neighbours, pegged most of the Adamson, Dobney and O'Connor deposits. This led to large-scale pegging of land in the Eneabba area and eventually along the entire length of the Gingin Scarp. Subsequently exploration companies purchased the mineral claims and now Ilmenite Pty Ltd, Jennings Mining Ltd, Western Titanium Ltd, and Allied Eneabba Pty Ltd control the higher grade portions of the deposits. In 1973 Allied Eneabba Pty Ltd began production from a pilot plant, Jennings Mining Ltd commenced production in 1974.

During exploration of the heavy mineral deposits by Allied Minerals N.L. and Jennings Mining Ltd a vast amount of data has

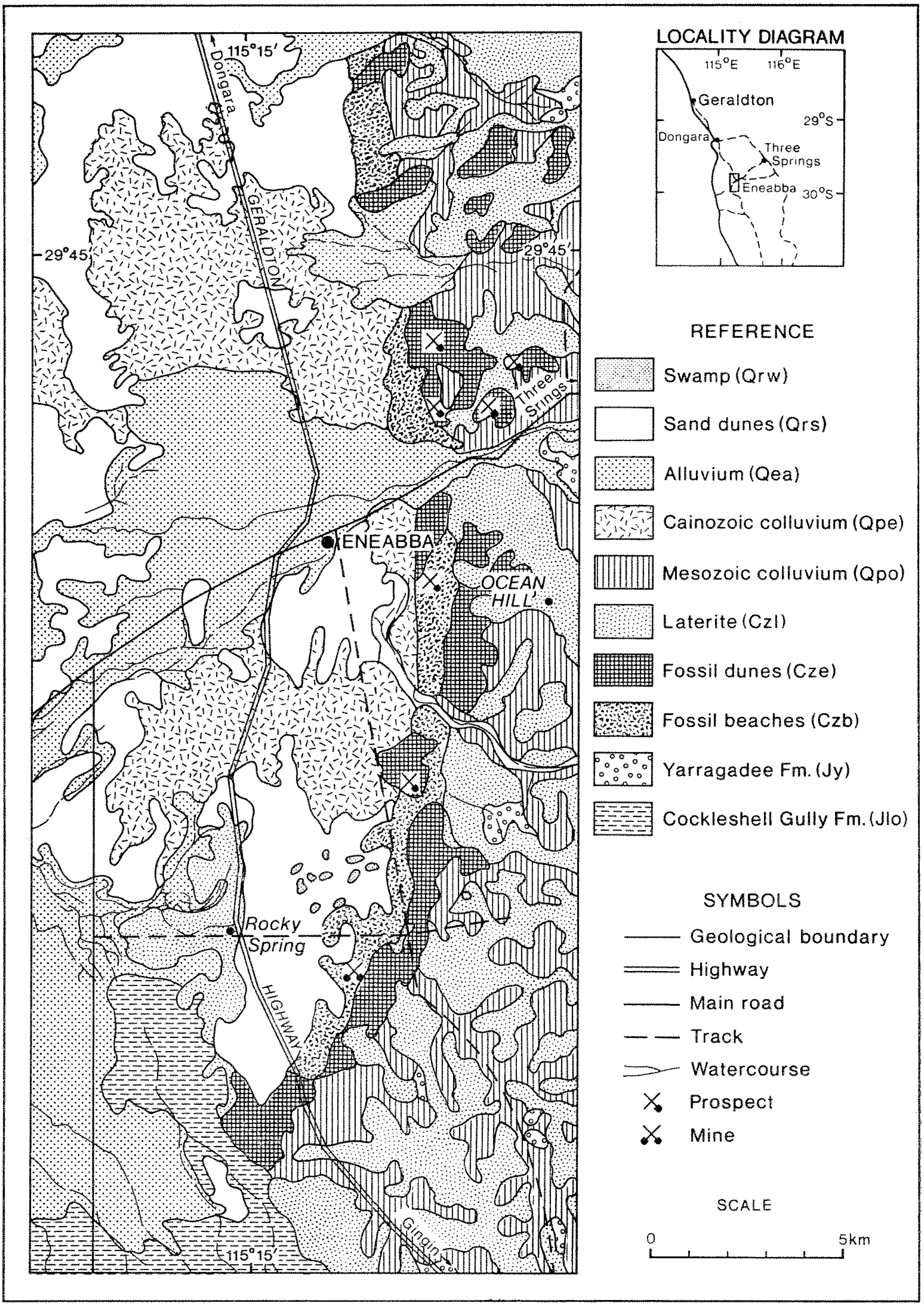


Figure 13. Geological map of the Eneabba heavy mineral field.

accumulated on the Eneabba deposits. These are summarized by Lissiman and Oxenford (1973). A summary of a geological reconnaissance of the district was published by Baxter (1972) during the early stages of exploration of the Eneabba field and a reinterpretation of this is shown in Figure 13.

The Eneabba deposit consists of an association of beach and dune sand, with fluviatile, lacustrine and dunal sediments deposited in a paralic sequence. The Mesozoic Cockleshell Gully and Yarragadee Formations underlie the heavy mineral deposits and were eroded to form a sea cliff, wave-cut platform and zeta-shaped bay prior to deposition of the heavy mineral deposits (Fig. 14). The wave-cut platform is composed of Cockleshell Gully Formation and the sea cliff (Gingin Scarp) of the Yarragadee Formation. Eneabba Creek and other creeks discharged into the sea at the foot of the ancient sea cliff introducing material eroded from the Yarragadee Formation to the coastal sediments. Sorting was probably effected by southwest swell, microtidal fluctuation and northwest storms. The coastal environment was evidently similar to that of the present, but there was apparently less carbonate influx than now. As shown on Figure 14 there are three distinct paralic successions at Eneabba containing heavy mineral concentrations. They represent marine-estuarine, beach and dune environments of deposition. The *marine-estuarine succession* was deposited in a north-facing bay and contains distinct lensoid beach sediments separated by silt, sand, clay and granule deposited in fluviatile, lagoonal and lacustrine conditions. These are the oldest deposits containing concentrations of heavy minerals at Eneabba. The northern part of the marine-estuarine deposit is overlain by alluvial sands and granule beds, but the southern part is exposed. Unconformably overlying these deposits along their western margin is a *beach sand* deposit which extends from west of Rocky Spring through the east side of Eneabba townsite and then north along the foot of the Gingin Scarp. This deposit contains heavy mineral concentrations both north and south of Eneabba Creek, but their tenor is lower than those in the marine-estuarine succession. Beach sediments consist of moderately well sorted fine to medium-grained sand with granule beds and a small amount of silt and clay. This deposit appears to contain reworked material derived from the marine-estuarine sediments to the east. Overlying both the beach and marine-estuarine deposits is a complex series of *dunes* which are generally poorly to moderately sorted and consist of sand derived from both beach and estuarine material. These dunes extend up the face of the Gingin Scarp and into the Arrowsmith Region.

ADAMSON DEPOSIT

(Lat. 29°54′S, long. 115°16′E)

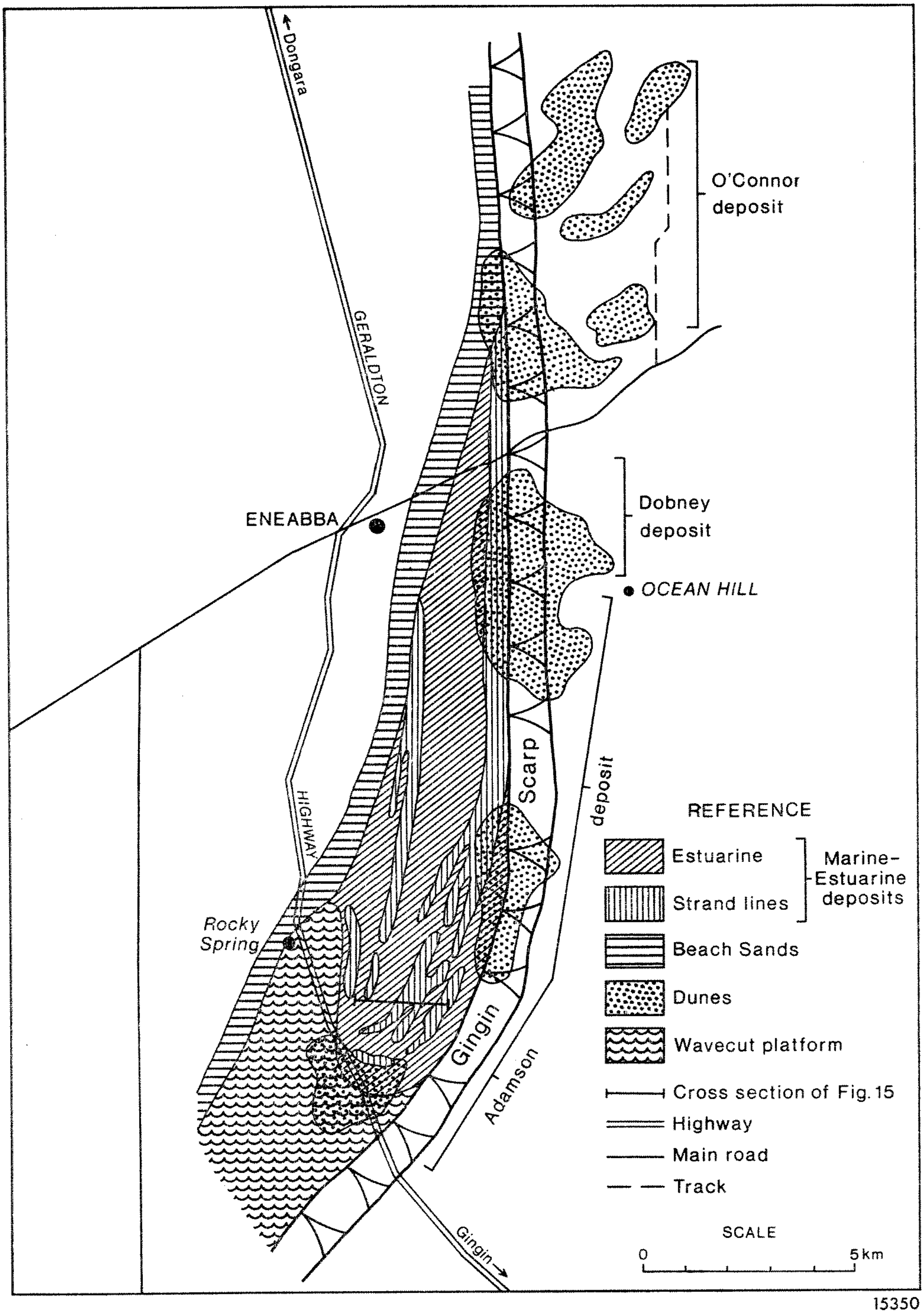
General information

The Adamson deposit is centred about 10 km south of Eneabba townsite, east of the Brand Highway. The deposits occur on Victoria Locations 10235, 10240 and 10262. They are accessible on mine roads from the Brand Highway and from Eneabba. Allied Eneabba Pty Ltd are mining the southern part of the deposit.

Geological information

Heavy mineral deposits are located along the foot and on the face of the Gingin Scarp. Exploratory drilling by Consolidated Goldfields (Australia) Ltd, Allied Eneabba Pty Ltd and Ilmenite Pty Ltd showed

Figure 14. Diagrammatic map of the fossil geomorphic units at Eneabba.


Dongara
GERALDTON
HIGHWAY
ENEABBA
Rocky Spring
O'Connor deposit
Dobney deposit
OCEAN HILL
Gingin Scarp
Adamson deposit
Gingin
REFERENCE
Estuarine
Strand lines
Marine-Estuarine deposits
Beach Sands
Dunes
Wavecut platform
Cross section of Fig. 15
Highway
Main road
Track
SCALE
0
5 km
15350

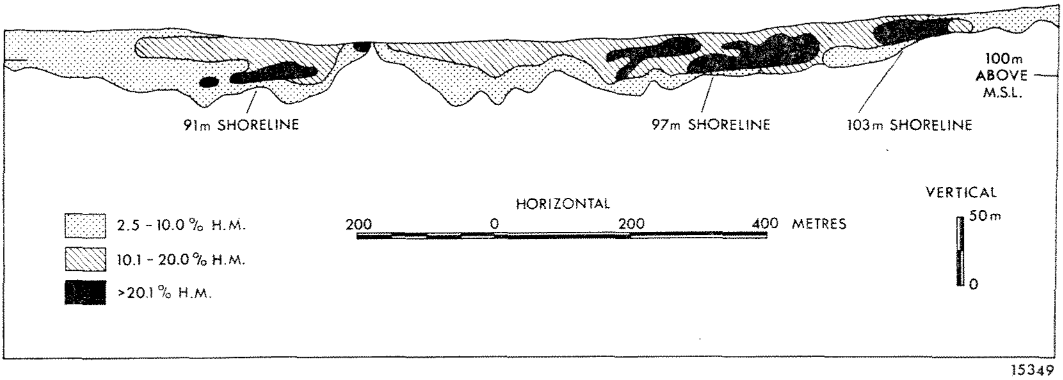


Figure 15. Diagrammatic cross section of the Adamson deposit, Eneabba.

the deposits to be about 12 km long and up to 1 200 m wide. Beach, estuarine and dune sediments are found in a paralic sequence associated with shorelines between 82 and 128 m above sea level. Most of the deposits occur at the foot of the Gingin Scarp, but in the southern portion they are situated below the scarp along an arcuate line parallel to the outline of a zeta-shaped bay formed between the Gingin Scarp and a wave-cut platform. A typical cross section of the southern part of the Adamson deposit, presented in Figure 15, is compiled from information on the grades of the deposit (high grade zones approximately correspond to beach sands).

The mineral sand unconformably overlies the Yarragadee and Cockleshell Gully Formations. The Yarragadee Formation is exposed in breakaways in the Arrowsmith Region and along the Gingin Scarp. It consists of lenticular beds of sandstone and conglomerate with minor micaceous siltstone. One sandy unit contains up to 3 per cent heavy minerals. The Cockleshell Gully Formation in this area consists of lenticular sandy members and coal measures; it is being tested by Taylor Woodrow International Ltd for its coal potential.

Marine-estuarine deposits: The marine-estuarine deposits (Fig. 14) occupy a former bay at the foot of the Gingin Scarp and consist of a lenticular paralic succession including sand, silt, conglomerate and granule beds combined with varying amounts of clay. The sediments are generally immature, although some sands exhibit maturity.

Allied Eneabba Pty Ltd subdivide the marine-estuarine succession into a number of sub-parallel "beach deposits" (Lissiman and Oxenford discuss these). The physical characteristics of sand and heavy mineral grains are shown in Table 14. The sands are poorly consolidated and poorly sorted with strong fine-skewness and leptokurtic size-distribution. The heavy mineral fraction is, according to Smith (1972), texturally sub-mature; it shows well-sorted, nearly symmetrical, fine-skewed, mesokurtic distribution and the grains have a roundness between 0·3 and 0·7 and sphericity between 0·3 and 0·7.

The deposits in the southern end of the marine-estuarine succession are finer grained, and tend to be less well sorted than those to the north. On the other hand the heavy mineral fraction shows an increase in maturity and a decrease in grain size to the south (Table 15). The strand lines contain the highest heavy mineral grades in the Adamson deposit (Table 16). The clay fraction associated with these

TABLE 14. PHYSICAL PROPERTIES OF SAND AND HEAVY MINERALS FROM THE MARINE-ESTUARINE ENVIRONMENT AT ENEABBA

Elevation of Deposit (*metres*)	Heavy Mineral Mean Diam.	Quartz Sand			
		Mean Diam.	Mode Diam.	Sorting	Skewness
115	2·55	2·4	2·3	poor to very poor	strong fine-skewness
103	2·70	2·62	2·5		
97	2·53	2·69	2·4		
91	2·77	2·62	2·6	....	....

Data from Smith (1972) and Peel (1972).
NOTE: All units expressed in phi scale.

deposits increases towards the centre of the fossil bay (Fig. 15). Some of the clay material is in pellet-form and may represent weathered feldspar; some is derived from adjacent lacustrine and estuarine deposits.

TABLE 15. MEAN DIAMETERS OF HEAVY MINERAL FRACTIONS FROM THE 91 AND 97 M SHORELINES AT ENEABBA

Shoreline (*metres*)	North	Central	South
97	2·71	2·92	3·00
91	2·26	2·61	3·20

Table from Smith (1972).
NOTE: All units expressed in phi scale.

Between the strand lines is a sequence of poorly sorted, immature, lenticular estuarine and lagoonal sands, silts and clays. This unit contains up to 60 per cent clay and may contain between 30 and 40 per cent heavy minerals. The material is generally finer grained than the adjacent beach sands. No detailed study of the wide variety of sediments included in this unit has been attempted.

The heavy mineral fraction (Table 17) of the marine-estuarine deposits shows a regionally consistent composition in all units; approximately 90 per cent by weight of combined ilmenite, zircon and rutile. Ilmenite and zircon have an approximately inverse relationship in all deposits. Rutile content decreases on shorelines higher than the 97 m strand Kyanite is associated with coarse-grained sediments. Monazite content varies throughout this deposit, ranging from 0 to 35 per cent of the heavy mineral fraction; it is common in the 91 m strand. Minor tourmaline, amphibole, pyroxene, brookite and limonite are reported throughout the deposit. The distribution of heavy mineral species within size grades indicates that the deposits formed under the influence of a southward flowing marine current from near the coastal outlet of Eneabba Creek.

Beach sand deposits: West of the marine-estuarine deposits a near linear fossil beach has been investigated by Ilmenite Pty Ltd. It consists of poorly to moderately sorted sand apparently derived by reworking of material from the marine-estuarine deposits. Where this fossil beach deposit dissects high-grade concentrations within the marine-estuarine deposits, it contains lenticular zones of heavy minerals.

In general heavy mineral concentrations in the fossil beach tail off towards the north, probably indicating deposition under the influence of northerly marine currents.

TABLE 16. CONTENTS OF HEAVY MINERALS AND CLAY IN DUNE DEPOSITS AND VARIOUS STRAND LINES AT ENEABBA

Sample Locality	Clay		Heavy Minerals	
	Average	Range	Average	Range
	Weight Per Cent			
Dune	25	22–45	15	6–30
115 m strand	12	5–20	30	6–70
103 m strand	20	9–38	25	14–40
97 m strand (E)	14	12–22	32	22–52
97 m strand (W)	18	12–40	32	12–55
91 m strand	12	5–20	38	20–45

TABLE 17. COMPOSITIONS OF HEAVY MINERAL FRACTIONS FROM STRAND LINES IN THE ADAMSON DEPOSIT

Mineral	Strand Line *metres above m.s.l.*				
	128 m	115 m	103 m	97 m	91 m
	Weight Per Cent				
Ilmenite	37·9	43·9	61·4	64·8	66·1
Leucoxene	n.d.	1·7	2·1	2·2	1·9
Rutile	7·0	8·6	9·7	10·9	8·6
Zircon	19·6	39·7	18·6	17·1	15·0
Monazite	n.d.	0·4	0·1	0·2	0·2
Kyanite	1·7	1·6	2·4	2·7	4·1
Others	32·6*	3·7	5·7	2·3	3·2

* Includes 24·2 per cent limonite. n.d. = not determined. m.s.l. = mean sea level.

Dune deposits: Overlying the marine-estuarine and beach sand deposits are accumulations of unconsolidated yellow dune sand. This sand is also deposited, up to 180 m above sea level, on the face of the Gingin Scarp where it is restricted to west and south facing sides of valleys. The dune sand is generally more mature than the beach deposits and has a similar heavy mineral content throughout. The deposits are generally between 6 and 10 m thick but range up to 20 m. They contain 5 to 10 per cent of heavy minerals and 5 to 40 per cent of clay. The heavy mineral fraction usually contains slightly less rutile and ilmenite and more kyanite and zircon than in nearby fossil beach deposits.

Coffee-rock: Massive, columnar, honeycomb and pod-form coffee-rock types have developed in the Adamson heavy mineral deposit. The massive, columnar and honeycomb types are common in the marine-estuarine deposits adjacent to the Gingin Scarp. The beach deposits contain honeycomb and columnar coffee-rock, but occasionally massive coffee-rock is also found. Pod-form coffee-rock is present in all eolian deposits and is common in the marine-estuarine deposits towards the centre of the ancient bay.

Overburden: All members of the Adamson heavy mineral deposit are overlain in part by unmineralized, moderately sorted, white to grey quartz sand. This is considered to be part of the Bassendean Sand.

References: Baxter (1971, 1972), Lowry (1972), Smith (1972, 1973), Peel (1972), Lissiman and Oxenford (1973).

O'CONNOR MINE

(Lat. 29°46'S, long. 115°19'E)

General information

The deposits in the O'Connor mine area are situated north of the Eneabba-Three Springs Road, about 2 km east of Eneabba on Victoria Locations 10221 and 10222. Originally it was pegged by Mr R. O'Connor and ultimately the deposit was bought by Jennings Mining Ltd. Jennings Mining Ltd began mining in 1974.

Geological information

Jennings Mining Ltd divides the deposit into zones (identified by the letters A to F) corresponding to discrete heavy mineral concentrations. Zones A to E are located in dune sands and zone F is buried beach sand.

Zone F is situated at the foot of the Gingin Scarp north of Eneabba Creek. The deposit contains pockets of up to 40 per cent heavy minerals; the composition of the heavy mineral fraction is shown in Table 18. The beach deposit appears to have formed north of the mouth of the Eneabba Creek when the coastline was about 106 m above present sea level. The heavy mineral distribution is asymmetric with much greater enrichment at the southern end. The fossil coastal deposits can be traced north as far as the Arrowsmith River, but the heavy mineral content of the sediments decreases rapidly away from Eneabba Creek. There is minor columnar coffee-rock in the eastern side of zone F, but it is unlikely this will affect mining of the ore. The zone lies on a hard clay floor of deeply weathered Yarragadee Formation.

Zones A to E are sand dunes up to 18 m thick, deposited on the south and west-facing slopes of Eneabba Creek and the unnamed creek 2 km farther north. The deposits unconformably overlie lateritized Yarragadee Formation. The bedrock surface dips steeply to the southwest and in some places is irregular. The dune sands occur up to 152 m above sea level, and down to about 110 m above sea level, covering the beach deposits in some places. They are unconsolidated and contain minor pod-form coffee-rock. The dunes contain an average of between 10 and 12 per cent clay fraction and 2 to 14 per cent heavy minerals; composition of zone A material is given in Table 18. The sands are well sorted and the quartz grains are moderately rounded with fair to moderate sphericity.

References: Baxter (1971, 1972), Lowry (1972), McDonald (1974).

DOBNEY PROSPECT

(Lat. 29°47'S, long. 115°19'E)

General information

The Dobney prospect, situated south of the Eneabba-Three Springs Road, is on Victoria Location 10239. It is a northward extension of the Adamson deposit, following the base of the Gingin Scarp for some 3·5 km south of Eneabba. The prospect is being investigated by Jennings Mining Ltd, who refer to it as zone G.

