DEPARTMENT OF NATIONAL RESOURCES

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1977/34

HEAVY-MINERAL SAND DEPOSITS ALONG THE COAST OF WESTERN AUSTRALIA

BY

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Abstract

This synthesis of available information, the third of its kind, identifies significant factors in the accumulation of mineral-sand deposits.

Provenance, coastal geomorphology, and climatic and oceanographic effects influence the location and composition of heavy-mineral sand accumulations. These parameters are shown diagrammatically on maps of the Western Australian coastline, together with the distribution, size, and mineralogy of the heavy-mineral deposits. Plans and diagrammatic cross-sections of the sequences containing the main deposits are also presented.

The two most important factors which governed the creation and preservation of heavy-mineral deposits in Western Australia were: (1) the presence of Mesozoic sandstones containing heavy minerals, and (2) sea level change, which resulted in progradation of the coastline from the late Tertiary to the present.

Coastal outline, wave characteristics, and longshore drift have also influenced the concentration of heavy minerals.

1. INTRODUCTION

This report is a synthesis of information available in published and unpublished literature on heavy-mineral sand deposits along the Western Australia coastline. It is similar to earlier reports on the heavy-mineral deposits of eastern and southern Australia (Gardiner, 1975, 1976). The aim of the synthesis is to determine if any factors are clearly more important than others in the accumulation of heavy-mineral sands.

The report is accompanied by a series of maps which show the locations of known heavy-mineral deposits, together with factors commonly held to be important in the genesis of these deposits, namely geological provenance, climate, oceanography, and coastal geomorphology.

1.1 Acknowledgements

I wish to thank Mr J. Baxter, Geological Survey of Western Australia, for making available his bibliography on heavy minerals in Western Australia, and Mr J. Sofoulis, Westralian Sands Pty Ltd, for providing information on the heavy-mineral deposits at Geographe Bay and along the Gingin Scarp.

2. THE OCCURRENCE OF HEAVY-MINERALS

The economic heavy-mineral deposits in Western Australia are in the southwest of the state, in the Geographe Bay and Gingin Scarp areas (Fig. 1B). Uneconomic deposits have been reported in the northwestern part of the state, north of Broome (Fig. 1A), and along the southern coastline east of Cape Leeuwin (Fig. 1B).

In the following description of the distribution, size, and type of heavy-mineral deposits on the Western Australian coast, production figures compiled by the Western Australian Department of Mines, and company estimates of reserves have been used (Table 1). Table 2 lists demonstrated reserve figures that have been obtained from company annual reports and from descriptions of the deposits by the authors cited. Table 3 lists the heavy-mineral assemblages at the various deposits.

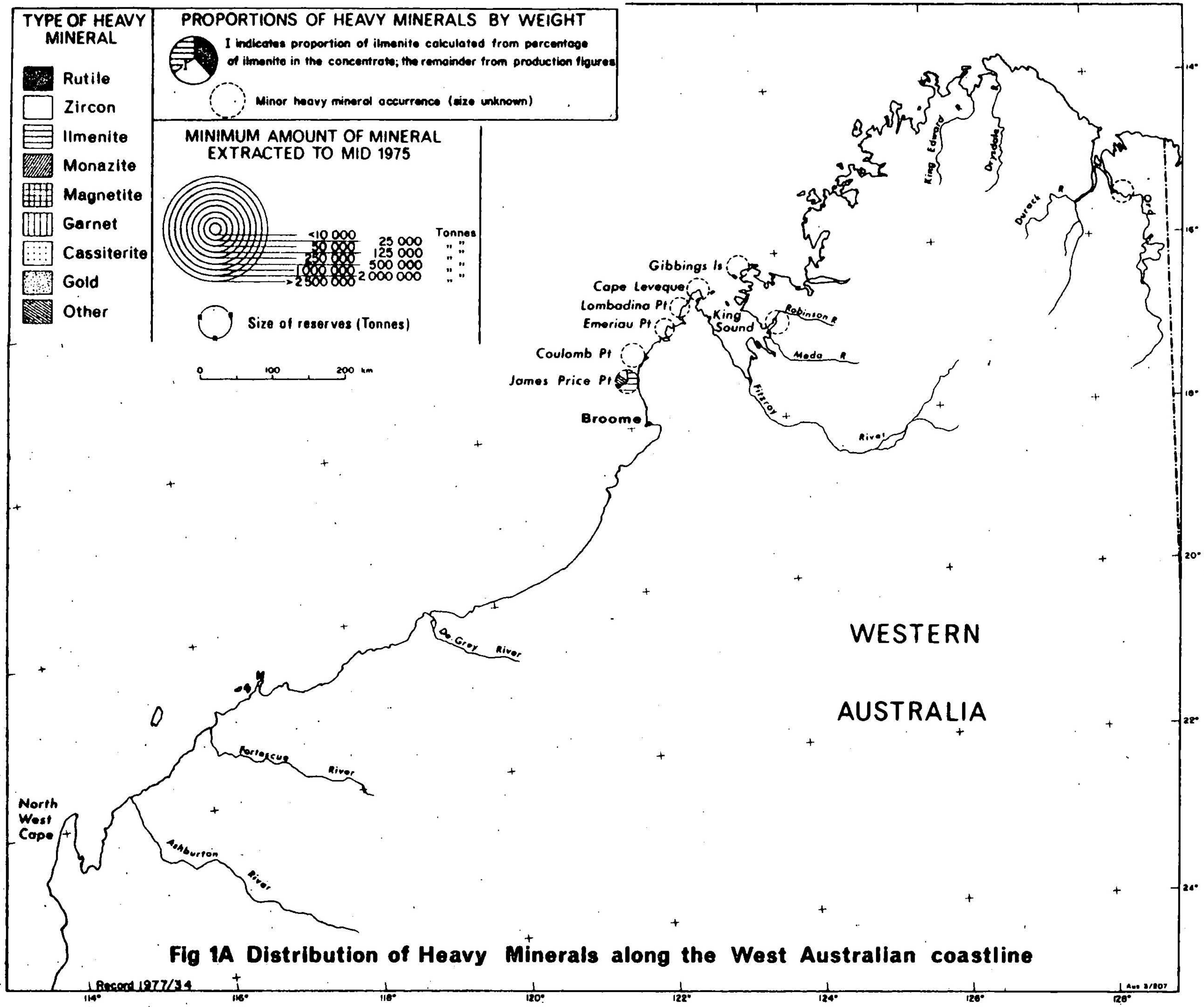

Fig 1A Distribution of Heavy Minerals along the West Australian coastline