Geological information

The deposit consists of a dune which overlies a beach deposit and extends up the face of the Gingin Scarp. The beach deposit rests unconformably on the Yarragadee Formation and lies between 97 and 103 m above present sea level. Most of the mineralized sand is contained within the dune deposits.

The dune sand is fine to medium grained, moderately to poorly sorted and generally subrounded to sub-angular. A quartz granule bed at the base of the deposit, with fragments up to 5 mm in diameter, contains rich lenses of heavy minerals in some places. A heavy mineral analysis is presented in Table 18.

MINOR OCCURRENCES

Mount Adams

(Lat. 29°25'S, long. 115°13'E)

The Mount Adams occurrence is located 45 km north of Eneabba at the foot of the Gingin Scarp. It has been investigated by Hawkstone Minerals N.L. who identified beach sands containing less than 2 per cent of heavy minerals.

Drummond Crossing

(Lat. 29°38'S, long. 115°15'E)

The Drummond Crossing occurrence, also known as the Correy prospect and Eneabba Area C, is situated at the foot of the Gingin Scarp, on the northern boundary of Victoria Location 10213, and extends 1 km south of the Arrowsmith River. The deposit is 2 km east of Drummond Crossing and approximately 19 km north of Eneabba. It has

TABLE 18. COMPOSITIONS OF HEAVY MINERAL FRACTIONS FROM O'CONNOR AND DOBNEY DEPOSITS

Mineral	O'Connor				Dobney
	Zone A	Zone F (East)	Zone F (Middle)		
	1	2	3	4	5
	Weight Per Cent				
Ilmenite, Altered Ilmenite	59·48	61·66	59·16	60·32	65·91
Rutile	7·97	8·14	13·45	15·00	10·63
Zircon	11·96	15·43	11·68	15·42 (Zircon and Kyanite)	15·68
Kyanite	8·91	7·34	3·61		7·05
Others*	8·89	6·04	12·07†	9·26	0·72

* Includes quartz, tourmaline, staurolite and monazite.
† 8·60 quartz.

KEY TO COLUMNS:

1, 2 and 5. Composite drill hole samples determined by Jennings Mining Ltd, Geraldton, using variable magnetic and electrostatic separation and weighing.

3. Wet plant concentrate (100 lbs) determined by AMDEL, Adelaide, using riffled, heavy liquid separation, point counting and weighing.

4. Bulk sample (35 tons) from pilot plant concentrate determined by Mineral Deposits Ltd, Southport, Qld., using variable magnetic and electrostatic separation and weighing.

been drilled by Carr Boyd Minerals Ltd and consists of a series of mixed sandy sediments, in some places overlain by barren quartz-sand dunes. A persistent claystone basement to the deposit is probably Yarragadee Formation. Heavy mineral grades, estimated at between 3 and 5 per cent, occur from the surface to a depth of 12 m. The heavy mineral fraction is reported to contain 5 per cent zircon and 12 per cent rutile. The clay fraction varies from 5 to 50 per cent. There are no heavy mineral concentrations north of creeks running through the area. The deposit is interpreted as part of a paralic sequence formed at the mouth of an ancestral Arrowsmith River. Overlying dunes are correlated with the Bassendean Sand.

Bindoon Creek

(Lat. 29°59′S, long. 115°14′E)

The Bindoon Creek deposit, approximately 9 km south-southeast of Eneabba townsite, is situated on the southern boundary of Victoria Location 10253, lying between two tributaries of Bindoon Creek.

The occurrence was located by Western Titanium Ltd while drilling to trace the southern extension of the Eneabba Shorelines. It consists of yellow sand containing between 1 and 2 per cent heavy minerals. On the surface, patches of up to 15 per cent heavy minerals have been located, but these are small and usually less than 10 cm thick. The site is interpreted as a dunal remnant of Eneabba Shoreline sediments eroded by Bindoon Creek. Any former beach deposits have presumably been removed by erosion.

Lake Indoon

(Lat. 29°52′S, long. 115°08′E)

Lake Indoon is 12·5 km west-southwest of Eneabba and can be reached by road. Lake Logue is about 1 km north of Lake Indoon. As a result of drilling by Cable (1956) Ltd and Norseman Titanium N.L. rutile was recognized in lake-shore deposits, this being the first recorded occurrence of a significant accumulation of rutile in a shoreline sediment in Western Australia. Lake Indoon and Lake Logue are terminations of a west-flowing drainage which includes Eneabba and Bindoon Creeks. These creeks dissect heavy mineral deposits at the foot of the Gingin Scarp and concentrations on the lake shore have the same general composition as the older deposits. Concentrations are less than 1 m thick.

DEPOSITS ON THE MUNBINEA SHORELINE

Following the discovery of rich heavy mineral deposits at Eneabba, prospecting along the foot of the Gingin Scarp led to the discovery of the Munbinea Shoreline south of the Hill River. The Jurien deposits were pegged for West Coast Rutile Pty Ltd by Mr C. R. Gibson in April 1971. Further prospecting south of the deposit led to the discovery of concentrations near Cooljarloo Well and these are held by the same company. West Coast Rutile Pty Ltd is now called Black Sands Ltd. WMC Mineral Sands Ltd now control Black Sands Ltd. Allied Minerals N.L. prospected the country between the Jurien deposits and the Gingin Scarp, but have been unsuccessful in identifying economic reserves of heavy mineral.

The Jurien deposits consist of a paralic sequence in which three distinct shorelines are recognized between 36 and 43 m above present sea level. The deposits are up to 500 m west of the Gingin Scarp and are covered in part by mineralized dunes. The shoreline sediments include a basal conglomerate with clasts of Mesozoic basement rocks overlain by a medium to coarse-grained mineralized sand. The heavy mineral concentrations in the deposit tend to have tails pointing north and it appears that the source for the material was a drainage outlet to the fossil shorelines about 5 km south of the present course of the Hill River. The Hill River dissected the deposit, but reconnaissance drilling failed to locate significant mineralization north of the river. Initial production feasibility studies have been carried out on these deposits by Black Sands Ltd and WMC Mineral Sands Ltd.

Included in the Munbinea Shoreline are the deposits near Cooljarloo Well. These occur as three sub-parallel lines of immature paralic sands and appear to be deposited in channels cut into the underlying Mesozoic rocks. The deposits are lenticular and mineralization is patchy. The sands have up to 30 per cent of clay at the surface. Mullering Brook dissects the southern end of the deposit. No reduced level data are available on the base of the deposits, but these appear to be about 50 m above sea level.

JURIEN PROSPECT

(Lat. 30°19′S, long. 115°10′E)

General information

The Jurien prospect, on Victoria Locations 3750 and 3927, is about 15 km east of Jurien townsite, south of the Hill River and north of Silver Tyre Road. The deposit is to be mined by Black Sands Ltd (formerly known as West Coast Rutile Pty Ltd), a former subsidiary of Kamilaroi Mines Ltd and Mining Corporation of Australia Ltd, now owned by WMC Mineral Sands Ltd.

Geological information

Black Sands Ltd have identified five distinct lenses with heavy mineral concentrations now referred to as A to E as shown on Figure 16. Lenses A, B and C are buried beach deposits which rest unconformably on Lesueur Sandstone. They consist of disrupted-framework conglomerate in a matrix of clayey sand overlain by moderately well-sorted and well-rounded quartz sands containing heavy minerals. The bases of the beach deposits occur at 36 m, 39 to 40 m and 43 m above sea level and slope gently north at about 1 in 1 000. The content of heavy minerals varies between 6 and 97 per cent. An asymmetric distribution of heavy minerals within the lenses indicates the influence of currents from the south during formation of the deposit. The northern ends of the deposits have been eroded by the Hill River; the southern ends become dispersed along the Munbinea Shoreline.

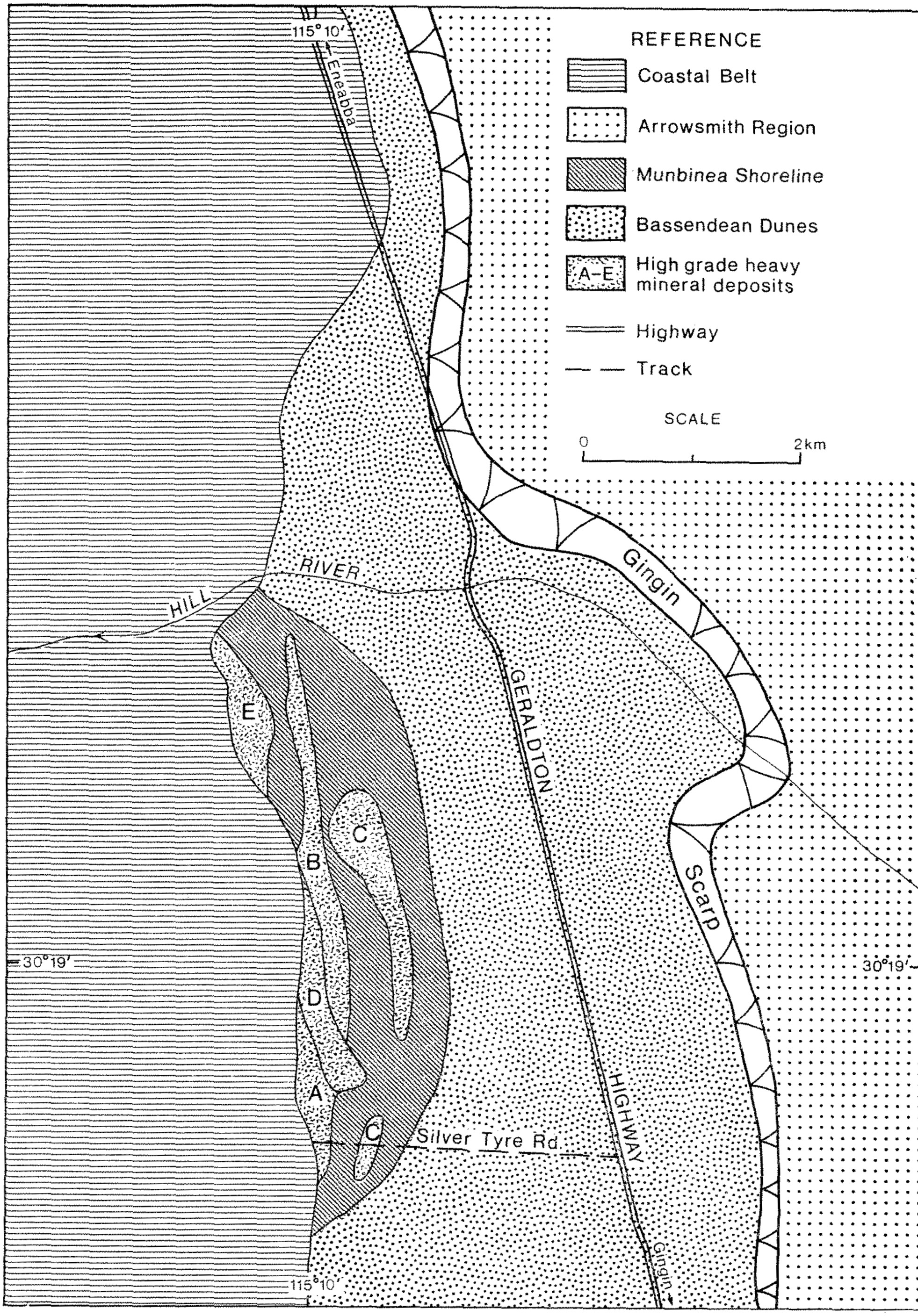


Figure 16. Map showing geomorphic units and fossil shorelines at the Jurien deposit.

The D and E deposits consist of lenticular bodies of mineralized eolian quartz and lime sand containing higher percentages of garnet, kyanite and staurolite than the beach deposits. They are thought to be associated with an as yet unrecognised shoreline to the west of lenses A to C.

Overlying the heavy mineral deposits on the west, with distinct unconformity, is a group of calcarenite and lime sand dunes of the Tamala Limestone. These are mineralized adjacent to the underlying ore deposits, but the grades are low and the mineral distribution is erratic. The eastern side of the deposits is commonly covered by up to 1 m of unconsolidated white sand which contains some heavy minerals. The mineral suite in the white sand is richer in garnet, kyanite and staurolite than in lenses A to C.

Coffee-rock is formed in all of the heavy mineral lenses. The eastern beach deposits (B and C) contain well developed massive, columnar and honeycomb forms, while the western deposit (A) and dunes (D and E) contain pod-form coffee-rock, with minor honeycomb coffee-rock being sometimes present in basal sections.

Black Sands Ltd have announced measured (proven) reserves of 1·178 Mt and 0·71 Mt of indicated (probable) reserves of contained heavy minerals, at an average grade of 9 per cent in the ore. The composition of the heavy mineral fraction in the five lenses is shown in Table 19. Chemical analyses of these fractions are given in Table 20.

COOLJARLOO PROSPECT

(Lat. 30°40′S, long. 115°20′E)

General information

The Cooljarloo prospect is about 170 km north of Perth and west of the Brand Highway. It is located on Crown Land along a line running about 9 km southeast from Wongonderrah Spring Reserve 26248 on Melbourne Location 3864. The northern portion of the deposit crosses Strathmore Road adjacent to Melbourne Location 3861. WMC Mineral Sands Ltd are currently assessing the potential of the deposit in conjunction with development of the Jurien mine.

Geological information

WMC Mineral Sands Ltd (formerly Black Sands Ltd) recognise three distinct sub-parallel lines of mineralization up to 900 m apart. The western deposit is lenticular and eroded; mineralization has been identified along a line 30 to 100 m wide and down to 30 m deep. The middle deposit consists of about 9 m of mineralized sand, overlying 7 to 10 m of barren quartz sand, below which there is a further 10 m maximum thickness of mineralized sand 40 to 120 m wide and 5 km long. The eastern deposit is the most continuous of the three, consisting of about 10 m of mineralized sand forming a line 7 to 8 km long and up to 250 m wide. All the deposits appear to have accumulated in trenches cut into the Yarragadee Formation. They are composed of angular to sub-angular, medium-grained quartz sand and contain between 0 and 30 per cent clay and up to 20 per cent heavy minerals. As yet the environment of deposition of these sediments is not known.

MINOR OCCURRENCE

Cockleshell Gully

(Lat. 30°09′S, long. 115°06′E)

The occurrence is situated between 19 and 26 km north-northeast of Jurien townsite and lies north and south of Cockleshell Gully. The road from Eneabba to Jurien passes along the eastern side of the deposit. It consists of white to yellow quartz sands containing between 0·2 and 2 per cent heavy minerals. Clay content of the deposit increases with depth and lateritic ferruginous gravels are common. No beach sediments have been identified.

DEPOSITS ON THE GINGIN SHORELINE

Heavy mineral deposits on the Gingin Shoreline were first tested by Westralian Sands-Lennard Explorations in late 1971. Most of the mineralized portion of the shoreline occurs on land where mineral rights are endowed with the land title. The deposits extend from Regans Ford to Bullsbrook. One orebody has been identified at Gingin; Lennard Oil N.L., a partner in this venture, announced indicated ore reserves of 2·3 Mt of heavy mineral from this area (West Australian, May 18, 1974).

The Gingin Shoreline deposits follow the foot of the Gingin Scarp and consist of beach and dune sands lying unconformably on Mesozoic rocks correlated with the Coolyeena

TABLE 19. COMPOSITIONS OF HEAVY MINERAL FRACTIONS FROM THE JURIEN DEPOSITS

Mineral	Deposit A		Deposit B		Deposit C		Deposit D		Deposit E	
	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average
	Weight Per Cent									
Ilmenite	17·0–26·5	23·9	5·1–25·3	16·5	6·8–15·1	11·7	49·0–51·4*	50·2	1·9–21·3	8·8
Altered Ilmenite	28·9–32·1	30·0	34·0–53·6	46·1	46·4–56·1	50·0	....	....	30·9–47·7	41·7
Leucoxene	4·1–13·4	7·5	0·9–3·9	3·0	4·1–7·6	5·2	7·5–9·9	8·7	8·0–9·5	8·8
Rutile	6·7–10·5	8·3	6·4–11·8	8·5	9·1–11·7	10·3	6·2–10·4	8·3	6·8–7·5	7·2
Zircon	6·5–22·5	12·8	12·3–18·7	14·3	12·3–13·9	13·1	10·5–9·3	9·9	8·2–8·9	8·5
Monazite	0·6–1·1	1·4	0·5–2·5	1·2	0·6–1·6	1·1	0·2–0·5	0·4	0·4–0·8	0·6
Kyanite	1·6–6·5	3·7	1·4–4·9	3·2	3·0–5·7	3·9	3·8–4·6	4·2	5·0–8·8	7·4
Garnet	0·3–15·7	6·6	0·4–11·1	4·1	1·1–1·6	1·4	11·5–14·5	13·0	8·0–15·2	10·8
Staurolite	0·6–2·9	1·8	0·6–3·1	1·7	1·7–2·9	2·4	2·1–1·9	2·0	2·4–4·9	3·7

* Includes ilmenite and altered ilmenite.

TABLE 20. ANALYSES OF ILMENITE, ALTERED ILMENITE, RUTILE AND ZIRCON FRACTIONS FROM THE JURIEN DEPOSITS

Oxide *Per Cent*	Ilmenite and Altered Ilmenite					Rutile				Zircon	
	1	2	3	4	5	6	7	8	9	10	11
ZrO_2	....	....	....	....	....	1·80	....	0·30	0·22	n.d.	62·8
TiO_2	54·5	54·9	57·2	59·3	63·0	92·8	95·1	95·8	96·55	0·90	0·26
Fe_2O_3	22·3	22·5	23·8	28·0	27·9	0·58	....	....	2·80	0·17	0·16
FeO	18·5	17·4	14·4	6·9	1·2	....	....	....	....	....	....
Al_2O_3	0·50	0·52	0·56	0·68	0·83	....	....	....	0·208	1·06	0·40
Cr_2O_3	0·04	0·03	0·04	0·04	0·06	....	....	....	0·161	0·015	....
MgO	0·42	0·41	0·41	0·37	0·30	....	....	....	0·035	0·017	....
V_2O_5	0·22	0·21	0·20	0·21	0·16	....	....	....	....	....	....
Nb_2O_5	0·09	0·06	0·06	0·06	0·14	....	....	....	....	....	....
Total Insoluble	2·36	2·25	2·95	5·14	9·34	....	....	....	....	....	....
Insoluble TiO_2	1·60	1·80	2·11	3·12	7·64	....	....	....	....	....	....

Analyses: 1–8. Analytical Services (Nickel) Pty Ltd. n.d. = not determined.

9–11. Chemical Consultant Pty Ltd.

and Warnbro Groups. It seems likely that material deposited on the shoreline was derived by erosion of Mesozoic rocks in the sea cliff, with contributions from creeks such as Gingin Brook.

The heavy mineral sands are uniform medium-grained quartz sands set in a clay matrix, the latter amounting to between 10 and 30 per cent of the deposit. Yellow dune sand overlies the deposit in many places. The dunes are mineralized, but generally contain less than 10 per cent heavy minerals.

West of the beach is a sequence of yellowish-brown and reddish-brown clayey sands which appears to overlap the deposits in places. This material is referred to as the Guildford Formation. Overlying this unit is white sand assigned to the Bassendean Sand.

GINGIN PROSPECT

(Lat. 31°17′S, long. 115°52′E)

General information

The Gingin prospect is 85 km north of Perth on the Perth to Dongara road. It is centred about 3 km northwest of Gingin townsite on Swan Locations 355, 506, 511, 536, 569, 627 and 1659, extending across the Gingin-Dongara road in two places, 2 km and 5·5 km north of the townsite. Mineral rights of the land are alienated from the Crown.

Geological information

The deposit comprises a clayey sand member within a paralic succession lying at the foot of the Gingin Scarp. The ore zone occurs north of Gingin Brook which has truncated the southern part of the deposit. The deposit to the north interfingers with brownish-grey to white sand which appears to represent a facies change along the shoreline. The base of the deposit is between 70 and 80 m above sea level. One zone of mineralization is over 5 km long, up to 250 m wide and between 2 and 20 m thick. The orebody contains up to 60 per cent heavy minerals and between 12 and 30 per cent clay. West of, and interfingering with, the deposit is a yellowish-brown and reddish-brown clayey sand. These sediments, deposited in an alluvial environment, are correlated with the Guildford Formation and contain no concentrations of heavy minerals.

Overlying these units poorly to moderately sorted quartz sand contains insignificant heavy mineral concentrations. This overburden is up to 16 m thick.

Reference: Newstead (1973).

MINOR OCCURRENCES

Bullsbrook

(Lat. 31°37′S, long. 116°02′E)

The Bullsbrook deposit is situated 4 km north of Bullsbrook townsite to the east of the Great Northern Highway. The deposit lies within Mineral Claims 70/12208 and 70/12209. Bullsbrook is approximately 40 km north of Perth and is connected to Perth by a narrow gauge railway line.

The prospect is a lenticular beach sand which contains between 5 and 50 per cent of heavy minerals. The sand contains up to 30 per cent of clay. The deposit is up to 10 m thick, generally less than 80 m wide and has been traced over a length of 6 km. There is between 2 and 8 m of unmineralized overburden.

Reference: Newstead (1971a).

Muchea

(Lat. 31°32′S, long. 115°57′E)

The Muchea deposit is 10 km north of Muchea railway station on the east side of the Gingin Road, about 9 km north of the junction with Great Northern Highway. It is covered by Mineral Claims 70/12375, 70/12382 and 70/12387. The deposit was drilled by Westralian Sands-Lennard Explorations.

A small lenticular heavy mineral deposit, 100 m wide, 10 m thick and 1·5 km long was identified along the foot of the Gingin Scarp. It is covered by a variable amount of unmineralized overburned. No further information is available.

Reference: Masters (1973).

Regans Ford

(Lat. 30°49′S, long. 115°42′E)

The Regans Ford deposit is situated parallel to and on the west side of the Brand Highway, 51 km north of Gingin. It occurs on Melbourne Locations 3716, 3717, 3718 and 3865. The deposit has been drilled by Westralian Sands-Lennard Explorations.

The heavy mineral concentration lies north of the Moore River at the foot of the Gingin Scarp, the base being reported as 67 m above sea level. It is a lenticular paralic sequence of clay and clayey sands containing up to 15 per cent heavy minerals. Mineralization is known to occur over a length of 3·5 km and widths of between 30 and 150 m.

Reference: Newstead (1973).

DEPOSITS ON THE COAST

Heavy mineral deposits along the modern shoreline in the Midlands area are reported at Mosman Beach, Snag Island and Green Head. These deposits are small, are restricted to the beach, and are of no economic importance. The distribution of heavy minerals is erratic and appears to bear no relation to modern drainage. Along the Midlands coast a high influx of carbonate particles from the littoral and neritic zones dilutes the heavy minerals deposited in the dunes and beaches. It is possible that this carbonate influx has lowered the proportions of heavy minerals along the modern coast to a level at which commercial concentrations do not develop.

REPORTED OCCURRENCES

Mosman Park

(Lat. 32°00′S, long. 115°45′E)

Mosman Beach is between Cottesloe and Leighton and immediately west of Cable Street, Mosman Park. The area is described as being 64 m southwest of the corner of Sydney Street and Marine Drive.

Small concentrations of heavy minerals were reported by Low between the foredune and the high water mark. They were restricted to minor lenses within the beach sand. The deposit averaged 14 m wide and was less than 1·2 m deep. The grade was not recorded, but 550 t of heavy mineral was reported when the deposit was tested in 1957.

Reference: Low (1960b)

Green Head

(Lat. 30°04′S, long. 114°58′E)

A small concentration of heavy minerals is reported in the berm and beach sediments along the shoreline north of Green Head townsite. The deposit contains less than 200 t of heavy minerals, and is possibly of similar form to the Mosman Beach deposit.

Snag Island

(Lat. 29°56′S, long. 114°59′E)

Heavy minerals are concentrated in slicks on the beach between Drummond Rock and Snag Island. These deposits are similar to those at Green Head. No detailed information is available on them.

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CHAPTER 6

Southern Deposits

Deposits of heavy mineral bearing Cainozoic sediments formed in coastal environments between Dunsborough and Eucla, are grouped as the Southern deposits. They occur in four distinctive geological environments. Two are adjacent to sedimentary basins, namely the southern part of the Perth Basin and the Eucla Basin; and two are associated with high-grade metamorphic belts, the Albany-Fraser Province and the Leeuwin Block. Deposits adjacent to the Albany-Fraser Province lie within the Bremer Basin.

Sub-economic mineralization has been discovered at Scott River, Yallingup and Hassell Beach. Smaller deposits are known at Cheyne Bay, Gordon Inlet, Windy Harbour and Israelite Bay. The individual deposits are too small to justify construction of a separation plant, but a combined operation using ore from groups of deposits may be feasible in the future. No heavy mineral deposits of economic importance have been discovered along the coast of the Eucla Basin.

All deposits of possible economic importance lie within 3 km of the coast, the scenic nature of which has led to local groups opposing all mining in its vicinity. This opposition, together with the small size of the deposits, may be sufficient to prevent their development.

DEPOSITS ADJACENT TO THE LEEUWIN BLOCK

Heavy mineral concentrations in sediments deposited along the coast between Dunsborough and Augusta on the flanks of the Leeuwin Block or Naturaliste Region are grouped together. Their provenance is the horst of high-grade metamorphic rocks forming the Leeuwin Block. Regional geology and geomorphology are summarized by Lowry (1967), Peers (1975), and Playford and others (1975).

REGIONAL GEOMORPHOLOGY

The Naturaliste Region (Playford and others, 1976) is subdivided into the Witchcliffe Upland and Coastal Belt (Fig. 17). The Witchcliffe Upland is a high undulating upland (up to 220 m above sea level) between Cape Naturaliste and Cape Leeuwin. It is dissected by many youthful streams flowing to the coast, and is breached by the Margaret River. The result of dissection has been to produce youthful relief, particularly on the western side of the upland. Dunes of the Coastal Belt are formed on the steep western side of the Witchcliffe Upland extending from just above sea level (near the mouths of the larger creeks) to at least 200 m above sea level. In several areas the dunes are lithified with caves developed within them. Along much of the coast the dunes are fixed within 0·5 km of the shoreline, but in several places large blowouts such as the Boranup Sand Patch are formed.

The shoreline consists of a series of roughly omega-shaped bays separated by rocky headlands. Beaches are narrow with cobbles and boulders common in the southern part of the bays, their northern reaches being sandy.

REGIONAL GEOLOGY

The oldest rocks of the Leeuwin Block are high-grade metamorphic mafic and felsic rocks. Some are interpreted as metamorphic derivatives of igneous rocks and these are considered to be the source of ilmenite found in the heavy mineral deposits. Information on the regional distribution of rock types and structure of the metamorphic rocks is scanty as exposure of these rocks is poor.

Cretaceous sediments, known to contain heavy mineral deposits, onlap the Leeuwin Block on the eastern side. These sediments however, do not appear to contribute material to the heavy mineral deposits on the coast.

Cainozoic deposits of limestone, sand, laterite and clay occur on the Leeuwin Block. The limestone is a partially lithified eolianite found on the western slopes of the block. It contains between 10 and 90 per cent calcium carbonate and may have up to 10 per cent heavy minerals. It contains soil horizons (Fairbridge and Teichert, 1953) which are difficult to correlate over any distance. Laterite occurs over the metamorphic rocks of the Leeuwin Block and is usually associated with thick clay. The clay contains quartz and other minerals resistant to weathering and is considered to be a source for sand and heavy minerals in beach and dune sands. The beaches are commonly composed of boulder conglomerates, lime sand and quartz sand, and are usually less than 5 m thick.

BUNKER BAY PROSPECT

(Lat. 33°33′S, long. 115°02′E)

General information

Bunker Bay on the coast, is approximately 3 Km east-southeast of Cape Naturaliste, and approximately 34 km west of Busselton with access along Bussell Highway and Caves Road. The deposit is situated immediately south of the beach on Sussex Locations 422, 302, 595 and D.

Geological information

The prospect was tested by the Griffin Coal Mining Company. It consists of beach and dune deposits lying parallel to the coast, formed in an embayment cut into the Leeuwin Block, immediately east of Cape Naturaliste. The beach deposit contains high-grade sections with up to 90 per cent ilmenite, but in the dune, grades are generally less than 20 per cent ilmenite. There is no accurate height information on this deposit but the northern part appears to lie about 1 m below sea level.

The composition of the heavy mineral fraction is shown in Table 21. High manganese in the ilmenite analysis is attributed to the presence of garnet in the sample.

References: Lowry (1967), Kay (1958), Baxter (1970).

YALLINGUP PROSPECT

(Lat. 33°39′S, long. 115°01′E)

General information

The deposit, approximately 2 km south of Yallingup, is some 34 km from Busselton along Bussell Highway and Caves Road. It is situated immediately inland from Smith Beach mainly on the north side of Gunyulgup Brook on Sussex Locations 77, 78, 86, 88 and 122. The area has been known as Gibbs-Telfer, Gibbs Flat, Telfer Extended and Yallingup.

Geological information

Reconnaissance drilling by Busselton Minerals N.L. indicated a low grade heavy mineral deposit in dunes and around the estuary at the mouth of Gunyulgup Brook. The dunal material interfingers with and overlies the estuarine deposits; the latter are known as Gibbs Flat.

The dune is composed of mixed grey, yellow and orange-brown sand interbedded with calcarenite. Its base lies between 12·2 and 61·0 m above sea level. The dune is mineralized on the northern and western

TABLE 21. COMPOSITIONS OF HEAVY MINERAL FRACTIONS FROM DEPOSITS ADJACENT TO THE LEEUWIN BLOCK

Mineral	Bunker Bay	Ensor	Redgate		Flinders Bay
		Weight Per Cent			
Ilmenite	74·0	63·0	23	28	45–62
Altered Ilmenite	....	3·9	....	....	2–4
Leucoxene	0·75	....	....	....	tr.
Zircon	3·5	2·2	....	....	0·00
Monazite	0·08	....	....	....	0·00
Garnet	*	13·9	64 (d)	53 (c)	....
Staurolite	....	1·0	....	....	....
Actinolite	....	....	....	....	....
Others	....	14·5 (a)	13 (b)	19 (b)	30–50 (d)

Ilmenite Composition

TiO_2	54·4	51·3	....	....
Cr_2O_3	0·05	....	....	....
MnO	1·2	....	....	....

tr. = trace. * Present.

NOTES: (a) hornblende, spinel, quartz. (b) Quartz feldspar and shell fragments. (c) Almandine (d) Hornblende.

slopes of Gunyulgup valley, containing between 1·5 and 10 per cent heavy minerals which are fairly uniformly distributed. Clay forms between 0·5 and 4 per cent of the deposit.

Gibbs Flat is underlain by a complex marine and fluviatile sequence of sand, silt and clay deposited at the mouth of the Gunyulgup Brook where heavy mineral sands are known to occur down to 12 m below sea level. Black, brown and yellow sand and buff clay are the principal sediments, though red clay is found upstream on the southern side of the Gunyulgup valley. The sediments are deposited on weathered metamorphic rock exposed in the flanks of the creek. The heavy mineral content varies between 2 and 20 per cent and the clay content between 2 and 30 per cent.

The area is situated close to a popular beach and a Caves Reserve and will almost certainly be the subject of land utilization disputes prior to mining.

ENSOR PROSPECT

(Lat. 33°47′S, long. 115°00′E)

General information

The deposit is situated on the south side of the mouth of Willyabrup Brook about 10 km south of Cape Clairault. It is approximately 51 km from Busselton along Bussell Highway and Caves Road, on Sussex Locations 748, 920, 350 and part of 731 to which there is no made road. It was covered by Mineral Claims 3998H, 3999H, and 4001H.

Geological information

Reconnaissance drilling and sampling of this deposit were carried out by Busselton Minerals N.L. It is an unconsolidated dune up to 24 m thick with a base dipping west to northwest, from between 54·8 and 91·4 m above sea level to the beach. The contact between the dune and the underlying limestone is very irregular. The dune is composed of brown sand with irregular zones of calcarenite throughout. It has soil horizons similar to those described by Fairbridge and Teichert (1953). Yellow sand is often found along its base.

Heavy mineral concentrations occur in zones between 6 and 20 m thick. The grade varies from less than 1 per cent to 25 per cent heavy minerals, with between 7 and 30 per cent clay. Ilmenite from this deposit contains less TiO_2 than deposits in the Southwestern area (Chap. 4); mineralogical data are given in Table 21.

Enrichments have formed in places on the weathered surface of the underlying metamorphic rock; in one locality up to 5 per cent of heavy minerals were intersected over 6 m during test drilling.

References: Lowry (1967), Baxter (1970).

MINOR OCCURRENCES

Telfer East

(Lat. 33°39′S, long. 115°03′E)

This small dunal deposit of heavy minerals was discovered during exploration of the Yallingup prospect by Busselton Minerals N.L. It is situated east of Caves Road in the headwaters of the Gunyulgup Brook, on the eastern part of Sussex Location 4308 and the northern part of Sussex Location 3797, and is covered by Mineral Claims 2744H and 2745H. Heavy minerals, yielding grades between 1 and 10 per cent, are concentrated in unconsolidated dune sand high on the Witchcliffe Upland.

Cape Clairault

(Lat. 33°42′S, long. 114°43′E)

The Cape Clairault deposits were held by Westrand Pty Ltd but not extensively prospected. They are approximately 19 km south of Cape Naturaliste and 1 km east of Cape Clairault, situated at the southern end of a bay west of the Witchcliffe Upland. Access is by road connecting Caves Road to Cape Clairault and then by sand tracks.

Underlying the mineral sands are high-grade Proterozoic metamorphic rocks and Quaternary limestone. The heavy mineral deposits appear to have formed in embayments in the underlying rocks and are up to 30 m above sea level with concentrations in bands approximately 30 m wide, along the face of the dunes. The environment of deposition is similar to the Yallingup prospect, but there is a lower heavy mineral content. No data on the heavy minerals are available.

References: Lowry (1967), Baxter (1971).

Redgate

(Lat. 34°02′S, long. 114°52′E)

The deposit is reported to be on a beach, due west of Witchcliffe. Ellis describes the locality: "The coastline here consists of garnetiferous gneiss overlain by coastal limestone forming rugged headlands with considerable stretches of sandy beach, backed by low sand dunes, to a depth of 4 chains [80 m] (max.). The limestone cliffs are up to 60 ft [18 m] in height in some places. The general relief away from the beach is low and undulating". The beach is about 400 m long and is set between rocky headlands. Screen analysis of garnet from the concentrate shows that 98·4 per cent is between 0·0178 and 0·490 mm in diameter. A mineralogical analysis of the heavy mineral concentrate is given in Table 21.

References: Ellis (1948), Lowry (1967).

Flinders Bay

(Lat. 34°21′S, long. 115°08′E)

The deposit was investigated by Western Titanium Ltd who drilled three reconnaissance traverses. It is situated approximately 2·5 km west of Flinders Bay Siding and 5 km north of Cape Leeuwin on the northern edge of Location h, and is accessible from Augusta by Forestry roads.

The deposits unconformably overlie metamorphic and granitic rocks. Dune sand between 1 and 16 m thick on the east of the Witchcliffe Upland, composed of free running quartz and lime sand with local zones of cemented calcarenite, carries minor concentrations of heavy minerals. The base of the deposit is uneven and there are large boulders of metamorphic rocks scattered across its floor. The deposit, up to 670 m wide, was traced by drilling over a length of over 900 m. Ilmenite is the only mineral of commercial interest (Table 21) in the prospect.

References: Lowry (1967), Matheson (1970).

DEPOSITS ADJACENT TO THE ALBANY-FRASER PROVINCE

Concentrations of heavy mineral in beach and dune sand deposits between Bilabalanya Dune and Northcliffe are grouped for the purpose of description. These deposits, derived from metamorphic and granitic rock of the Albany-Fraser Province, are small and found in omega-shaped bays. Information on offshore deposits is described elsewhere

(p. 103). Descriptions of regional geology and geomorphology are given by Clark and Phillips (1953), Cockbain (1968), Playford and Low (1972b), Doepel (1975) and Playford and others (1975). The physiography of the adjacent sea floor is described by Conolly and von der Borch (1967) and Carrigy and Fairbridge (1954).

REGIONAL GEOMORPHOLOGY

The coastline is rugged with cliffs up to 300 m high. Its shape is related to geological variations of the hinterland. Uniform rock types give long straight reaches; granite forms headlands, while migmatite and gneiss produce rugged coasts; and sediments of the Plantagenet Group give rise to long straight coasts with high sea cliffs.

Bays with sandy beaches and dunes are uncommon. Where present they are rarely more than 2 km in length and are usually omega or zeta shaped, providing some protection for beaches from southwest winds and currents. Where beaches are well developed, such as at Hassell Beach, there are commonly low dunes. Some beaches which are known to be prograding, may be trapping sediment moving along the coast. Raised beaches 3 m above sea level have been reported from Dillon Bay, west of Bremer Bay, and Cheyne Bay. Kendrick (pers. comm., 1970) identified a raised beach 9 m above sea level west of Point D'Entrecasteaux. Sea caves, notches and wave-cut platforms are reported by Clark and Phillips (1953) at 12 to 15 m, 30 m, 61 to 76 m, 152 m and 230 m above sea level. Dunes occur on tops of sea cliffs up to 120 m high.

The offshore area, known as the Recherche Shelf, is generally 30 to 50 m deep within 8 km of the coast, and is dotted with rocky islands. Tides have an annual range of 1·5 m at Albany, but the diurnal range never exceeds 0·75 m. Currents are westerly throughout the year, with local variations where influenced by the shape of the coast. Prevailing winds are westerly and southwesterly.

REGIONAL GEOLOGY

Rocks of the Albany-Fraser Province are exposed along the coast; sediments occur in the Bremer and Eucla Basins.

The Albany-Fraser Province consists of Proterozoic metamorphic and igneous rocks, including migmatite, gneissic granite and massive granite. Alumina-rich paragneiss, calc-silicate gneiss, charnockitic rock, graphitic schist and actinolite-anthophyllite hornblende rock are present in minor proportions, and are probably the source rocks for most of the heavy minerals in the coastal deposits. Where massive granite is exposed on the coast, there are no large concentrations of heavy minerals. Associated with the Albany-Fraser Province are discrete Proterozoic sedimentary basins with quartzite, mica schist and conglomerate, intruded by quartz veins, dolerite dykes, aplite and pegmatite.

The Bremer Basin sediments, exposed onshore in scattered occurrences, are marine and continental Tertiary rocks. The Plantagenet Group occurs in a belt about 64 km wide along the south coast between Northcliffe and Cape Arid. The basin extends inland for at least 150 km where isolated deposits containing similar rocks are termed the Eundynie Group. The Plantagenet Group unconformably overlies parts of the Albany-Fraser Province, and consists of a basal paralic sequence of grey and black clay, siltstone, sandstone, lignite and carbonaceous siltstone, conformably overlain by marine, white, brown and red siltstones and spongolite. The Eundynie Group, which overlies rocks of the Yilgarn Block, is composed of bryozoan limestone, white dolomite and spongolite with minor clay and shale.

TABLE 22. COMPOSITIONS OF HEAVY MINERAL FRACTIONS FROM DEPOSITS ADJACENT TO THE ALBANY-FRASER PROVINCE

Mineral	Hassell Beach	Cheyne Bay	Gordon Inlet	William Bay fossil beach	William Bay modern beach	Parry Inlet	Oldfield Inlet	Stokes Inlet	Alexander River		Israelite Bay	
	Weight Per Cent											
Ilmenite	....	73·5	59	35–48	38–53	....	} 28·6	64·0	61·5	66·7	} 33·9	25·0
Altered Ilmenite	26	....	....	....	....	73		20·5(*f*)	....	....		....
Leucoxene	18	....	10	....	....	10·2	....	....	....	....		11·0
Rutile	18	2·6	tr.	<0·5	....	....	....	1·5	....	....		....
Zircon	21	19·7	17	33–51	30–53	5·0	29·6	1·5	28·2	14·8	14·1	14·7
Monazite	0·41	0·2	....	<0·5	....	....	1·7	....	2·18	0·1	....	0·6
Kyanite	....	....	....	1·2–2·1	1·1–4·3	....	2·6	....	....	....	1·8	....
Garnet	....	1·3	....	6–21	8–22	....	20·0	2·3	5·1	16·0	18·0	....
Staurolite	....	....	....	<0·5	1·4	....	4·3	0·2	....	....	3·1	....
Others	....	2·6(b)	14(c)	3·5–9	....	....	12·9(d)	5(e)	2·95	2·37	29·0(d)	....
Ilmenite Composition												
TiO_2	62·7(a)	52·2	54	....	....	62·7(a)	....	....	....		87(g)	....
Cr_2O_3	0·03	0·04	....	0·04	....	....	....	....	....		....	....
V_2O_5	0·14	....	....	....	....	....	....	....	....		....	....

tr. = trace.

(a) Altered ilmenite. (b) Shell fragments. (c) Garnet, staurolite, hypersthene, spinel, hornblende, tourmaline, chrysoberyl, andalusite and tremolite. (d) Hornblende, tourmaline. (e) Hematite-goethite. (f) Includes exsolved spinel, magnetite and hematite. (g) Leucoxene.

The Tertiary sediments are overlain by Quaternary silts of terrestrial origin, and river, beach and dune deposits, some of which contain heavy materials.

HASSELL BEACH PROSPECT

(Lat. 34°40′S, long. 118°25′E)

General information

The area, shown on maps as Hassell Beach, is known locally as Cheyne Beach. The southern end of the deposit is approached by road from Albany for 48 km along the Hassell Highway and then 10 km on a graded road south to Lookout Point. The deposit extends for 20 km along the coast, lying up to 2 km from the beach. Sandy tracks provide access throughout the area.

Geological information

The heavy mineral deposits occur in beach sands, and in dunes which overlie migmatite and are banked against rocks of the Plantagenet Group. The dunes are more prominent to the north, and extend from Freshwater Lake to 5 km north of the mouth of Bluff River. The deposits were drilled by Laporte Titanium (Australia) Ltd. Campbell and Welch divide the area into two; a southern area of approximately 550 hectares and a northern area of about 670 hectares, separated by a 120 m barren reach of coast with mobile dunes.

In the southern area the dunes, partly fixed and of irregular shape, are poorly mineralized with an average of 1.1 per cent heavy minerals. The beach is sandy and more than 5 m thick in some places, with an average of 4 per cent heavy minerals. No concentration of heavy minerals constituting a presently economic deposit was located.

Dunes of the northern area have an average thickness of 3 m and a widely distributed heavy mineral content ranging from 1·3 to 7·9 per cent. The associated beach is shallow, between 0·6 and 2·4 m thick, and has a low heavy minerals content. In the dunes, richer heavy mineral concentrations (more than 4 per cent) occur on the landward side; a mineralogical analysis is given in Table 22.

References: Low (1960a), Campbell and Welch (1965), Martin (1970), Baxter (1971).

CHEYNE BAY PROSPECT

(Lat. 34°32′S, long. 118°43′E)

General information

From Albany the deposits are reached along the Hassell Highway (80·5 km) and then by gravel road to Cape Riche homestead (32 km) where access is attained along 8 to 10 km of sandy tracks. Cheyne Bay extends approximately 15 km north from Cape Riche, and the deposits are situated at the foot of its prominent cliffs. The prospect has also been known as the Cape Riche deposit.

Production: Rare Metals Pty Ltd produced 158·5 t of heavy mineral concentrate between 1949 and 1950, but since that time no mining has taken place.

Geological information

The deposits have been investigated by the Mines Department and small companies at various times since 1940. They rest on Plantagenet Group sediments overlying migmatite. The Plantagenet Group is principally siltstone and sandstone though Low reports limestone from some cliff sections. Pegmatites intruding migmatite at Cape Riche contain monazite.

Prominent cliffs of Plantagenet Group sediments, standing up to 24 m high above a narrow beach, are dissected by numerous creeks and have large talus slopes due to undercutting by marine erosion. A raised beach (3 m above sea level) contains a shell conglomerate composed of the bivalve *Glycymeris radians* (Lamark) with the gastropod *Campanile symbolicum* (Iredale). These fossils are known in Pleistocene to Recent sediments along the south coast of Western Australia. The narrow modern beach is formed on a wave-cut bench which dips seaward at approximately 10 degrees and is swept clean by winter storms. Sand on the beach is thicker adjacent to the mouths of creeks where accretion deposits with heavy mineral concentrations are formed. The heavy mineral content of sand decreases towards the north. The concentrates are mainly ilmenite and zircon with minor garnet, rutile and monazite (Table 22). The ilmenite is suitable for sulphate route pigment manufacture; analyses are given in Table 23. McMath reported 305 000 t of heavy minerals in these deposits in 1949.

A discontinuous line of reefs extends northward from Cheyne Island. This partially protects the floor of the bay, but McMath states that any sand on the floor of the bay will be scoured by storms and that consequently accumulation of heavy minerals offshore will be erratic. Low reports that heavy minerals were obtained 200 m offshore in 13·7 m of water from sand, on the floor of the bay, which was up to 47 cm thick in the southwest and 15 cm in the northeast.

References: McMath (1949a, 1949b, 1950a), Low (1960b), Campbell and Welch (1965).

TABLE 23. ANALYSES OF ILMENITE FROM CHEYNE BAY

Major Oxides *per cent*	1	2
SiO_2	0·18	1·22
TiO_2	52·12	51·4
Fe_2O_3	16·15	16·2
FeO	29·04	27·8
MgO	0·28	....
P_2O_5	....	0·035
MnO	1·61	1·35
Cr_2O_3	0·04	0·023
V_2O_5	0·14	0·007

KEY TO COLUMNS: *Analyses:*
1. J. Hayton, Govt. Chemical Laboratories.
2. British Titan Products Co. Ltd.—1947.

GORDON INLET PROSPECT

(Lat. 34°20′S, long. 119°30′E)

General information

The Gordon Inlet prospect is 15 km northeast of Bremer Bay, extending along the coast from Fishery Cove to Point Anne. The main heavy mineral concentrations are around Gordon Inlet, the estuary of the Gairdner River. The deposit, examined periodically since 1948, has been known as the Bremer Bay, Doubtful Island Bay, and Gairdner River deposits.

Geological information

The deposit was drilled by the Geological Survey of Western Australia, New Consolidated Goldfields (Aust.) Pty Ltd, Laporte Titanium (Aust.) Pty Ltd, and Day Dawn Minerals N.L. Heavy mineral concentrations are reported from the beach, which is the richest deposit, the foredune, which carries minor concentrations, and a buried beach with a very low heavy minerals content. Dunes behind the foredune are reported to contain between 0·3 and 0·5 per cent heavy minerals. McMath and de la Hunty report 372 000 t of contained heavy minerals in the beach sand at an average grade of 11·8 per cent; it is not considered to be economic.

The beach deposit rests on a 15 m wide wave-cut platform of limestone which may belong to either the Plantagenet Group or the Tamala Limestone. The landward side is marked by a buried sea cliff up to 6 m high. Heavy mineral concentrations ranging to 70 per cent have been reported, the main deposit extending 12 km south of Gordon Inlet, with a rich pocket 3 km south of the inlet. The deposit is up to 6 m thick and contains an average of 25 per cent heavy minerals. The heavy mineral assemblage is reported by Arthur (Table 22); the ilmenite contains between 54 and 55 per cent TiO_2 (Campbell and Welch).

The foredune deposit, inland of the sea cliff, is usually less than 1 m thick and extends along the length of the beach deposit. It contains an average of 2 per cent heavy minerals.

Pratt reports that mineral sands in the mouths of Gordon Inlet and Kellys Creek (north of Gordon Inlet) lie below sea level, providing evidence for the existence of these lines of drainage when sea level was lower than today.

The fixed and seif dunes inland from the coast have little heavy mineral content. It is assumed that there is a fossil beach buried by the dunes, but it is unlikely to contain heavy mineral concentrates worthy of drilling.

References: McMath and de la Hunty (1951b), Low (1960a), Pratt (1965), Campbell and Welch (1965), Martin (1970), Arthur (1971), and Baxter (1971).

MINOR OCCURRENCES

Windy Harbour

(Lat. 34°49′S, long. 116°00′E)

Windy Harbour is 25 km south of Northcliffe by road, the prospect being situated immediately east and north of Point D'Entrecasteaux. The deposits lie parallel to the coast for about 10 km and are up to 3 km inland.

Geological information on this area is mainly derived from a report of Day Dawn Minerals N.L. Martin correlates limestone cliffs at Point D'Entrecasteaux with the Spearwood Dune System (McArthur and Bettenay, 1960) and considers there has been recent lowering of the sea level in the area. Heavy minerals are brought to the beaches by streams which derive them from two parallel limestone dunes immediately inland from the beach. Salmon Beach, immediately west of Point D'Entrecasteaux, contains minor heavy mineral concentrations within the modern beach and berm; ilmenite, rutile, zircon, pink and colourless garnet, and hornblende have been identified.

G. W. Kendrick (pers. comm. 1970) identified, 9 m above sea level, a wave-cut bench which locally has up to 5 per cent heavy minerals deposited on it.

References: Martin (1970), Baxter (1971).

Northcliffe

(Lat. 34°38′S, long. 116°08′E)

The deposits are located approximately 4 km east of Northcliffe, on the east side of the Gairdner River, between Muirillup Road and the Northcliffe-Shannon Road. They are situated on Nelson Locations 9925, 9926 and 9929. This description is based on a report for Stanford and Atkinson Pty Ltd.

The deposits are disposed in an approximately north-trending body situated approximately 100 m above sea level. The southern end lies 4 km east of Northcliffe and the accumulation extends for approximately 2 km. It is between 3 and 4·5 m thick; the width is not known.

The sediment is a sandy clay with about 40 per cent clay and up to 18 per cent heavy minerals. Between 40 and 95 per cent of the heavy mineral content is ilmenite and less than 1 per cent consists of zircon, rutile or monazite. Heavy silicate minerals and limonite are common.

Reference: Cocks (1972).

William Bay

(Lat. 35°02′S, long. 117°10′E)

The deposits lie immediately east of William Bay and are reached from Albany along the South Coast Highway (24 km) and then 4 km by road and track to the coast.

Basement in the area is coarse-grained porphyritic granite and gneiss, which is exposed along the coast. Johnson identified two fossil beach deposits, separated by a gneiss ridge and exposed in the base of the modern dunes below at least 6 m of sand and peat, approximately 20 m inland. The deposit's heavy mineral fraction, principally of ilmenite, zircon and garnet, is given in Table 22.

Modern beaches contain heavy minerals but the combined average thickness of these deposits is less than 0·3 m over an overage width of 9 m and total length of 170 m. Johnson considers that the source of the heavy minerals is probably gneiss and dolerite dykes in the immediate hinterland.

References: Johnson (1950), Low (1960a), Baxter (1971).

Parry Inlet

(Lat. 34°59′S, long. 117°12′E)

The deposits are approximately 19 km west of Denmark on the South Coast Highway and are situated immediately north of the road. The area lies within Plantagenet Locations 2094 and 4323.

Reconnaissance drilling by Cable (1956) Ltd showed two distinct deposits at 68·3 and 100·5 m above sea level, covered in some places by up to 1·5 m laterite. The deposits are up to 100 m apart, and extend over a width of 150 m. They consist of clayey sand unconformably overlying a sandy clay in which heavy minerals are sparse. Heavy mineral content up to 30 per cent (of which 73 per cent is altered ilmenite) is reported. Mineralization is patchy, though usually rich; an average mineral breakdown of the heavy fraction is given in Table 22.

Wilson Inlet

(Lat. 35°01′S, long. 117° 23′E)

The deposit is situated on the east side of Wilson Inlet, north of the creek connecting Nenamup Inlet to Wilson Inlet. It can be reached from the Coast Road between Albany and Denmark by turning west 40 km west of Albany and following the road to Wilson Inlet for 11 km.

No Precambrian rocks have been seen in the area. The heavy mineral concentrates occur as small slicks at or about high water mark and become thinner towards low water mark. A slick 40 m long, 1 m wide and 30 cm thick at high water mark, occurs 100 m east of Nornalup Point. Heavy minerals have been seen in slicks within the low dunes along the southern coastline of the inlet, but no economic concentrations have been located.

Reference: Noldart (1960).

Torbay

(Lat. 35°04′S, long. 117°40′E)

The Torbay occurrences are found on the beach between Richards Island and Port Harding, principally in a drain in the vicinity of Port Harding. Port Harding lies at the mouth of Torbay Inlet and is accessible by 7·5 km of roads and tracks on the south of the Albany-Denmark Coast Road some 4·5 km west of Albany. The deposit has been known as the Port Harding deposit.

The beach between Richards Island and Point Hughes is about 4 km long and the average width is 21 m; migmatite is exposed in several places. A line of fixed dunes separates the beach from lowland. At the base of the dunes, on their seaward side, is exposed coffee-rock which McMath and de la Hunty consider may represent a fossil shoreline. The coffee-rock contains less than 0·3 per cent heavy minerals. A drain cuts this area and samples of heavy minerals concentrated at its mouth grade 4·8 and 17·5 per cent, and are reported to contain between 40 and 45 per cent ilmenite and 20 and 40 per cent of zircon.

Low reports slicks of heavy minerals on the beach 0·8 km from the north end of Migo Island. Here there is an enriched berm with grades of up to 50 per cent over a thickness of 15 cm.

Progradation of the shoreline has occurred and is particularly evident on the eastern side of Torbay Inlet, which, according to Clarke and Phillips (1953), was once connected to Princess Royal Harbour.

References: McMath and de la Hunty (1951a), Low (1960a), Baxter (1971).

Oldfield Inlet

(Lat. 33°55′S, long. 120°50′E)

The deposits are adjacent to the inlet at the mouth of the Oldfield River, being accessible from Esperance (88 km west) along the Esperance-Ravensthorpe road and then 32 km by road and tracks to the coast.

The beach has a moderate slope with very little berm. To its rear limestone dunes of the Tamala Limestone reach 20 m high. Heavy minerals are concentrated between the high and low water marks; a mineralogical analysis is given in Table 22. P. G. Crabb carried out reconnaissance hand augering of the deposit but no economic concentration was located.

Most sand dunes along the shores of the inlet are weakly mineralized. The dunes are in part overlain by the Tamala Limestone and appear to be unconformably overlying a laterite surface.

Reference: Baxter (1971).

Margaret Cove

(Lat. 33°50′S, long. 121°00′E)

Margaret Cove is a southeast-facing bay at the mouth of the Torradup which drains migmatite and sedimentary rock terrains. It is accessible from the Esperance-Ravensthorpe road 90 km from Esperance over 15 km of gravel and sandy tracks.

Surface reconnaissance work carried out by Laporte (Australia) Pty Ltd and P. G. Crabb on the dunes and beaches, on both sides of the small inlet at the mouth of the Torradup River, indicated small quantities of heavy minerals. They appear to be restricted to the beach and dunes inland from limestone foredunes.

Campbell and Welch report 3·1 per cent heavy minerals containing 21 per cent titanium oxide in the dune deposits, this possibly representing 40 per cent ilmenite in the heavy fraction. No other data from the deposits have been obtained.

References: Campbell and Welch (1965), Baxter (1971), Thom and Lipple (1973).

Stokes Inlet

(Lat. 33°48′S, long. 121°03′E)

Stokes Inlet, a barred estuary of the Lort and Young Rivers, is accessible from the Ravensthorpe-Esperance road by various southerly tracks from about 75 km west of Esperance. Most of the information in this description was obtained from Western Collieries Ltd.

The heavy mineral occurrence is situated in dunes inland from a foredune of lithified limestone. Very little heavy mineral has concentrated on the narrow beach below Tamala Limestone cliffs. The limestone foredune is lithified and has caprock often exposed at the surface; it contains disseminated heavy minerals of low grade.

Dunes immediately inland from the limestone foredune contain disseminated mineralization for 3 km west and 1·5 km east of Stokes Inlet. They are deposited on a limestone platform which appears to be between 3 and 4 m above sea level. The dunes are generally fixed, although minor reworking occurs along the edge of the inlet. Indurated calcareous sand cores are found within some dunes. Their heavy mineral fraction is mainly ilmenite, with minor rutile, zircon, garnet, hornblende and tourmaline (Table 22). Some ilmenite contains inclusions of pyrrhotite, chalcopyrite, cubanite and pyrite, an association which suggests a mafic igneous source.

Minor mineralization occurs along the shores of Stokes Inlet, particularly on the southern shore, and appears to be the result of reworking of the dune deposits.

Barker Inlet

(Lat. 33°48′S, long. 121°20′E)

Barker Inlet is accessible from the Esperance-Ravensthorpe road 42 km west of Esperance over 8 km of sandy tracks south to the coast. Heavy mineral concentrations are reported from its shores.

The inlet drains swamps; it is a land-locked body of water except during flash floods when it opens to the Southern Ocean. Tamala Limestone, exposed in the foredune, is overlain by dune sands. No information on the heavy mineral deposits has been reported.

Alexander River

(Lat. 33°52′S, long. 122°46′E)

Mineral sand samples were collected by a prospector from a beach at the mouth of the Alexander River on the shores of Alexander Bay, about 80 km east of Esperance. An analysis by the Government Chemical Laboratories shows the concentrates are mainly ilmenite, zircon and garnet, with a small amount of staurolite and monazite, minor spinel, leucoxene and rutile (Table 22). The two samples contained 78 and 81 per cent heavy minerals.

Israelite Bay

(Lat. 33°50′S, long. 124°00′E)

The deposit extends for 95 km north of Israelite Bay along the coast on the western margin of the Great Australian Bight. It is 195 km east of Esperance by road, of which 64 km is sealed road and the remainder sand track. Access to the deposits from Israelite Bay is obtained either along the old telegraph track or along the beach.

Basement rocks are equigranular leucocratic granite north of Wattle Camp, and garnet-biotite-quartz-feldspar gneiss south of Wattle Camp. The Wylie Scarp formed by the Toolinna Limestone, runs parallel to the coast some 19 km from it at Israelite Bay and 3 km inland at Bilabalanya Dune to the north. At the foot of the scarp is a fossil beach, approximately 30 m above sea level. Clark and Phillips identified a pebble bed and a raised beach at about 12 to 18 m and 6 m respectively, above sea level. D.C. Lowry (pers. comm. 1971) identified the latter surface approximately 0·6 to 0·9 m above sea level.

Heavy mineral concentrates occur in both the modern beach and a fossil beach beneath the foredune. A low berm is usually formed in front of a partly stabilized foredune and in some places large seif dunes associated with swamps are developed inland from the berm. Mineralization is discontinuous and mineral proportions vary from south to north. The average grade is less than 5 per cent with a range of 0·5 to 28 per cent. Two analyses are shown in Table 22.

References: Clark and Phillips (1953), Lowry (1968), Lowry (1970), Doepel (1970), Martin (1970), Baxter (1971).

DEPOSITS ON THE SCOTT COASTAL PLAIN

Heavy mineral deposits in shoreline sediments on the Scott Coastal Plain were first noted in 1969 by Union Oil Development Corporation during a seismic survey. These deposits are similar to those on the southern part of the Swan Coastal Plain. They occur on a relatively straight coastline with a hinterland of soft sedimentary rocks. Most of the economically important deposits are found on fossil shorelines.

Regional descriptions of the geomorphology and geology are presented by Lowry (1965, 1967), Martin (1970), Larson (1973) and Playford and others (1976). There is no published account of the heavy mineral deposits.

REGIONAL GEOMORPHOLOGY (Fig. 17)

The area in which the Scott Coastal Plain deposits have formed is a low-lying swampy region with four lines of subdued sand dune ridges running subparallel to the coast. The northern edge of the plain is separated from the southern side of the Blackwood Plateau by the *Barlee Scarp*, a marine scarp, extending from Augusta to Point D'Entrecasteaux and lying about 15 km inland north of Ledge Point. It is similar to the Whicher Scarp on the north of the Blackwood Plateau. Recent soil erosion and landslips have subdued its relief.

The *Scott Coastal Plain* contains the same geomorphic elements as the Swan Coastal Plain, consisting of a piedmont alluvial plain with four shoreline and dune systems. The alluvial plain, 8 to 10 km wide, is similar in form to the Pinjarra Plain (p. 39). It falls south from about 35 m above sea level at the foot of the Barlee Scarp to about 5 m above sea level.

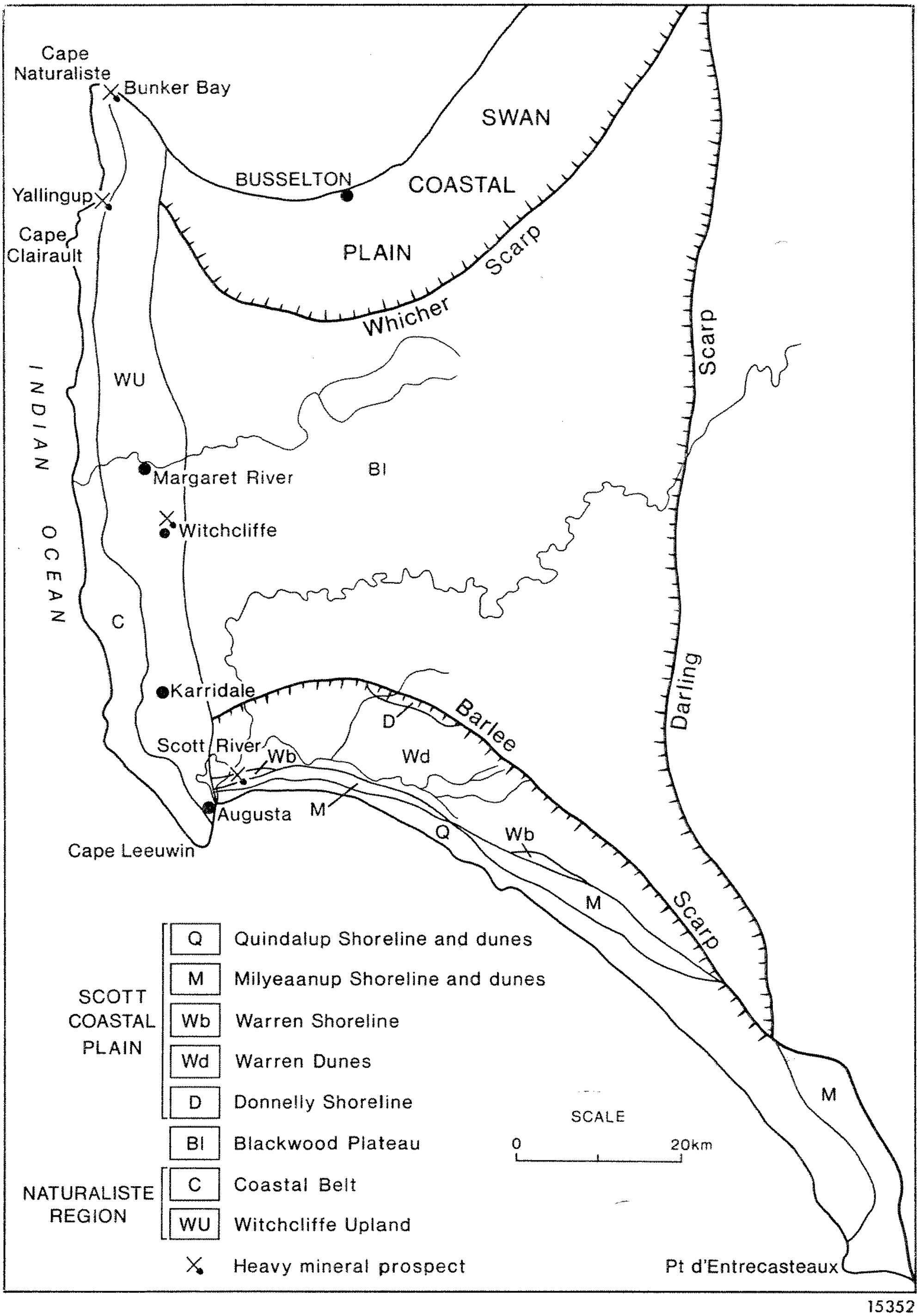


Figure 17. Map showing geomorphic units in the Naturaliste-Scott Coastal Plain region.

The dune and shoreline systems are named Quindalup, Milyeaanup, Warren and Donnelly, Quindalup being the nearest to the coast, the others progressively further inland. The Donnelly Shoreline, at the base of the Barlee Scarp, lies between 20 and 35 m above sea level. It is dissected and often buried below alluvial fans. It is seen at the foot of the Barlee Scarp between Callcup Hill and Alexandra Bridge. The Warren Shoreline occurs north of the Scott River, where it forms a series of low subdued dunes associated with swamp lands. The Milyeaanup Shoreline is recognized in the area between Scott River and Swan Lakes where discon inuous dune and beach forms are encountered. On the eastern side of the Scott Coastal Plain, the Warren and Milyeaanup Shorelines merge. The Quindalup Shoreline, a continuation of the shoreline on the Swan Coastal Plain, is related to sea level. Dunes on the Quindalup Shoreline tend to be transverse and large blowouts are common. The Donnelly, Warren and Milyeaanup Shorelines appear to be equivalent respectively to the Yoganup, Capel and Spearwood Systems on the Swan Coastal Plain.

Larson described the palaeogeomorphology of the Blackwood River which appears to have captured both the Capel and Preston Rivers on the Darling Plateau. On the Scott Coastal Plain the river has migrated to the west following the formation of the shoreline systems and, as a result, has destroyed parts of the Donnelly and Warren Shorelines and eroded the Barlee Scarp.

REGIONAL GEOLOGY

Rocks of the Yarragadee Formation, which consist of feldspathic sandstone, conglomeratic sandstone, siltstone, shale and lignite, are the oldest exposed in the area. These are overlain unconformably by both theoliitic Bunbury Basalt, and sediments of the Warnbro Group tentatively correlated with Leederville Formation. In this area the group is composed of sandstone (frequently feldspathic and occasionally glauconitic), and conglomerate with siltstone and claystone. Heavy mineral deposits are present in the group at Witchcliffe, Brockman and Alexandra Bridge (Chapter 7). All units are deeply weathered to depths of more than 50 m

Laterite and associated sand and clay deposits occur over most of the Blackwood Plateau and Barlee Scarp. Quaternary or Late Tertiary dune, beach, swamp and alluvial deposits cover much of the Scott Coastal Plain, and are almost identical in lithology to accumulations of the same age on the Swan Coastal Plain though the only defined unit is the Tamala Limestone, which is exposed along the coast. Heavy mineral deposits are found in bodies of sand in paralic sequences.

SCOTT RIVER PROSPECT

(Lat. 34°16′S, long. 115°16′E)

General information

The deposits are situated north of the Scott River and south of Three Chain Road. They are approximately 16 km east-northeast of Augusta, and are accessible from Brockman Highway via Dennis Road, 22·5 km east of Karridale, then 9·6 km to Three Chain Road where access is obtained by sand tracks. The deposit is situated on Sussex Locations 4155 to 4159 inclusive and is covered by Mineral Claims 2338H to 2343H, 7530H to 7534H, 7881H to 7893H and 1400H to 1400H.

The heavy mineral deposits were explored by Union Oil Development Corporation and Samedan (Aust.) Ltd who demonstrated a marginally economic prospect. They occur immediately east of the Scott River bog iron ore deposit (a lateritized Quaternary sandstone) (Burns and Carruthers, 1965).

Geological information

The heavy mineral deposits are 6 to 30 m above sea level, and are associated with parallel dunes along the Warren Shoreline. Swamp sediment occurs throughout the heavy mineral sands.

Larson suggests that the Blackwood River entered the sea 6·5 km east of Molloy Island at the time these deposits were being laid down. The now buried mouth is thought to be marked by Governor Broome Swamp.

Transgressive dunes in the area containing minor clay and silt are generally barren of heavy minerals. Their relief is subdued, being between 1·5 and 4 m above the surface of the Scott Coastal Plain.

Coffee-rock occurs beneath 1 to 2 m of sand as thin discontinuous bands throughout the prospect. The level of the coffee-rock approximates to that of the water table; it is possible that it is an eastward extension of the iron-rich layer in the Scott River ironstone.

The deposits contain up to 10 per cent heavy minerals, with an average of about 5 per cent, and up to 40 per cent clay, with an average of about 20 per cent. There is an average of approximately 58 per cent ilmenite in the heavy mineral fraction containing an average 51·6 per cent TiO_2. Minor zircon, rutile and monazite are accompanied by garnet, limonite, pyrite, magnetite, staurolite, kyanite, hornblende, spinel and sphene as accessories in the deposit.

References: Lowry (1965, 1967), Martin (1970), Larson (1973), Ljung (1973).

MOLLOY PROSPECT

(Lat. 34°16′S, long. 115°30′E)

General information

The deposits, which are submerged, are situated at the mouths of the Scott and Blackwood Rivers, in Hardey Inlet, and along the southern end of Molloy Island. The deposits were also known as Augusta. Hardy Inlet is a popular tourist resort and any proposals for the development of the deposits will raise issues of environmental protection. Project Mining Corporation Ltd and Norwest Development Corporation Ltd drilled several reconnaissance traverses of the deposit.

Geological information

The mineral sand on the estuary floor is lenticular and interfingers with silt and clay containing little or no heavy minerals. Grades of between 1 and 6 per cent heavy minerals have been obtained from sandy sediments, higher grade material occurring adjacent to the mouth of the Blackwood River. An estimate of ilmenite content of the heavy mineral fraction is 50 per cent by volume.

Reference: Atkinson (1971).

SWAN LAKE DEPOSITS

(Lat. 34°49′S, long. 115°10′E)

General information

The deposits are situated between 1 and 5 km east of Augusta on the eastern side of Hardy Inlet, being north of Swan Lake and mainly south of Road No. 308. They are accessible by roads and tracks south from Alexandra Bridge. Samedan of Australia and Project Mining Corporation Ltd conducted a joint drilling programme and the following summarizes the results of this work.

Geological information

Seven separate zones of heavy mineral enrichment are identified in three zones lying almost parallel to the coast. Larson states these deposits are typical offshore bar, beach and parallel dune sediments and were deposited in a littoral environment near the mouth of the Blackwood River at a time when sea level was between 2·5 and 9 m above the present. The sediments have been correlated with the Milyeaanup Shoreline.

The deposits are composed of calcareous and silica sand with silt and clay and show marked and rapid facies variation which appears to be unrelated to concentration of heavy minerals. Heavy mineral rich layers commonly occur at two levels within the parallel dunes. The lower deposit contains a high clay fraction and in general is less well sorted than the upper deposit, a lighter coloured calcareous sand with a lower clay content and irregular barren zones. The lower deposit may be an ancient beach or offshore bar, and the upper, a dune.

The average grade of the deposit is 6·5 per cent heavy minerals. The heavy mineral fraction is reported. to have 60 per cent ilmenite containing an average of 48·8 per cent TiO_2.

Overlying the deposits in some places is a high, transgressive dune which occasionally contains rich patches of heavy minerals. These are of little consequence from an economic viewpoint.

Reference: Larson (1972).

MINOR OCCURRENCES

Lion Island

(Lat. 34°19′S, long. 115°10′E)

The deposits occur on the floor of Hardy Inlet between Seine Bay and Lion Island and are submerged, being accessible by boat from Augusta. They have been called the Augusta deposits.

The accumulations are between 0·6 and 3·4 m thick and occur over the width of the estuary. Heavy mineral values between 0·5 and 7 per cent of the sample have been obtained from gritty sediments on the estuary floor; fine-grained silt interfingering with the deposits has very little heavy mineral content. At the base of the deposit is hard rock (which may be either Tamala Limestone or migmatite).

Reference: Atkinson (1971).

Ledge Point

(Lat. 34°18′S, long. 115°14′E)

The deposits are situated on the coast east of Road 1542, and extend from Ledge Point for 1·5 km to the west. This district is approximately 6 km east of Augusta and is accessible by various tracks and roads south from Alexandra Bridge.

Two subparallel areas of mineral sand were located west of Ledge Point during reconnaissance drilling by Project Mining Corporation Ltd and Samedan of Australia. These are dune deposits and they have been breached and overlain by high, transgressive dunes with little heavy mineral content. The ilmenite content of the sand is reported to be about 2 per cent, insufficient to claim economic interest.

Reference: Larson (1972).

Bullrush Swamp

(Lat. 34°17′S, long. 115°18′E)

Bullrush Swamp is about 8 km east of Augusta on the coast. The prospect covers a series of dunes between the Scott River and the coast and is accessible from Road 1542 (Cane Break Road) which joins the Brockman Highway about 40 km east of Karridale. The area has been known as Scott River. Day Dawn Minerals N.L. carried out surface prospecting. The area lies west of a former mouth of the Scott River and covers the Quindalup and Milyeaanup Shorelines. Transverse dunes and seif dunes have broached the heavy mineral bearing parallel dunes. Panning the dunes indicated 2 to 3 per cent heavy minerals; no further work was carried out to test the deposit.

Reference: Martin (1970).

Callcup Hill

(Lat. 34°27′S, long. 115°52′E)

The prospect, situated between the mouths of the Donnelly and Meerup Rivers, is about 30 km by road southwest of Pemberton; access is obtained from Callcup Beach Road by sandy tracks.

Martin reports that remnants of the Milyeaanup Shoreline can be identified though generally the shoreline is buried by transgressive and seif dunes, rich in calcareous debris. Heavy mineral concentrations occur in beds of creeks draining the dunes, but no significant mineralization has been identified. It seems likely that any heavy mineral concentrates in the Milyeaanup Shoreline here will be diluted by calcareous sands and limestone of the Tamala Limestone. No drilling results have been reported.

Reference: Martin (1970).

CHAPTER 7

Miscellaneous Occurrences

DEPOSITS ASSOCIATED WITH CRETACEOUS UNITS IN THE PERTH BASIN

A review of the geomorphology and stratigraphy of the Mesozoic in the Perth Basin is presented by Playford and others (1976). Heavy mineral rich units are recorded in rocks correlated with the Lesueur Sandstone, Cockleshell Gully Formation, Yarragadee Formation and Leederville Sandstone, and low concentrations of heavy minerals occur throughout the remainder of the Mesozoic succession. Most of the succession was deposited in continental environments, although paralic and marine sequences are found in all units. Scattered enrichment of heavy minerals in Mesozoic sediments are reported from the Yandanooka-Three Springs area in the northern part of the Perth Basin and from the Witchcliffe-Alexandra Bridge area in the southern part. At Witchcliffe a sub-economic deposit of heavy minerals was located, but no other occurrence is likely to prove economic. Individual members of the Mesozoic succession are lenticular and consequent variations in stratigraphy makes prospecting for heavy minerals difficult.

WITCHCLIFFE PROSPECT

(Lat. 34°01′S, long. 115°06′E)

General information

Witchcliffe, on the Bussell Highway, is about 120 km south of the port of Bunbury. The heavy mineral deposits lie east of the townsite on Sussex Locations 2810 to 2816, 2802 to 2804 and 1604, and are accessible by road from Witchcliffe.

Geological information

Electrolytic Zinc Corporation Australia Ltd drilled the deposits and identified a small sub-economic ore zone in the Leederville Sandstone overlying granitic and migmatitic rocks of the Leeuwin Block. The base of the deposit is irregular, there being up to 25 m relief on the unconformity. The Mesozoic rocks have been lateritized and laterite remnants overlie the heavy mineral deposits on hill tops. Mineralization occurs within a complex lenticular paralic succession including arkose, clayey sand, wood ash, dark grey clay, conglomerate, granule and fine to medium-grained sand. The mineralized sediments are up to 18 m thick with marked facies variations. Lagoonal, swamp and fluviatile sediments are more abundant than beach and dune sands. Pyrite nodules have formed in the carbonaceous clay members of the ore zone. Coffee-rock is forming in the mineralized zone, at or about the level of the water table.

TABLE 24. COMPOSITIONS OF HEAVY MINERAL FRACTIONS FROM CRETACEOUS DEPOSITS

Mineral	Witchcliffe		Alexandra Bridge	
	Weight per cent			
Ilmenite	18·5	21	73	85
Altered Ilmenite	34·4	61	....	....
Leucoxene	6 (a)	3·5	10	6
Zircon	6·7	9	5	8
Monazite	tr.	....	1	1
Garnet	3·1	4·3	....	....
Pyrite	....	2	....	....
Others	....	1	11 (b)	....

NOTES: (a) includes some garnet.
(b) rutile, actinolite, epidote, stuarolite, kyanite, anthophyllite, tourmaline, augite, wollastonite.

Heavy mineral concentrates occur throughout the succession, but are slightly more consistent in grade in the light-coloured coarse-grained sediments with low ash content. The grade of ore varies between 1 and 25 per cent heavy minerals. The heavy fraction contains mainly ilmenite with leucoxene, zircon and garnet being common accessories (Table 24). Lateritized and coffee-rock sections of ore contain up to 50 per cent over-size (> 3 mm) and clay fractions.

References: Adams (1971a), Ingram (1971), Baxter (1971).

MINOR OCCURRENCES

Upper Chapman

(Lat. 33°59′S, long. 115°10′E)

A minor deposit of heavy minerals was located on the western side of Upper Chapman Brook by Electrolytic Zinc Corporation Australia Ltd. The area about 9 km east-northeast of Witchcliffe, falls within Sussex Locations 2838, 2839, 3189 and 3190, and is accessible by graded roads.

A variable development of sediments similar to those found at Witchcliffe unconformably overlies rocks of the Leeuwin Block in the upper reaches of the Upper Chapman Valley. Heavy mineral concentrates occur in surface exposures and road cuttings, but the extent and grade of the deposit are not known.

Reference: Adams (1971a).

Alexandra Bridge

(Lat. 34°06′S, long. 115°12′E)

The Alexandra Bridge deposits occur on Sussex Locations 2407 to 2414, on the east side of the Blackwood River, north of Alexandra Bridge. They can be reached from Karridale by the Bussell Highway and then along the Brockman Highway for 10 km and various roads leading north of Alexandra Bridge.

The small dispersed zone of heavy mineral enrichment was located by Amax Mining (Australia) Incorporated, immediately southeast of a prominent bend in the Blackwood River, north of Alexandra Bridge. The deposits occur in a mixed sequence of sand and silt and are generally unconsolidated. Ilmenite is the principal heavy mineral; leucoxene and zircon are common (Table 24).

Reference: Connelly (1969).

Brockman

(Lat. 34°14′S, long. 115°28′E)

The Brockman deposits are situated 39 km east of Karridale, south of the Brockman Highway, and lie within State Forest No. 58, being bounded by Canebreak Road, Great North Road and Brockman Highway. The area was drilled on a reconnaissance grid by Electrolytic Zinc Corporation Australia Ltd.

Heavy mineral concentrates were identified in a paralic succession of dark clays, wood ash beds, sandy clay, charcoal and sand which appear to overlie Bunbury Basalt. There are marked lateral and vertical facies variations in the sediments, and the heavy mineral distribution also has no consistent pattern. Overlying the mineralized sequence is about 5 m of fine-grained massive, white to grey clay of uniform texture which does not contain heavy minerals.

Reference: Adams (1971b).

Yandanooka

(Lat. 29°21′S, long. 115°33′E)

The Yandanooka deposit, situated on Yandanooka Lot 117, is approximately 2·5 km southwest of Yandanooka Siding, on the North West Coastal Highway, 150 km south of Geraldton. Mid-east Minerals N.L. investigated the deposit. The heavy mineral concentrate is described as being in a red to yellow sandy clay, and assays between 0·1 and 9·4 per cent are reported from drillholes. The zone has been traced over a distance of 1 km and is an average of 5·4 m thick. In some places yellow sand overlies the deposit.

Reference: Mid-east Minerals N.L. (1972).

Arrino

(Lat. 29°27′S, long. 115°34′E)

The Arrino occurrence lies on Victoria Locations 6127, 7230 and 7254, 6·5 km west of Arrino, which is situated about 160 km south of Geraldton on the North West Coastal Highway. The ground was pegged by Mr. J. J. Turner. The deposit is on the east bank of the Arrowsmith River in sand which contains up to 20 per cent heavy minerals.

Durack

(Lat. 29°33′S, long. 115°38′E)

The Durack deposits are about 9·5 km west of Three Springs, occurring on Victoria Locations 3766, 5600, 5943, 8820 and 10728. They can be reached by road and tracks serving farms. An eluvial sand containing heavy minerals derived from erosion of the Yarragadee Formation is present on the Durack property. The sand is yellow and contains up to 10 per cent heavy minerals.

COASTAL DEPOSITS

Deposits of heavy minerals in unconsolidated sand along the modern coast are generally small and of low grade. The main concentrations occur at the horizon of the Safety Bay Sand but some are found in Tamala Limestone. The richest concentrations occur in berms and foredunes. Farrand (1965) described the composition of heavy mineral concentrates from islands and beaches north of latitude 18°S and west of longitude 117°E.

Ilmenite is the principal mineral in coastal deposits though at Onslow iron sands are concentrated in dunes adjacent to the beach. Zircon and garnet are the only other economically valuable minerals reported from the deposits and these are commonly minor constituents.

The isolated and scattered nature of occurrences is such that a description of related geology is beyond the scope of the bulletin and the reader should refer to the State Geological Map (1973) and Geological Survey of Western Australia (1975).

ONSLOW PROSPECT

(Lat. 21°43′S, long. 114°54′E)

Onslow is approximately 1 500 km north of Perth and about 200 km southwest of the port of Dampier. The iron sand is found between 10 and 30 km southwest of the town on both sides of the mouth of the Ashburton River, and is accessible from a section of the former North West Coastal Highway. The deposit has also been known as Urala East.

Geological information

Heavy mineral concentrations in sand dunes parallel to the shore near the Ashburton River were drilled by Ashburton Sands Pty Ltd and Ferrovanadium Corporation N.L. The dunes overlie deltaic sediments at the mouth of the river, and have an average height of about 7·5 m above the surrounding flood plain, though some dunes are as high as 15 m. The swale between foredunes and inland dunes is commonly flooded at high tide.

Two lines of mineralized dunes were delineated, one in the foredune to the rear of the tidal beach and the second in dunes behind the swale belt. The foredune deposit is 1 m or less above high tide and includes a zone which contains more than 15 per cent heavy minerals over a length of 11 km and a width of 300 m. Mineralization is richest near the river but diminishes rapidly in both directions away from the river. The contact between underlying sand and the dune is irregular and dips steeply north towards the sea, being marked by a shell band about 1·5 m thick.

The inland dunes, about 2 km from the shore have been eroded by tributaries of the Ashburton River and are now found as discrete bodies of sand separated by alluvial clays. These contain a high-grade zone more than 3 km long and up to 200 m wide. The base of the deposit is about 3 m above sea level and dips slightly north.

TABLE 25. COMPOSITIONS OF HEAVY MINERAL FRACTIONS FROM THE ONSLOW PROSPECT

Mineral	1	2	3	4	5
	Volume per cent				
Hematite	36	....	....	....	54
Martite	8	29	17	20	....
Magnetite	....	0·1	1·5–2	10·5	....
Goethite	17	49	65	20	14
Ilmenite	4	6	3·5	8·5	14
Altered Ilmenite	9	....	....	....	4
Leucoxene	7	4	7–8	6·5	1
Rutile	....	0·5	0·5–1	....	....
Zircon	4–5	0·5–1	....	....	3
Pyroxene	10	....	0·5	....	....
Tourmaline	tr.	1–1·5	0·5	0·5	....
Amphibole	1–2	....	1	1	....
Garnet	....	0·5	1	....	....
Staurolite	....	0·5	....	....	....
Epidote	....	1·0	0·5	2·5–3	....
Others	....	....	....	....	10

tr. = trace.

KEY TO COLUMNS: *Determinations:*
1. AMDEL.
2–5. Geotechnics (Aust.) Pty Ltd.

TABLE 26. ANALYSES OF HEAVY MINERAL CONCENTRATES FROM THE ONSLOW PROSPECT

Oxide *Per cent*	1	2	3	4	5
SiO_2	....	....	36·7	....	4·0
TiO_2	7·2	7·0	4·6	7·0	4·5
Al_2O_3	....	....	5·4	....	3·1
Fe_2O_3	n.d.	n.d.	n.d.	n.d.	77·25
FeO	5·46	6·1	3·0	6·3	5·27
Total Iron	**44·45**	**53·4**	**31·5**	**54·9**	....
CaO	....	....	1·9	....	0·28
MgO	....	....	0·9	....	0·66
Mn	....	....	0·2	....	0·21*
S	....	....	0·07	....	....
P	....	....	0·18	....	0·25*
Cu	....	....	0·01	....	....
Ni	....	....	0·006	....	....
Cr	....	....	0·18	....	....

n.d. = not determined. *Reported as oxides.

KEY TO COLUMNS:

1, 2. Magnetic concentrates from Yoshida (1970).

3, 4. Gravity concentrates from Yoshida (1970).

5. Magnetic concentrate reported by Exmouth Salt Pty Ltd.

Mineralized sand in the dune systems has been traced over a length of 24·3 km to a maximum width of 3 km. The average grade of all dunes is between 8 and 11 per cent heavy minerals of which 60 tp 70 per cent is iron ore (Table 25). The main minerals are hematite, martite and goethite with varying amounts of ilmenite, magnetite and zircon. Chemical analyses of the heavy mineral concentrates are given in Table 26. There is a high per centage of iron-stained quartz in the deposit and it is difficult to mechanically prepare a high-grade iron ore product.

MINOR OCCURRENCES

Gibbings Island

(Lat. 16°09'S, long. 123°31'E)

Gibbings Island, some 125 km north of Derby, is 5 km from the mainland and about 12 km southwest of Cockatoo Island off the northwest coast of Western Australia.

The island consists of sandstone and siltstone correlated respectively with the Pentecost Sandstone and the Elgee Siltstone of the Kimberley Group. The Pentecost Sandstone corresponds with the iron ore bearing horizon mined at Koolan and Cockatoo Islands in Yampi Sound. Rocks on the island are commonly intensely folded and in some places strongly deformed. A mica schist with abundant prismatic rutile is reported.

TABLE 27. COMPOSITION OF MAGNETICALLY SEPARATED HEAVY MINERAL FRACTIONS FROM GIBBINGS ISLAND

Fraction	Mineral Content	Weight Per Cent
Ferromagnetic fraction	Magnetite	8·6
Paramagnetic at:		
0·1 amp	Hematite, ilmenite, some rutile	40·0
0·5 amp	Riebeckite, rutile, hematite ilmenite, and tourmaline	31·8
Non-magnetic at 0·5 amp	Rutile, zircon, kyanite, quartz and carbonate. Rutile in this fraction amounts to 9·2 per cent of the original panned concentrate	19·6
Total	....	100·0

Data from Farrand (1965).

Heav, mineral concentrates amounting to 2·5 per cent of the beach sediment occurring on the shoreline, contain chiefly hematite, ilmenite and rutile (Table 27).

Reference: Farrand (1965).

James Price Point

(Lat. 17°29′S, long. 122°08′E)

A small deposit of heavy minerals occurs between James Price and Coulomb Points on the northern coast of Western Australia. It is about 58 km north of Broome and is accessible to four-wheel drive vehicles by 34 km of tracks leading from the Broome-Beagle Bay Road, 24 km north of Broome.

The deposits are underlain by Cretaceous Broome Sandstone and Tertiary Pender Bay Conglomerate and overlain in places by Tamala Limestone (Coastal Limestone). The Broome Sandstone consists of a fine to coarse-grained, commonly friable, micaceous quartz sandstone with micaceous sandy siltstone. The Pender Bay Conglomerate is a conglomerate, with sandy matrix partly cemented by iron oxide, deposited in a continental environment.

Between Coulomb and James Price Point is a moderately straight sandy beach about 13 km long and between 18 and 36 m wide, overlying a platform cut into the Brooke Sandstone, at the foot of a cliff between 6 and 12 m high. Some of the beach sands, particularly those around the headlands, have been cemented by carbonate minerals. Heavy minerals, including ilmenite, magnetite, zircon and rutile (Table 28), with grades of up to 90 per cent are reported from the beach. Drilling carried out by Enterprise Exploration Co. Pty Ltd indicated 42 600 t of mineral sands containing approximately 21 000 t of heavy minerals. The principal concentrations, between 20 and 80 per cent heavy minerals, occur in sands which are rarely thicker than 1·5 m.

References: Brunnschweiler (1952, 1957), Wilson (1953), Stillwell (1953).

Broome

(Lat. 18°00′S, long. 122°12′E)

Broome is approximately 1 700 km north-northeast of Perth on the north shore of Roebuck Bay. Deposits of heavy minerals occur along the beach between Broome and Gantheaume Point a distance of about 7 km. The deposits unconformably overlie Broome Sandstone and are overlain in some places by Recent marine sediments. The heavy mineral concentrate contains magnetite and martite with a little ilmenite, limonite, leucoxene, zircon, schorl (black tourmaline) and minor kyanite and staurolite; the light fraction consists mainly of quartz with minor feldspar. No information is available on the thickness or extent of the deposits.

References: Simpson (1952), Brunnschweiler (1952, 1957).

May River

(Lat. 17°12′S, long. 123°52′E)

The deposits, situated at the mouth of the May River, within the tidal estuary, are 28 km northeast of Derby and may be reached by track west of the Leprosarium. A sand sample from the river channel was reported to have 4·7 per cent heavy minerals, with ilmenite, leucoxene and zircon as the major constituents (Table 28).

Fitzroy River

(Lat. 17°28′S, long. 123°33′E)

The deposits occur in the estuary of the Fitzroy River some 15 km northwest of Yeeda homestead, and extend for 16 km along the estuary towards King Sound.

Carr Boyd Minerals Ltd and Metals Investment Pty Ltd located a large tonneage of low grade mineral sand in banks of compact, but unconsolidated, fine, sub-angular to sub-rounded, brownish quartz sand. The heavy mineral fraction contains magnetite, ilmenite, rutile and zircon (Table 28). The average grade is reported to be 5 to 6 per cent heavy minerals with up to 20 per cent in places. The remoteness of this locality and difficult weather conditions, coupled with the low TiO_2 content of the ilmenite, make the deposit uneconomic at the present time.

Robinson River

(Lat. 16°51′S, long. 123°56′E)

The deposits are located at the mouth of the Robinson River on the north side of King Sound. The track between Meda and Oobagooma homesteads passes within 4 km of the occurrence but tidal flats impede vehicular access. The deposits have been considered by Carr Boyd Minerals Ltd. A sample containing 25·6 per cent heavy minerals, consisting mainly of ilmenite and zircon (Table 28), was collected from the river channel.

Locker

(Lat. 21°49′S, long. 114°42′E)

The deposit at Locker Point, situated east of the mouth of Urala Creek, about 47 km southwest of Onslow, is accessible by sandy tracks on the west of

TABLE 28. COMPOSITIONS OF HEAVY MINERAL FRACTIONS FROM DEPOSITS ON THE KIMBERLEY COAST

Mineral	James Price Point 1	James Price Point 2	May River Prospect	Fitzroy River Prospect	Robinson River
Ilmenite	66·0	0·6	36·5	53	58·5
Altered Ilmenite	....	....	12·5	11·6	9·5
Leucoxene	....	....	13·5	6·1	6·6
Rutile	1·6	21·9	0·8	0·6	2·6
Zircon	11·0	32·0	10	15	14·1
Monazite	....	....	....	0·2	....
Kyanite	....	....	0·4	....	0·3
Garnet	....	....	1	1·0	0·3
Staurolite	....	....	3	....	0·6
Tourmaline	....	....	2	0·7	0·4
Epidote	....	....	11	1·7	3·5
Others	18·2 (a)	55·0 (b)	9·0 (c)	5·5 (d)	3·4 (c)

NOTES: (a) Magnetite, garnet, leucoxene, tourmaline, monazite. (b) Iron ores, tourmaline, staurolite, kyanite, andalusite, spinel, garnet, cassiterite. (c) Iron ores hornblende. (d) Iron ores, hornblende, pyroxene.

KEY TO COLUMNS: 1. Brunnschweiler (1952).
2. Stillwell (1953).

TABLE 29. COMPOSITIONS OF HEAVY MINERAL FRACTIONS FROM HUTT LAGOON AND BROKEN ANCHOR BAY

Mineral	Hutt Lagoon		Broken Anchor Bay
	South End	North End	
	Weight per cent		
Ilmenite	39·9	23·5	20·0
Leucoxene	3·0	1·6	3·0
Rutile	5·8	2·1	1·0
Zircon	9·8	2·9	1·3
Monazite	2·0	0·4	....
Kyanite	0·9	0·3	....
Garnet	38·3	69·0	70·0

Urala homestead. Parallel dunes similar to the foredunes of the Onslow Prospect contain between 5 and 10 per cent of erratically distributed heavy minerals consisting predominantly of hematite. The dunes are arcuate in form, being convex seaward, and are over 6 km long and up to 300 m wide.

Reference: Geotechnics (Australia) Pty Ltd (1969).

Hutt Lagoon

(Lat. 28°12′S, long. 114°19′E)

The Hutt Lagoon deposit is situated between Hutt Lagoon and Bishop Gully on the north side of the road between Northampton and Gregory and is accessible by tracks leading north about 3·5 km east of Gregory.

Research Exploration and Management Pty Ltd (a fore-runner of Jennings Mining Ltd) drilled the occurrences identifying a small uneconomic concent tration of ilmenite and garnet, within a high parallel dune on the eastern shore of Hutt Lagoon. The dune is composed of calcareous sand with an average of 3 to 4 per cent heavy minerals; an analysis is given in Table 29. Its western side is partially lithified but where mineralization occurs, along the eastern flank and in the higher grade crest, the dune is unconsolidated. Modern tributaries of Bishop Gully are eroding the sand deposits on their eastern sides.

Broken Anchor Bay

(Lat. 28°14′S, long. 114°18′E)

The Broken Anchor Bay deposits are situated south of the Hutt Lagoon occurrence on the coast, south of the Hutt River. They are about 68 km north of Geraldton and 6·5 km south of Gregory, and can be reached by road from Northampton. They have also been referred to as the Port Gregory deposits. The deposits were tested by Target Minerals N.L. and a large body of garnetiferous sand was delineated. They consist of sand dunes formed on a bench cut into the Tamala Limestone and extend for more than 5 km along the coast varying in width between 120 m and 700 m. The sand is medium-grained and consists of rounded quartz grains, shell fragments and an average of about 5 per cent angular to sub-rounded heavy mineral grains (Table 29).

Reference: Taylor (1973).

OFFSHORE DEPOSITS

Heavy mineral concentrations, of up to 3 per cent, have been located on the floors of both Flinders and Geographe Bay but are not economically significant. Offshore exploration for phosphate deposits along the south and west coasts has not indicated further heavy mineral accumulations.

The regional distribution of sediments on the continental shelves of Western Australia is described by Carrigy and Fairbridge (1954). Conditions offshore are generally suitable for the preservation of heavy mineral deposits. With the exception of Sahul Shelf in the north of the state, there is little recent terrigenous sedimentation on the continental shelf; carbonate sediments are common on the Rowley, Dirk Hartog, Rottnest, Recherche and Eucla Shelves, but the rate of deposition varies greatly in different areas.

The geomorphology of the continental shelves is insufficiently well known to allow possible submerged strand lines to be located. Usually the shelves are divided into an inner and outer platform; the inner platform often being less than 40 m deep is consequently more important for heavy mineral prospecting. Depths of platforms, and changes of slope recognised on the shelves are summarized in Table 30. In view of the paucity of terrigenous sedimentation and the generally slow rates of carbonate deposition, it seems possible that any submerged shorelines would be revealed by sub-bottom profiling.

Magnetometer surveys, bathymetry and bottom-sediment sampling of the Rottnest and Recherche Shelves by exploration companies searching for phosphate and heavy minerals are reported by Phizackerly (1967), Conolly and von der Borch (1967), Garrick Agnew Pty Ltd (1968), and Planet Mining Company Pty Ltd (1968a, 1968b). Other areas of the State are not known to have been investigated. Hails (1972) outlines problems of offshore exploration for heavy mineral deposits.

PROSPECTING RECOMMENDATIONS

As heavy mineral deposits are often associated with mouths of rivers, prospecting offshore with sub-bottom profiling, parallel to the coast, to determine the position of drowned river valleys, together with profiling of the valleys to locate any slight changes in slope, may lead to the identification of heavy mineral deposits. In view of the occurrence of economic deposits of heavy minerals on the Scott and Swan Coastal Plains, the more favourable areas for investigation apparently are the western part of the Recherche Shelf and the Rottnest Shelf.

TABLE 30. DEPTHS OF PLATFORMS REPORTED FROM WESTERN AUSTRALIAN OFFSHORE AREAS

Shelf	Sahul	Rowley	Dirk Hartog	Rottnest 1	Rottnest 2	Rottnest 3	Rottnest 4	Recherche 5	Eucla
Inner Shelf	5·5–9 m 18–27 m		18–27 m	21·3 m	5·5–9 m 18–22 m slope change		16·5 m	18–27 m	
					36·5–46 m	47·5 m* 49·4 m	36·5 m	36·5 m	
	46·5 m	111 m	55–128 m		5–64 m 64 m	58–79 m		79 m	128 m
Outer Shelf	550 m				100·5 m 110 m 137 m 155 m 180 m 183 m	155 m* 173 m* 164–190 m		91 m 137 m	

KEY TO COLUMNS: *Source references:* 1. Churchill (1969). 2. Carrigy and Fairbridge (1954). 3. Phizackerley (1967) (Leeuwin area). *Lancelin area. 4. Garrick Agnew Pty Ltd (1968) Geographe Bay. 5. Carrigy and Fairbridge (1954).

GEOGRAPHE BAY

(Lat. 33°35′S, long. 115°20′E)

The port of Bunbury is situated on Geographe Bay, a north-facing bay on the west coast. Exploration for heavy minerals has been undertaken by Garrick Agnew Pty Ltd and Planet Mining Company Pty Ltd; the first operator locating several magnetic anomalies on bathymetric rises which were not tested.

The floor of Geographe Bay is overlain by up to 5·2 m of unconsolidated sediment resting on a gently sloping shelf. Two submerged lines of beach sediments have been located in 16·5 and 36·6 m of water, respectively, and these carry small slicks of heavy minerals consisting of between 50 and 80 per cent ilmenite, 3 to 7 per cent zircon, 0·5 to 1 per cent monazite and a trace of rutile.

Reference: Carrigy and Fairbridge (1954), Garrick Agnew Pty Ltd (1968), Planet Mining Co. Pty Ltd (1968a).

FLINDERS BAY

(Lat. 34°17′S, long. 115°15′E)

Flinders Bay is a south facing bay on the southwest coast; the holiday resort of Augusta is located on its west side. Exploration for heavy minerals in Flinders Bay was conducted by Planet Mining Company Pty Ltd (1968b), in conjunction with a programme to explore the south coast for phosphate. Samples of sediment from the floor of the bay were reported to contain in excess of 1 per cent heavy minerals.

INLAND AREAS

Carroll (1932, 1934) and Simpson (1948) record numerous occurrences of heavy minerals associated with soils and rock outcrops in inland areas. Heavy mineral concentrations near lakes and rivers have been described from various localities but none is considered to be of economic value at present. A survey of the main drainages of the State during 1947 and 1948, designed to locate monazite and other radioactive heavy minerals, was carried out by the Geological Survey of Western Australia but no large accumulations of heavy minerals were found. The most important inland deposit occurs at Boodanoo, where a dune sand adjacent to a lake contains concentrations of heavy minerals weathered from nearby mafic igneous rocks (de la Hunty, 1966).

BOODANOO

(Lat. 28°37′S, long. 118°18′E)

The Boodanoo deposits are located on the southern shores of Lake Boodanoo, about 6·5 km south of Boodanoo Trig. The lake, situated about 350 km east of Geraldton, is accessible along station tracks from a road connecting Meeline and Boodanoo homesteads.

Geological information

The lake is typical of those in Salinaland, consisting of migrating clay pans flooded only during rainy seasons, with intervening dunes of sand and kopai. It is a linear feature extending for 56 km to the north but being less than 8 km wide. Rocks of the Murchison Province of the Yilgarn Block are exposed and consist of mafic igneous rocks with metasediments intruded by granitic rock. Ilmenite has been recorded from mafic rock and granitic rock in this area.

The parallel dunes on the south end of Lake Boodanoo trend mainly northwesterly; most are less than 1·5 km long, 200 m wide and 9 m high. Deposits with an average of about 5 per cent heavy minerals are distributed throughout the sand dunes, with ilmenite and magnetite the main constituents (de la Hunty, 1966, Fig 21). The surfaces of some dunes contain up to 63 per cent heavy minerals, but these richer sections are rarely more than 10 cm thick.

There is an estimated 1 Mt of sand containing 10 to 20 per cent ilmenite in the deposit. Several million tonnes of lower grade material, between 5 and 10 per cent, are estimated to occur around the higher grade deposit.

Reference: de la Hunty (1966).

MINOR OCCURRENCES

Lake Dumbleyung

(Lat. 33°20′S, long. 117°40′E)

The deposits are located on the northeast and southwest shores of Lake Dumbleyung approximately 24 km east of Wagin and some 137 km from Bunbury, the nearest port.

Lake Dumbleyung, a seasonal lake of approximately 62 km², occupies a shallow depression on the Darling Plateau, and is the drainage culmination of several creeks draining over 600 km² of the Yilgarn Block in sluggish swamp-line depressions. Cliffs, up to

18 m high, are developed in places along a narrow beach on the lake shore. Archaean granitic rocks are exposed in the vicinity of the lake and overlying these are up to 18 m of alluvium in drainage channels and 30 cm of saline sediment on the lake floor. Heavy mineral slicks up to 40 m long, 6 m wide and 10 cm thick have been reported near a promontory on the south side of the lake. There is estimated to be less than 1 000 t of heavy mineral concentrate in the deposit.

Reference: Low (1960).

Yulguring Well

(Lat. 31°02′S, long. 116°32′E)

The deposit is in Yulguring Gully, a tributary of the Mortlock River, about 8·8 km northeast of Calingiri. It is situated between a north-south road, marking the western boundary of Melbourne Locations 1113 and 1261, and Yulguring Well, and is accessible by road.

The ground is underlain principally by granitic rocks with mafic and felsic gneisses and associated pegmatites, all intruded by dolerite dykes. Rutile of the black ferruginous variety, nigrine, in crystal fragments up to 20 mm long and some weighing 15 gm, has been found in quartz and feldspar-bearing outwash sediments within the gully. At its head, where rutile was discovered, the sediments are only a few metres wide, but downstream the feature widens into alluvial flats in which no rutile has been recorded.

Durack Range

(Lat. 16°15′S, long. 128°00′E)

Heavy mineral deposits have been described from the Speewah Valley, approximately 113 km south of Wyndham, near the Durack Range. They are found in alluvium adjacent to the Warton Sandstone and Carson Volcanics, and extend over 15 km^2. They contain chiefly vanadiferous titano-magnetite with ilmenite, zircon, tourmaline and amphibole as accessory minerals.

Medium to coarse-grained mineral sands in the Carson Volcanics and Warton Sandstone have an average composition of 60 per cent ilmenite, 8 per cent anatase, 7 per cent zircon and 5 per cent monazite in the heavy fraction. The sands are up to 460 m long and between 12 mm and 0·8 m thick.

Manjimup

(Lat. 34°20′S, long. 116°08′E)

Heavy minerals are reported in a creek tributary of the Warren River approximately 19 km south of Manjimup. Pale-blue to white kyanite and nigrine (ferruginous rutile) with minor zircon, staurolite, garnet, ilmenite, and spinel are present in the alluvium; the material is between 0·1 and 5·1 mm in grain size.

Mullalyup

(Lat. 33°29′S, long. 115°06′E)

Heavy mineral concentrates have been reported from samples collected from drill cuttings of alluvium along the east bank of Mullalyup Brook for about 1 km south of Mullalyup townsite (about 58 km southeast of Bunbury). Two samples collected during the radioactive minerals survey conducted by the Geological Survey of Western Australia assayed 2 per cent and 90 per cent heavy minerals. The heavy mineral concentrate consisted chiefly of ilmenite containing between 0·03 and 0·06 per cent Cr_2O_3.

CHAPTER 8

Exploration Methods

Exploration for heavy mineral sand deposits in Western Australia, particularly on the Swan Coastal Plain, is based on consideration of levels at which beach deposits are recorded, and the relation of these to present geomorphology. Some guidelines are provided by the work in the southwest of Western Australia by McArthur and Bettenay (1960), Welch (1964) and Lowry (1965).

Techniques employed include aerial photograph interpretation, topographic contouring, geobotanical prospecting, geophysical surveying, and systematic or wildcat drilling. Neither geological nor geomorphic mapping of the coastal plains has been carried out in sufficient detail to be useful for exploration, though the Yoganup Formation, defined as a shoreline deposit which includes heavy mineral bearing sediments, is shown on 1:250 000 geological maps of the Perth Basin.

Previous summaries of the heavy mineral deposits of Western Australia have not included prospecting techniques and the intention here is to briefly describe methods which are employed during exploration programmes in the State. Most of this information has been obtained from exploration companies or from published material.

IDENTIFICATION OF FOSSIL SHORELINES

Although Woolnough (1920) noted and named the Ridge Hill Shelf, it was not until Prider (1948) described marine sandstone from it that its association with a marine incursion became clear. Work by McArthur and Bettenay (1960) on the geomorphology of the Swan Coastal Plain provided the background for Welch (1964) to recognize and name a number of fossil shorelines containing mineral sand deposits. Later reviews of the geomorphology of the southwestern part of the State were made by Lowry (1965) and Playford and others (1976). Nomenclature has varied between authors and a comparison is presented in Table 31.

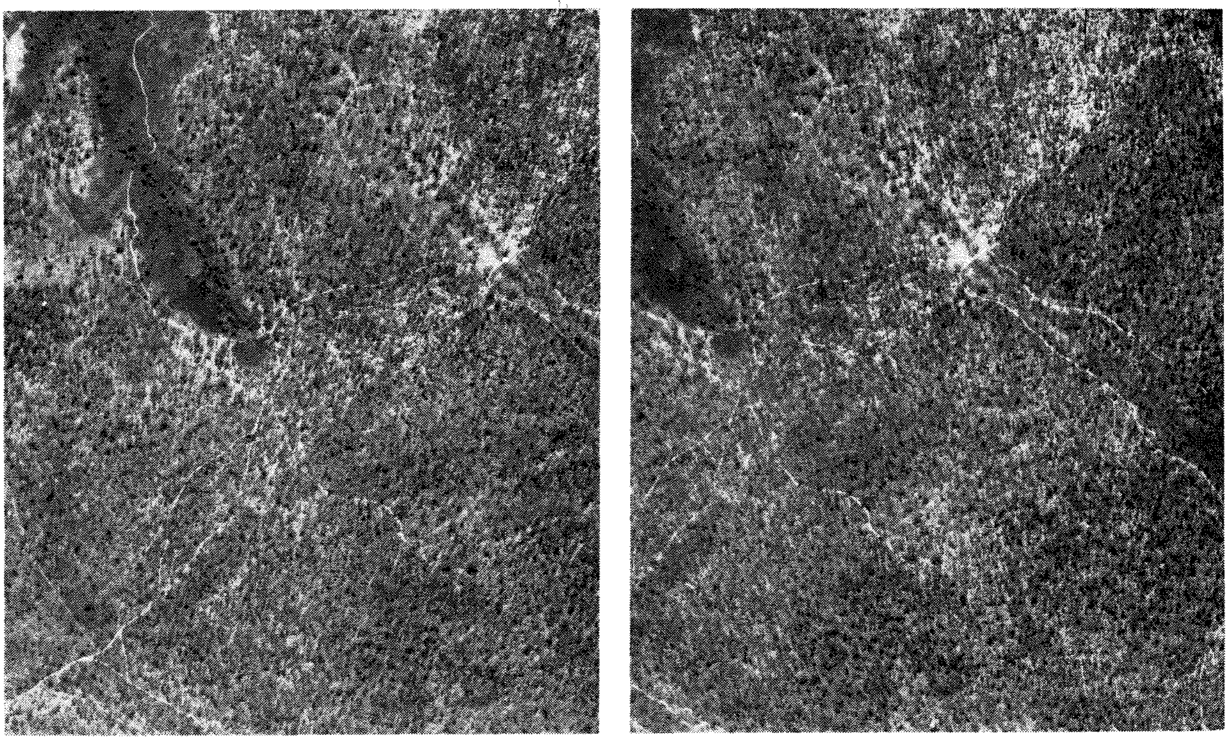
Heavy mineral deposits associated with fossil shorelines were first located near the coast at Koombana Bay and Wonnerup Inlet in about 1949. Discovery in 1954 of the Capel South deposit, some 6·5 km inland from the coast, led to exploration for fossil shorelines on the Swan Coastal Plain. In 1954 Westralian Oil Ltd (now Westralian Sands Ltd) discovered the occurrences of heavy minerals at Yoganup Central and Capel North. The shorelines are now referred to respectively, in order of distance from the coast, as Quindalup, Spearwood, Bassendean and Yoganup. The Ridge Hill Dune System, inland from the Yoganup Shoreline, is not as yet a scene of heavy mineral discovery.

AERIAL PHOTOGRAPHS

Lueder (1959), Ray (1960) and Norman (1968) provide information on the use of photographs with special reference to interpretation of landforms. For photo-geologic

TABLE 31. COMPARISON OF GEOMORPHIC NAMES IN SOUTHWESTERN AUSTRALIA

Levels *m*	Reference			
	McArthur and Bettenay (1960)	Welch (1964)	Lowry (1965)	This bulletin
0–3	Quindalup Dunes	Quindalup Shoreline	Quindalup Dune System	Quindalup Dune System (includes Minninup line)
0–5	Spearwood Dunes	Spearwood Shoreline	Spearwood Dune System	Spearwood Dune System
6–8	Bassendean Dunes	Bassendean Shoreline	Bassendean Dune System	Bassendean Dune System (includes Capel line)
	Pinjarra Plain	....	Carbunup Dune System	....
30–50	Ridge Hill Shelf	Lower Escarpment Shoreline	Ridge Hill Dune System	Yoganup Dune System (includes most of Yoganup line and part of Waroona line)
55–80	....	Middle Escarpment Shoreline	Middle Escarpment Dune System	Ridge Hill Dune System (includes part of Waroona line and a minor part of the Yoganup line)



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DONNYBROOK 441 RUN 7

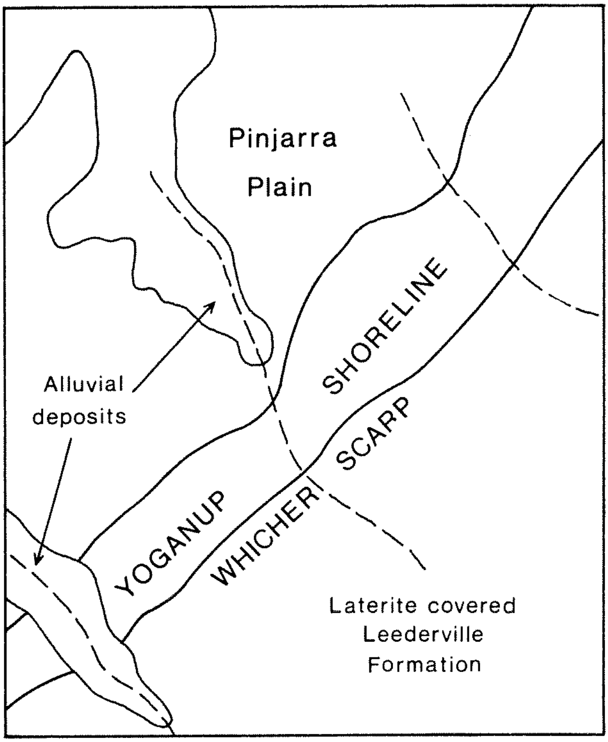

FIGURE 18 – Stereoscopic pair of photographs of the Yoganup Central Mine area prior to mining showing the appearance of the shoreline deposits and associated sediments.

Figure 18. Stereoscopic pair of aerial photographs of the Yoganup Central mine area prior to mining showing the appearance of the shoreline deposits and associated sediments.

mapping ground control is particularly essential if the significance of subtle variations in images associated with ancient features is to be recognized. For example, Figure 18 is a stereoscopic pair of photographs of the Yoganup Central area demonstrating faint, though definite, geomorphic features diagnostic of fossil shorelines. The landform most noticeable in such an area is the prominent slope change on the inland side of the former shoreline, attributed to compaction over the buried sea cliff. Most heavy mineral deposits in Western Australia occur in similar situations which may be identified on aerial photographs.

Colour aerial photography was used to identify fossil shorelines in the Busselton area by Busselton Minerals N.L. In conjunction with geophysical techniques it was successful in identifying new discoveries of heavy mineral sands on the Capel line. Deposits in the southwest of the State are commonly covered with a thin veneer of yellow sand which on colour aerial photographs usually contrasts clearly with adjoining white to grey sand. Commonly old shorelines are backed by low sand hills which also show as prominent yellow on colour photographs. For best results Minard (1960) recommends that colour aerial photographs should be taken at the time of maximum cultivation and minimum vegetation cover.

TOPOGRAPHIC SURVEYS

Heavy mineral sand prospecting in Western Australia is carried out along levels predicted from international eustatic correlation (see Fig. 6). Unfortunately many coastal areas of Western Australia are not contoured sufficiently accurately for the effective use of eustatic data.

Extrapolation of known fossil shoreline elevations over short distances (up to 2 km), in conjunction with geomorphic mapping, is of great value in exploration. For example, the Yoganup Extended deposit was discovered by extrapolation of levels from the northern end of the Yoganup Central deposit. Table 7 lists all available reduced levels of the bases of heavy mineral bearing beach deposits in Western Australia.

GEOBOTANICAL PROSPECTING

It has been reported that geobotanical prospecting methods can identify mineral sands. In the Southwestern area the green kangaroo paw (*Anigozanthus viridis*) is reported to be common on mineral sand deposits. Banksias are also common whereas jarrah trees (*Eucalyptus marginata*) are rare on heavy mineral deposits.

Although these plants are reported to show some affinity with mineral sand, no detailed study has been carried out. It seems more likely that the plants mentioned favour particular geological units (e.g. dunes, backdune swamps) rather than that they preferentially select concentrations of titanium minerals.

OFFSHORE EXPLORATION

The regional setting of the offshore areas in Western Australia is described by Carrigy and Fairbridge (1954). Exploration offshore for deposits of heavy minerals has been carried out in Geographe Bay and the Bremer Basin and the results reported by Phizackerley (1967), Connolly and von der Borch (1967), Planet Mining Company Pty Ltd (1968a,b,c) and Ocean Mining A. G. (1968). Bottom profile traversing, grab sampling, shallow drilling, and limited magnetometer surveying have been carried out. A magnetometer survey by Ocean Mining A.G. located a small deposit of heavy minerals in Geographe Bay offshore from Busselton.

Depths of platform and slope changes given in Table 30 may indicate old submerged shorelines.

GEOPHYSICAL METHODS

Magnetometer and scintillometer surveys are used in mineral sand exploration. Tests of other geophysical techniques such as induced polarization, resistivity and infra-red photography have been made but these are not in general use.

MAGNETIC METHODS

The magnetic method is described by Rowston (1965, 1966) from whom most of the information presented here is derived. The most suitable instrument for heavy mineral surveys is the proton precession magnetometer.

Magnetometer surveys are relatively cheap and are an efficient means of determining the position of heavy minerals prior to drilling and other more costly exploratory techniques. If a mineral sand is covered by a uniform thickness of non-magnetic overburden, a semi-quantitive distribution of ilmenite content can be determined with a magnetometer. Significant results can be obtained by magnetometer surveys from mineral sand deposits covered by between 3 and 20 m of overburden. At the Australind prospect the trend and extent of a buried deposit was determined in this way.

Airborne magnetic surveys at heights below 60 m have successfully delineated lines of heavy mineral sands in both the Midlands and Southwestern areas. As with ground surveys results are readily interpreted to indicate likely areas of mineralization. However coffee-rock and laterite, which often occur near economic heavy mineral deposits, are sources of significant magnetic interference. In some areas, such as Yoganup Central, this interference prevents meaningful results being obtained. Spurious results, which may render the magnetic method useless, are usually obtained from fences, macadamized roads, mafic rocks and steel-structured buildings.

RADIOMETRIC METHODS

Radiometric surveys of areas known to contain heavy mineral sand deposits have successfully outlined the concentrations despite the limitation that about 2 m of unreactive overburden can absorb all natural gamma radiation. Although ilmenite is non-radioactive it is frequently associated with gamma ray emitters such as monazite and zircon. In Western Australia the method has been effective at Capel, Busselton and Eneabba.

Instrumentation and survey methods have been described by Foote (1970); both airborne and ground techniques (including drillhole measurements) are applicable. Either total count or spectrometer type instruments can be used effectively and cheaply. It has been reported that spectrometer measurements have been employed to discriminate between the commonly encountered laterite or coffee-rock, which are also often radioactive, and economic mineralization. Detailed results of this application have not been published.

INFRA-RED PHOTOGRAPHY

Colour fill-in infra-red photography has been used experimentally in the southwest of the State. As the method readily detects wet ground (Polack and Wiebenga, 1968) it should show up the back-dune swamps in which many mineral sand deposits occur. However, other methods such as colour photography are capable of equal discrimination at lower cost.

TABLE 32. ELECTRICAL AND MAGNETIC PROPERTIES OF MINERAL SAND SAMPLES, YOGANUP CENTRAL DEPOSIT

Description	Chargeability (milliseconds)	Resistivity (ohm-metres)	Magnetic Susceptibility (cgs units)
Mineralized sand	8·4	280	40×10^{-6}
Mineralized sand	6·0	132	30×10^{-6}
Mineralized sand	6·8	210	....
Tailings	0·3	144	10×10^{-6}
Tailings	0·6	126	....
Tailings	3·8	400	20×10^{-6}
Tailings	3·3	440	....
Concentrate	19·0	78	900×10^{-6}
Concentrate	20·0	82	$1\,000 \times 10^{-6}$
Concentrate	18·6	80	....

Data from Watts (1972).

INDUCED POLARIZATION AND RESISTIVITY

Induced polarization and vertical electrical sounding (resistivity) methods using a dipole-dipole array have been tested over known heavy mineral concentrations. Watts (1972) reporting tests at Yoganup Central, states that although ilmenite is a suitable target for induced polarization methods the resistivity results were inconclusive. This survey showed a relationship between the chargeability (in milliseconds) and grade (in per cent by weight). The physical properties of samples of mineralized sand and concentrates are given in Table 32.

COHERENCY DETECTION SYSTEM

Watanabe and Baxter (1972) reported on experiments with a coherency detection system over a heavy mineral deposit. The method appears to respond to ilmenite but the effect is masked by coffee-rock or laterite. As most deposits of mineral sand in Western Australia are near laterite and coffee-rock it seems likely that application of this method will be limited.

SIDE-LOOKING RADAR

There are no reports on side-looking radar surveys for heavy mineral deposits in Western Australia, but the method has been recommended by Lyon and Lee (1970) as suitable for detecting linear topographic features, even though these may be slight. As heavy mineral deposits are commonly on the seaward side of subdued scarps this relationship may lead to use of side-looking radar. Aerial photography carried out when the sun is low in the sky may be a cheaper way of achieving similar results.

SAMPLING TECHNIQUES

This short section reviews those sampling techniques used by the mineral sand industry in Western Australia and it should be pointed

TABLE 33. COMPARISON OF ASSAY RESULTS OBTAINED FROM CONTINUOUS AUGER DRILL HOLES AND SHAFTS

Depth Interval *m*	Shaft and Drill Results (Per Cent Heavy Mineral Content)																	
	A			B			C			D			E			F		
	Shaft	Drill	Per Cent Diff.*	Shaft	Drill	Per Cent Diff.*	Shaft	Drill	Per Cent Diff.*	Shaft	Drill	Per Cent Diff.*	Shaft	Drill	Per Cent Diff.*	Shaft	Drill	Per Cent Diff.*
0– 1·83	2·2	2·3	+4	15·1	11·6	—23	5·1	4·0	—22	5·1	4·4	—14	4·4	3·8	—14	27·8	19·7	—29
1·83– 3·66	3·8	2·7	—29	25·7	12·9	—50	8·1	5·3	—35	8·8	4·6	—48	7·5	4·1	—45	42·4	25·1	—41
3·66– 5·49	4·6	3·1	—33	43·3	20·5	—53	15·0	7·7	—49	12·2	6·6	—46	14·9	8·8	—41	60·7	41·1	—32
5·49– 7·32	4·2	4·0	—5	47·4	33·4	—30	28·2	18·9	—33	29·9	13·0	—56	16·6	18·3	+10	42·9	46·1	+7
7·32– 9·14	14·3	6·3	—56	41·0	32·3	—21	26·5	26·0	—2	17·5	18·0	+3	10·5	14·2	+35	22·0	34·6	+57
9·14–10·97	38·2	7·4	+81	30·1	30·4	+1	20·9	23·1	+11	20·2	9·8	—51	....	....	....	52·1	28·3	—45
10·97–12·80	45·6	20·0	—56	....	....	....	15·5	18·8	+21	32·8	24·8	—24	....	....	....	....	....	....
	....	....	....	....	....	....	17·6	18·7	+6	32·5	37·6	+16	....	....	....	....	....	....
	....	....	....	....	....	....	....	....	....	33·5	42·2	+26	....	....	....	....	....	....
	....	....	....	....	....	....	....	....	....	31·8	24·3	—23	....	....	....	....	....	....

NOTE: * Per cent difference expressed as $\frac{\text{Difference}}{\text{Shaft Assay}}$ x 100.

out that the sampling of flat-lying orebodies is already the subject of numerous articles which should be consulted by geologists new to the techniques. In particular, the author believes that too little attention has been paid in this State to the application of statistical mathematics in designing exploration programmes and treating the sampling results.

NUMBERS AND SPACING OF SAMPLES

The practice of drilling closely spaced holes on pre-determined lines is well established in the Western Australian mineral sands industry, but may not always be the most economical way of assessing a deposit.

Heavy mineral deposits are similar to other tabular deposits such as clay and bauxite in being of ideal shape for applying statistical methods to sampling. Wolfe and Neiderjohn (1962) took this approach in the design of a sampling programme for a clay deposit. They established a grid over the deposit and drilled a pre-determined number of sites chosen at random. When compared with the cost of drilling the same deposit at regular grid spacings, the random method proved cheaper and was as efficient in locating and assessing the clay. The method should be used in conjunction with geological maps from which the orientation of the deposit may be determined. Mathematical methods, such as that presented by Agocs (1955), for estimating grid spacing should also be referred to.

SAMPLE COLLECTION

MacDonald (1966, 1968) discusses techniques for sampling placer deposits such as mineral sands, describing drilling, pitting, costeaning and surface sampling. Successful sampling of heavy mineral deposits below the water table is difficult, but has been managed in some areas using multiple tube drills and sludge pumps. Tables 33 and 34 compare the results obtained by different sampling methods.

TABLE 34. COMPARISON OF ASSAY RESULTS OBTAINED FROM DIFFERENT DRILLING TECHNIQUES

Hole No.	Sample Interval *m*	Assay Results *Per cent Heavy Minerals*		
		Continuous Auger	Hand Auger	Dead Stick
A	0–1·83	8·2	6·7	10·7
	1·83–3·66	4·1	....	8·4
B	0–1·83	10·4	8·6	9·9
	1·83–3·66	2·8	3·9	3·0
C	0–1·83	9·7	11·5	8·9
	1·83–3·66	7·6	....	5·7
D	0–1·83	2·1	3·0	4·5
	1·83–3·66	1·3	3·3	2·3
E	0–1·83	6·6	5·3	6·0
	1·83–3·66	5·0	....	4·6
F	0–1·83	6·8	7·0	7·4
	1·83–3·66	5·4	....	5·2
	3·66–5·49	3·4	....	5·2
G	0–1·83	2·9	2·7	2·1
	1·83–3·66	1·4	....	2·1
	3·66–5·49	2·2	....	7·1
H	0–1·83	4·3	6·8	6·7
	1·83–3·66	6·9	....	4·3
	3·66–5·49	4·8	....	4·4
I	0–1·83	0·8	0·9	1·5
	1·83–3·66	0·8	....	0·9
	3·66–5·49	0·6	....	0·4
	5·49–7·32	0·4	....	0·7
J	0–1·83	2·2	2·4	1·5
	1·83–3·66	2·0	....	2·3
	3·66–5·49	0·6	....	1·5
	5·49–7·32	2·0	....	1·3

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Hand-operated drills and grab samples

Hand-operated drills such as corkscrew augers, post-hole diggers and sludge pumps have been used to depths of up to 20 m, but are usually uneconomic for depths below 5 to 7 m. None of these drills will penetrate all coffee-rock, laterite or hard clasts within the deposit. Only the sludge pump, when used with casing, gives reliable results below the water table.

Power augers

Power augers are used for heavy mineral sampling at all stages of exploration in Western Australia. Several techniques developed to accommodate different types of sediments provide results of varying reliability.

Continuous augering: In this most common reconnaissance sampling method, the rods are not pulled until completion of the hole and the sample is brought to the surface along flights of the drill rods. Statistical analyses of results indicate a reliability of approximately ± 30 per cent, an accuracy satisfactory for establishing indicated ore reserves. The method is quick, with drilling rates of 100 to 150 m per day being common, and inexpensive, with costs of between $1.20 and $3.00 per metre. The drill is capable of sampling most sand and clay deposits and can penetrate some coffee-rock and laterite, but where the rate of penetration is slow, the risk of contamination increases.

Dead stick augering: In this technique the rotaty action is used only for drilling ahead, the sample being obtained by pulling flights of drill rod. Accurate results can be produced by exercising care. Considerably heavier equipment is required than for the continuous method and the drilling rate is slower. The cost of drilling is between $2.00 and $5.00 per metre. Statistical analyses of results indicate a reliability within ± 20 per cent and consequently the method is suitable for establishing measured ore reserves.

Core augering : Drilling with hollow-stem drill rods suitable for wireline core recovery, has been used successfully in unstable ground. The sample is usually only slightly disturbed and the reliability of the sample is high. A coring auger can drill between 30 and 100 m per day in most sediment, and the cost is between $2.50 and $10 per metre. A reliability of ± 10 per cent is expected and the technique can be used for establishing measured ore reserves, and for obtaining samples for sedimentology studies.

Vacuum augering: This method has been used with limited success at Eneabba and Jurien but the drills are prone to blockage, have difficulty penetrating clayey material, and are unworkable in wet areas. The sample collected may be representative where conditions are favourable, but clay makes reliable sampling difficult. Commonly 30 to 200 m per day of drilling are obtained using this method at a cost of approximately $2.50 to $5 per metre. If the drilling method is successful, reliability of sampling of ±20 per cent can be expected.

Multiple tube drilling

Recently drills have been developed with multiple tubes within the drill rod and as there is little contamination during drilling, this equipment has proved very useful. The developers of this drill, have successfully tested deposits in the Eneabba and Capel areas. The estimated reliability of sampling is ± 10 per cent. The cost of multiple tube methods of drilling ranges from $4.50 to $7.50 per metre and between 80 and 300 m per day can be drilled.

Air blast drilling

Air blast drilling with a rotary bit in uncased holes is satisfactory providing the clay content of the sediment is greater than

10 per cent by weight and the hole walls are stable. The technique is rapid and commonly 200 to 300 m per day can be drilled at a cost of $1 to $3 per metre. The reliability of the samples varies from ± 50 per cent to ± 20 per cent.

Pitting and trenching

Bulk samples of heavy mineral deposits are obtained by backhoe and clam-shell digging, costeaning and well sinking using concrete liners. The resulting pits are also useful for engineering and sedimentological studies. Clam-shell diggers and backhoes while mobile, generally can be used only to test sediments which are coherent and not susceptible to collapse. These techniques are useful to a depth of 5 to 7 m for backhoe and 8 to 12 m for clam shells.

Costeaning with a bulldozer and ripper is applicable for bulk sampling sediment where there is little clay and consequently poor coherency. Concrete lined wells may be necessary should bulk samples be required from loose, unconsolidated sediments. This method is relatively slow and expensive.

ESTIMATION OF ERRORS

Common practices designed to avoid handling errors when taking drill samples and to prevent contamination of the samples are described by McKinstry (1948) and Macdonald (1966, 1968). Mathematical methods of assessing the statistical reliability of any sampling programme are referred to by Krumbein and Miller (1953, 1954), Miller and Kahn (1967), and Koch and Link (1971). Error estimation and its applications and limitations in the mining industry are described by Hazen (1967). A recent review is given by Griffiths (1971).

COST BENEFIT ANALYSIS

Many modern exploration programmes are preceded by a cost benefit study to determine the minimum quantity of ore economically mineable at a given locality, which quantity in turn may influence the planning of exploration. Such methods are beyond the scope of this bulletin, but are considered by Slechter (1960), Harris and Euresty (1969) and Johnson and Bennett (1969). Chapters 4 to 7 of this bulletin provide information which will allow reasonable assumptions to be made of the expected orientation, length, width and grade of deposits sought in different parts of the State. These factors can be used in the mathematical equations proposed by the above-mentioned authors.

ORE RESERVE ESTIMATION

There are many standard methods of ore reserve estimation and some are modified for use with computers. These are reviewed below.

CUT-OFF GRADE

As the margins of most heavy mineral sands are gradational, mining limits are controlled by economic rather than geological factors. The economic factors can vary during the mining of a deposit, and must be assessed carefully. Methods of selecting an optimum cut-off grade are discussed by Lane (1964) and Taylor (1972).

CONVERSION FACTORS

As the density of a heavy mineral sand varies with its grade a range of factors for converting volume to mass must be used in calculating ore reserves. Figure 19 illustrates the range of conversion factors used in the industry; the median line is recommended for deposits on which little or no independent density data are available and the shaded area shows the range that can be expected due to varying clay contents and compaction.

METHODS OF CALCULATION

The five main methods used in Western Australia for calculating ore reserves of mineral sand deposits are:

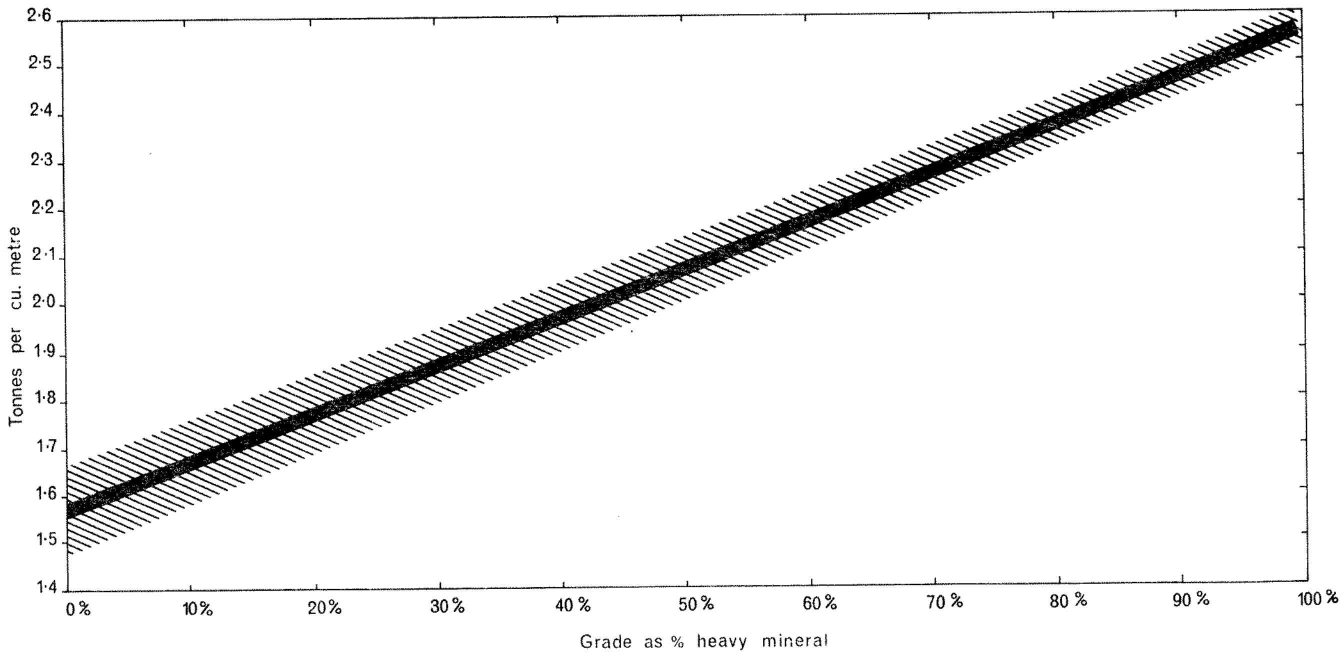

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Figure 19. Recommended conversion factors: cubic metres to tonnes of ore.

1. Weighted average line
2. Average depth
3. Cross-sectional area
4. Weighted hole
5. Between-the-line weighted average.

The ore reserves estimated by the different methods in the hypothetical case presented in Figure 20 are given in Table 35. They show that care is needed in choosing a suitable method.

TABLE 35. RESULTS OF FIVE METHODS OF CALCULATING ORE RESERVES OF DEPOSIT SHOWN IN FIGURE 20

Method	Tonnes of Ilmenite
Weighted average line	8 427
Average depth	8 262
Cross-sectional area	8 727
Weighted hole	8 742
Between-the-lines weighted average....	6 845
Mean of all results	8 200
Maximum deviation	16 per cent
Mean of first four results	8 539
Maximum deviation within the four....	3 per cent
Deviation of the fifth method	19 per cent

The *weighted average line* method is suitable for desk calculators. The average grade and depth is computed along each line of drill holes and assumed to represent an area covering (usually) half the distance between adjacent lines. The sum of the resulting volumes and the weighted-average grade can be used to estimate ore reserves.

In the *average depth* method the horizontal limits of the orebody are determined from an isograd map prepared from weighted average grades for each drill hole. The average depth of the deposit is calculated from all drill holes in the orebody and the area of the deposit is measured. The volume and weighted average grade of the deposit can then be calculated.

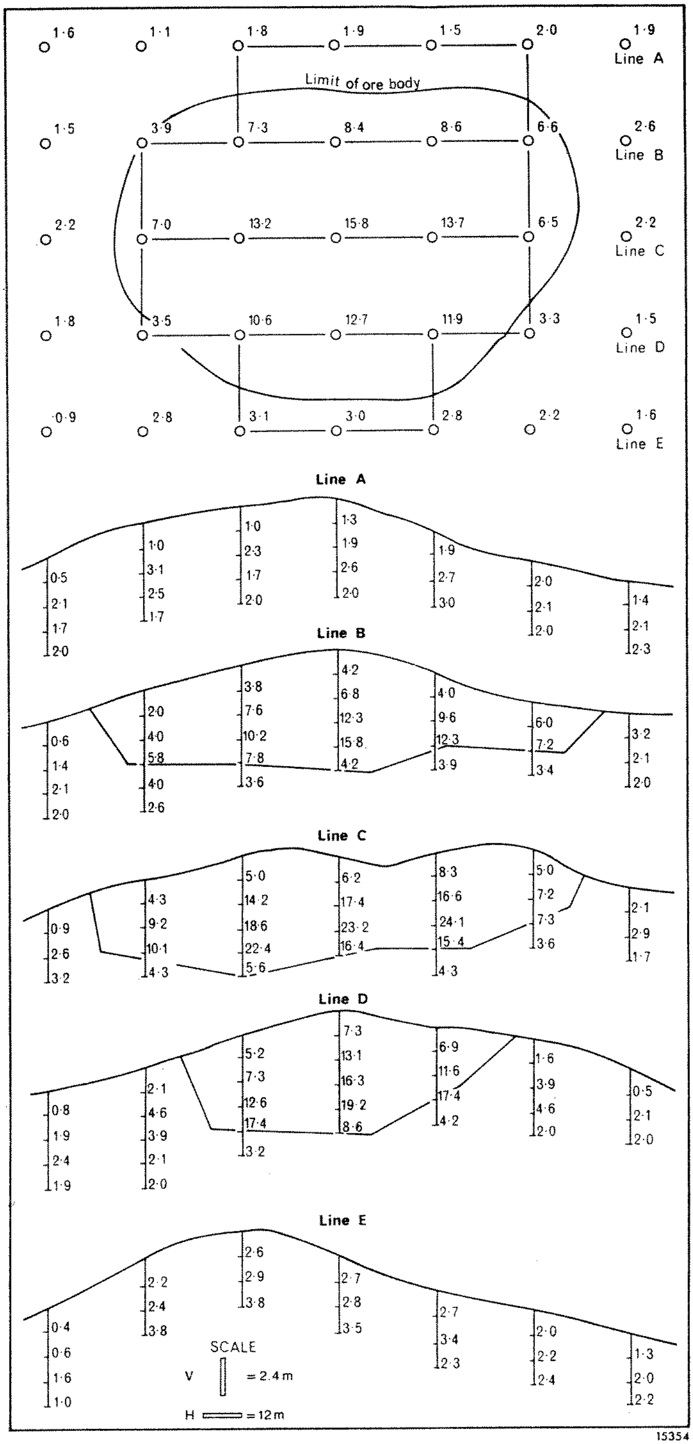
Cross-sectional area method requires a complete set of cross-sections with boundaries of the ore shown. The cross-sectional area of the orebody is measured and by applying this over the length of influence attributed to the section, a volume can be determined. The weighted average grade of all holes of the cross section gives the grade of ore from which its mass can be determined.

The *weighted average hole* method is time consuming but can give the most statistically significant results. It is suitable for computer application. The method involves applying the depth and weighted average grade of each hole to an area of influence which may be determined by the method of polygons or be related to section spacing. The volume of ore represented by each hole can then be calculated and final ore reserves are determined by summation.

Between-the-line weighted average method is a complex and conservative method for estimating ore reserves. The area of ore between adjacent drill hole lines is determined and the average depth and weighted average grade of the two sections is calculated. The volume of ore between the drilled section is calculated from the area of ore in plan view and the average depths.

DESCRIPTIVE AND ANALYTICAL TECHNIQUES

Observation of standard sedimentological parameters may give the exploration or mining geologist an insight into the depositional environment of a heavy mineral deposit or may aid identification of troublesome material during treatment (e.g. Lissiman and Oxenford, 1973). These parameters are grain size distribution, grain shape, surface texture and mineral assemblages. The statistical treatment of these parameters is described by Krumbein (1934), Griffiths (1953), Krumbein


1·6 1·1 1·8 1·9 1·5 2·0 1·9
Line A
Limit of ore body
1·5 3·9 7·3 8·4 8·6 6·6 2·6
Line B
2·2 7·0 13·2 15·8 13·7 6·5 2·2
Line C
1·8 3·5 10·6 12·7 11·9 3·3 1·5
Line D
0·9 2·8 3·1 3·0 2·8 2·2 1·6
Line E
Line A
0·5 2·1 1·7 2·0
1·0 3·1 2·5 1·7
1·0 2·3 1·7 2·0
1·3 1·9 2·6 2·0
1·9 2·7 3·0
2·0 2·1 2·0
1·4 2·1 2·3
Line B
0·6 1·4 2·1 2·0
2·0 4·0 5·8 4·0 2·6
3·8 7·6 10·2 7·8 3·6
4·2 6·8 12·3 15·8 4·2
4·0 9·6 12·3 3·9
6·0 7·2 3·4
3·2 2·1 2·0
Line C
0·9 2·6 3·2
4·3 9·2 10·1 4·3
5·0 14·2 18·6 22·4 5·6
6·2 17·4 23·2 16·4
8·3 16·6 24·1 15·4 4·3
5·0 7·2 7·3 3·6
2·1 2·9 1·7
Line D
0·8 1·9 2·4 1·9
2·1 4·6 3·9 2·1 2·0
5·2 7·3 12·6 17·4 3·2
7·3 13·1 16·3 19·2 8·6
6·9 11·6 17·4 4·2
1·6 3·9 4·6 2·0
0·5 2·1 2·0
Line E
0·4 0·6 1·6 1·0
2·2 2·4 3·8
2·6 2·9 3·8
2·7 2·8 3·5
2·7 3·4 2·3
2·0 2·2 2·4
1·3 2·0 2·2
SCALE
V = 2.4 m
H = 12 m
15354

and Graybill (1965) and Miller and Kahn (1967).

GRAIN SIZE DISTRIBUTION

Grain sizes are most usefully recorded on the Wentworth or phi scale which is shown with equivalent metric units in Figure 21.

Most heavy mineral deposits in Western Australia contain considerable amounts of clay which appears to be either derived from weathering of feldspar, or to have been introduced after the sands were deposited. Such clay should be removed by washing and the proportion of clay and the dominant size of the remaining particles recorded. The clay fraction is commonly termed "slimes".

The phi scale (Krumbein, 1936) is recommended for mathematical treatment of size distribution. It is defined as:

$$\phi = -\log_2 (\text{diameter in mm}).$$

The conversions from screens in common use to this scale are shown in Table 36. Parameters such as standard deviation, skewness and kurtosis can be determined graphically from phi scale data (Inman, 1952, Folk and Ward, 1957). A comparison of the methods for determining the parameters is given in Table 37. Table 38 gives names of the phi scale class intervals suggested for describing sediments. Cadigan (1954) has shown that graphic methods may introduce significant errors, but practice shows that provided the same method is used throughout an investigation, reproduceable and meaningful results can be obtained.

Pictorial representation of the results of grain size analyses can be made using histograms, distribution curves, cumulative frequency curves, or arithmetic probability curves. The best method for graphical determination of distribution parameters is to use the arithmetic probability curve (Folk,

TABLE 36. CONVERSION OF STANDARD SCREEN SIZES TO THE PHI SCALE

BSS Screen No.	Phi Scale	Tyler Screen No.	Phi Scale
4	—2·000	5	—1·9862
5	—1·7441	6	—1·7342
6	—1·4854	7	—1·4823
		8	—1·2400
7	—1·2630	9	—0·9862
8	—1·0000		
10	—0·7485	10	—0·7233
12	—0·4854	12	—0·4823
		14	—0·2240
14	—0·2630	16	0·0131
16	0·0000		
18	0·2345	20	0·2636
22	0·4941	24	0·5125
		28	0·7636
25	0·7370	32	1·0145
30	1·0000		
36	1·2515	35	1·2619
44	1·4941	42	1·5100
		48	1·7612
52	1·7370	60	2·0232
60	2·0000		
72	2·2515	65	2·2654
85	2·4739	80	2·5146
		100	2·7664
100	2·7370	115	3·0116
120	3·0000		
150	3·2515	150	3·2654
170	3·4739	170	3·5064
		200	3·7563
200	3·7370	250	4·0350
240	3·9885		
300	4·2379	270	4·2378
350	4·4739	325	4·5395
		400	4·7179

Figure 20. Plan and sections of a hypothetical mineral sand deposit used for comparing different methods of calculating ore reserves (see text for methods and Table 35 for results).

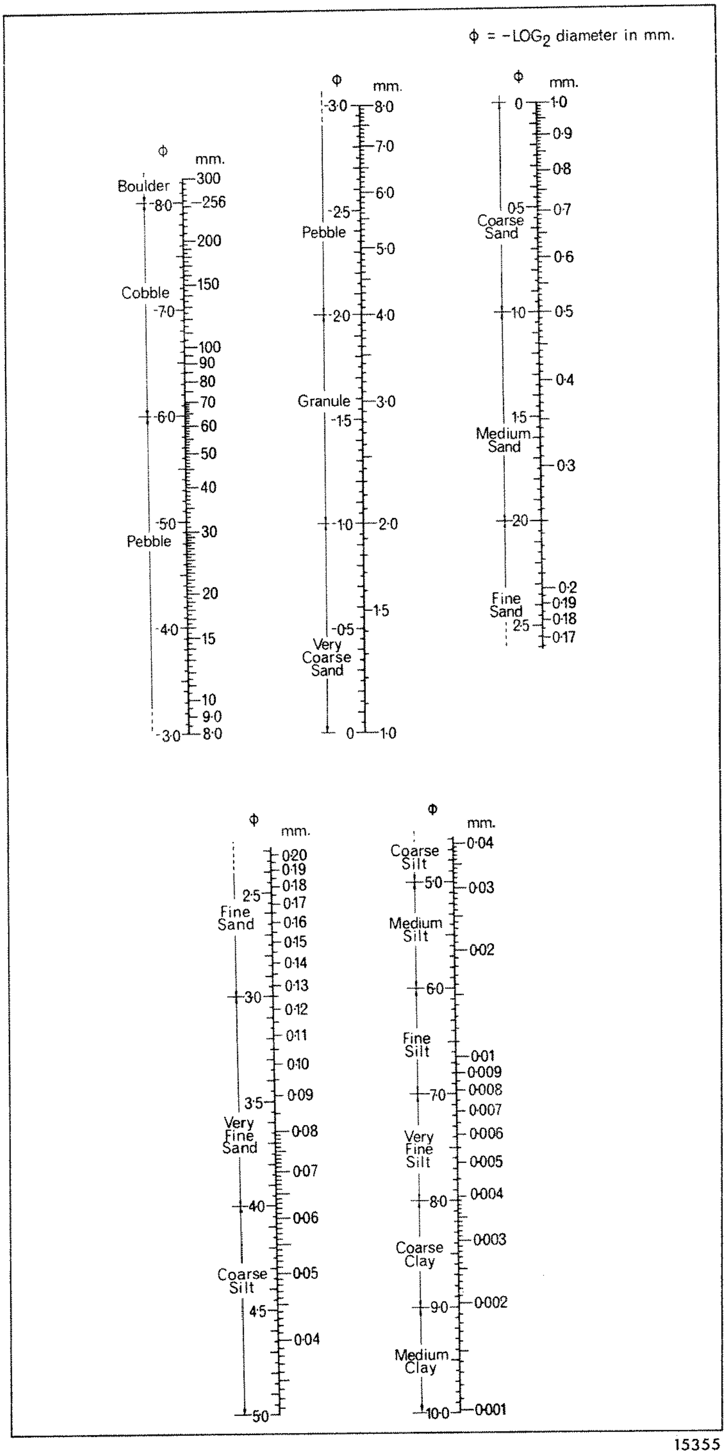


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Figure 21. Conversion chart for phi units and diameters in millimetres.

TABLE 37. SEDIMENTOLOGICAL PARAMETERS CALCULATED BY GRAPHICAL METHODS

	Parameter	Inman (1952)	Folk and Ward (1957)
Central Tendency	Phi Median Diam.	$Md_{\phi} = \phi 50$	Not recommended
	Phi Mean Diam.	$M_{\phi} = \frac{1}{2}(\phi 16 + \phi 84)$	.....
	Phi Mean Size	.....	$M_z = \frac{\phi 16 + \phi 50 + \phi 84}{3}$
Sorting or Dispersion	Phi Deviation Measure	$\sigma_{\phi} = \frac{1}{2}(\phi 84 - \phi 16)$	.....
	Inclusive Graphic Standard Deviation	.....	$\sigma_1 = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$
Skewness	Phi Skewness Measure	$\alpha_{\phi} = \frac{M_{\phi} - Md_{\phi}}{\sigma_{\phi}}$	.....
	2nd Phi Skewness Measure	$\alpha_{2\phi} = \frac{\frac{1}{2}(\phi 5 + \phi 95) - M_{\phi}}{\sigma_{\phi}}$	.....
	Inclusive Graphic Skewness	.....	$Sk_1 = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$
Kurtosis	Phi Kurtosis Measure	$\beta_{\phi} = \frac{\frac{1}{2}(\phi 95 - \phi 5) - \sigma_{\phi}}{\sigma_{\phi}}$	.....
	Graphic Kurtosis	.....	$K_G = \frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$

$\phi 20$ = diameter in ϕ units of the 20 percentile.

TABLE 38. CLASS INTERVALS OF STANDARD DEVIATION, SKEWNESS AND KURTOSIS USED IN DESCRIBING GRAIN SIZE DISTRIBUTION OF SEDIMENTS

Function	Value	Term
Standard Deviation (S)	<0·35	very well sorted
	0·35 to 0·50	well sorted
	0·50 to 1·00	moderately sorted
	1·00 to 2·00	poorly sorted
	2·00 to 4·00	very well sorted
	>4·00	extremely poorly sorted
Skewness (Sk)	—1·00 to —0·30	very negative skewed
	—0·30 to —0·10	negative skewed
	—0·10 to +0·10	near symmetrical
	+0·10 to +0·30	positive skewed
	0·30 to +1.00	very positive skewed
Kurtosis (Kg)	<0·67	very platykurtic
	0·67 to 0·90	platykurtic
	0·90 to 1·11	mesokurtic
	1·11 to 1·50	leptokurtic
	1·50 to 3·00	very leptokurtic
	>3·00	extremely leptokurtic

Data from Folk and Ward (1957).

1955). Plotting is with the phi scale on the arithmetic axis and cumulative percentage on the probability axis.

Results obtained from grain size analyses may aid the interpretation of the environment of deposition by statistical comparison with published results. Table 39 presents the commonly used criteria. Distinguishing between the various environments involves plotting mean against standard deviation, or skewness against standard deviation. For such plots the sieve interval should be approximately a quarter phi.

PARTICLE SHAPE

The shape of sedimentary particles is described by two parameters; roundness and sphericity. Although mathematically based they are commonly determined by using comparison by charts such as those in Krumbein (1941), Rittenhouse (1943) and Powers (1953). Folk (1955) demonstrates the errors that may accrue using such techniques but generally these techniques are satisfactory for use in the mineral sands industry.

Roundness

Roundness can be determined by viewing the grain through a binocular microscope and comparing its shape with a chart, such as Figure 22. Powers (1953) has established the six-fold subdivision of roundness in sand grains given in Table 40. Other charts for determining roundness are presented by Krumbein (1941) and Shepard and Young (1961). A representative number of grains should be examined when using such charts.

TABLE 39. SUMMARY OF PUBLISHED METHODS FOR DISTINGUISHING BETWEEN ENVIRONMENTS OF DEPOSITION BY GRAIN SIZE DISTRIBUTIONS

Author	Beach	Coastal Dunes	Eolian Flats	Alluvial	Remarks
Mason and Folk (1958)	Normal curves	Positive skew mesokurtic	Positive skew leptokurtic	....	Beach sorting is poorer than dune
Shepard and Young (1961)	Not significant	Not significant	....	....	Separation possible using roundness, silt content, black minerals, zircon crystals, shell content in areas of onshore winds
Friedman (1961)	Negative skew	Positive skew mean 1·49 ϕ	....	Usually positive skew	Beach and dune separated by plotting skewness against mean Beach and river by kurtosis against skewness, dune and river by mean against standard deviation
Chappell (1967)	Negative skew	Positive skew	....	....	Resolving power decreases with lithification. Identification of fossil dunes by positive skewness not confident
Moiola and Weiser (1968)	Very well sorted, nearly symmetrical, mesokurtic	....	....	Poorly sorted, very positive skew to positive skew, leptokurtic	No significant difference between beach and dune
Hodgson and Scott (1970)	Generally normal, negative skew, well sorted	....	....	Generally positive skew, and poorly to moderately sorted	Supported by electron microscopy of the surface of quartz grains

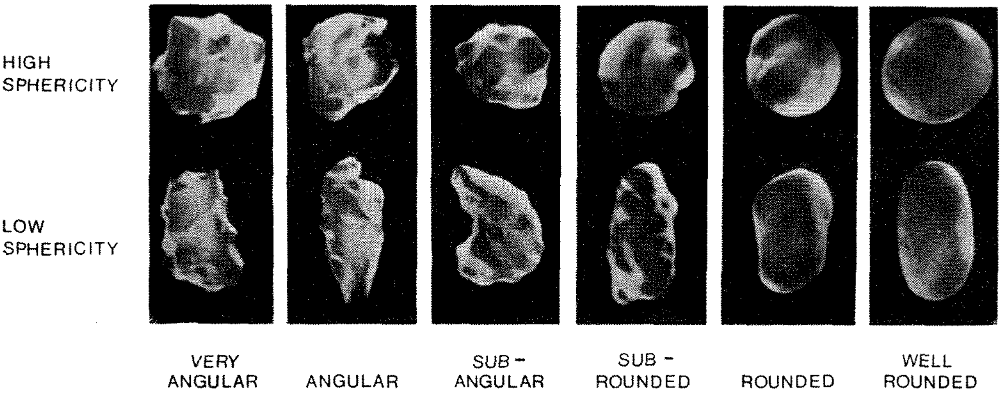

Figure 22. Comparison chart for determining grades of roundness.
(after Powers, 1953)

TABLE 40. CLASS INTERVALS USED IN DESCRIBING GRADES OF ROUNDNESS OF SEDIMENTARY GRAINS

Grade Terms	Class Intervals	Geometric Means
Very angular	0·12–0·17	0·14
Angular	0·17–0·25	0·21
Subangular	0·25–0·35	0·30
Subrounded	0·35–0·49	0·41
Rounded	0·49–0·70	0·59
Well rounded	0·70–1·00	0·84

After Powers (1953).

According to Beal and Shepard (1956), Waskom (1958) and Shepard and Young (1961), roundness may be used to determine the environment of deposition of a sand. For example, sand grains in dunes are more rounded than those in beaches.

Sphericity

The most commonly used chart for determining sphericity is that by Rittenhouse (1943), reproduced here in Figure 23. Other methods are presented by Wadell (1932), Krumbein (1941), Aschenbrenner (1956), Boggs (1967) and Perez-Rosales (1972).

A brief review of the use of sphericity in sedimentology is given by Sahu and Patro (1970). Sphericity does not have a normal statistical distribution and is influenced by original particle shape and the agents acting during transportation and deposition (Blatt, 1967). Sphericity may be a useful descriptive tool but is not diagnostic of the sediment's environment of deposition.

SURFACE TEXTURE

Surface textures of sand grains seen under a binocular microscope include polishing, frosting, striations, scratches, percussion marks, indentations and pits. Several of these are diagnostic of the sedimentary environment, but others may be due to one of several causes. For example frosting of quartz grains has generally been attributed to wind action, but leaching in an alkaline environment can give a similar effect.

Data given by Krinsley and Donahue (1968) may allow interpretation of surface textures seen under an electron microscope.

HEAVY MINERAL ASSEMBLAGE

Mineral species present in heavy mineral deposits are described in full by Baker (1962) Usually the composition of the heavy mineral fraction is obtained from grain counts, but during feasibility studies it may be done using electrical and magnetic separations.

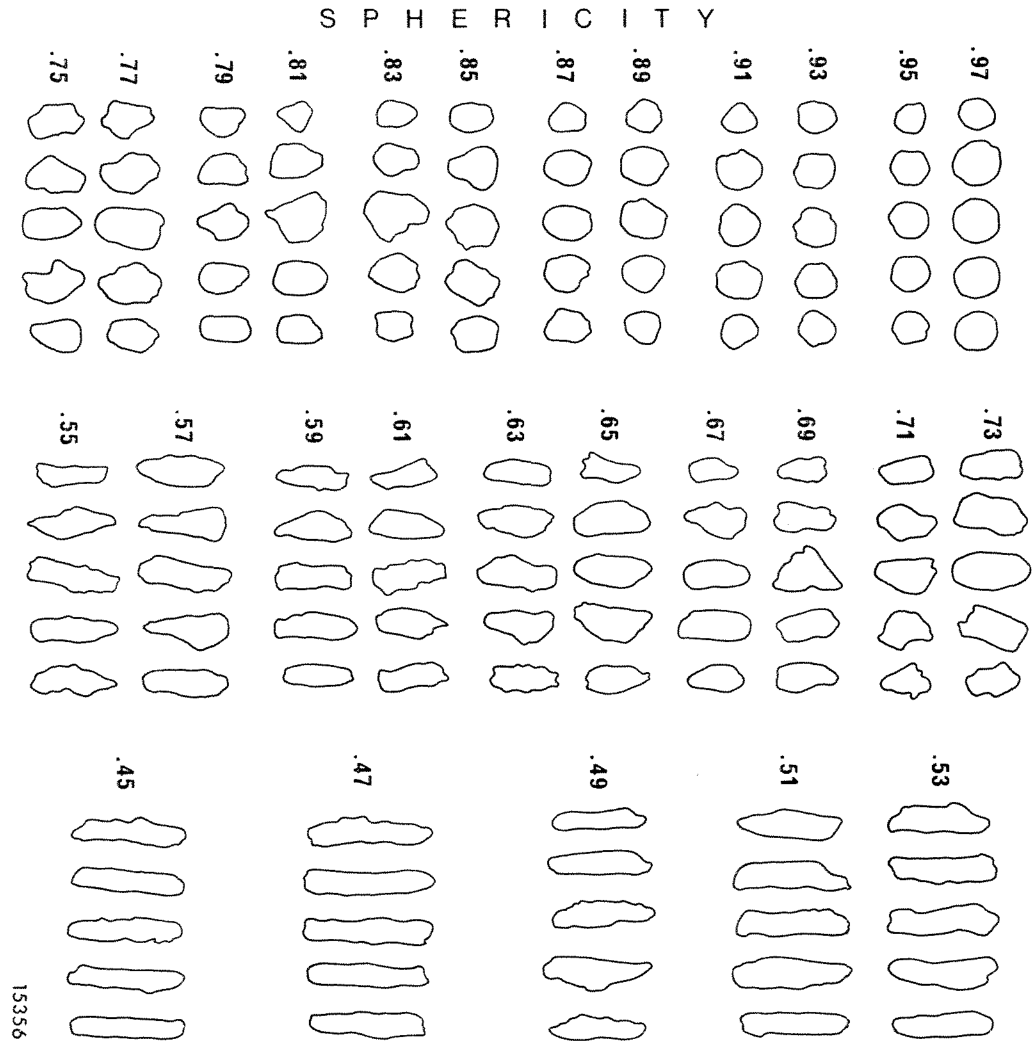

Figure 23. Visual comparator for estimating two-dimensional sphericity of sand grains. (after Rittenhouse, 1943)

Grain counts of mineral species can be converted to weight per cent by using either the specific gravities or the weight per grain of the minerals present. The calculation is:

$$(\text{weight per cent})_n = \frac{F_n\, d_n}{\sum_{i=1}^{n} (F_i\, d_i)}$$

where F is the frequency of occurrence of the grain and d is the specific gravity or the weight per grain of the mineral being tested (Kellagher and Flanagan, 1956). Determinations of this type should be done on sieved samples with no more than 0·25 phi unit variation in grain size, as the diameter of particles has a significant effect on the calculated weight per cent.

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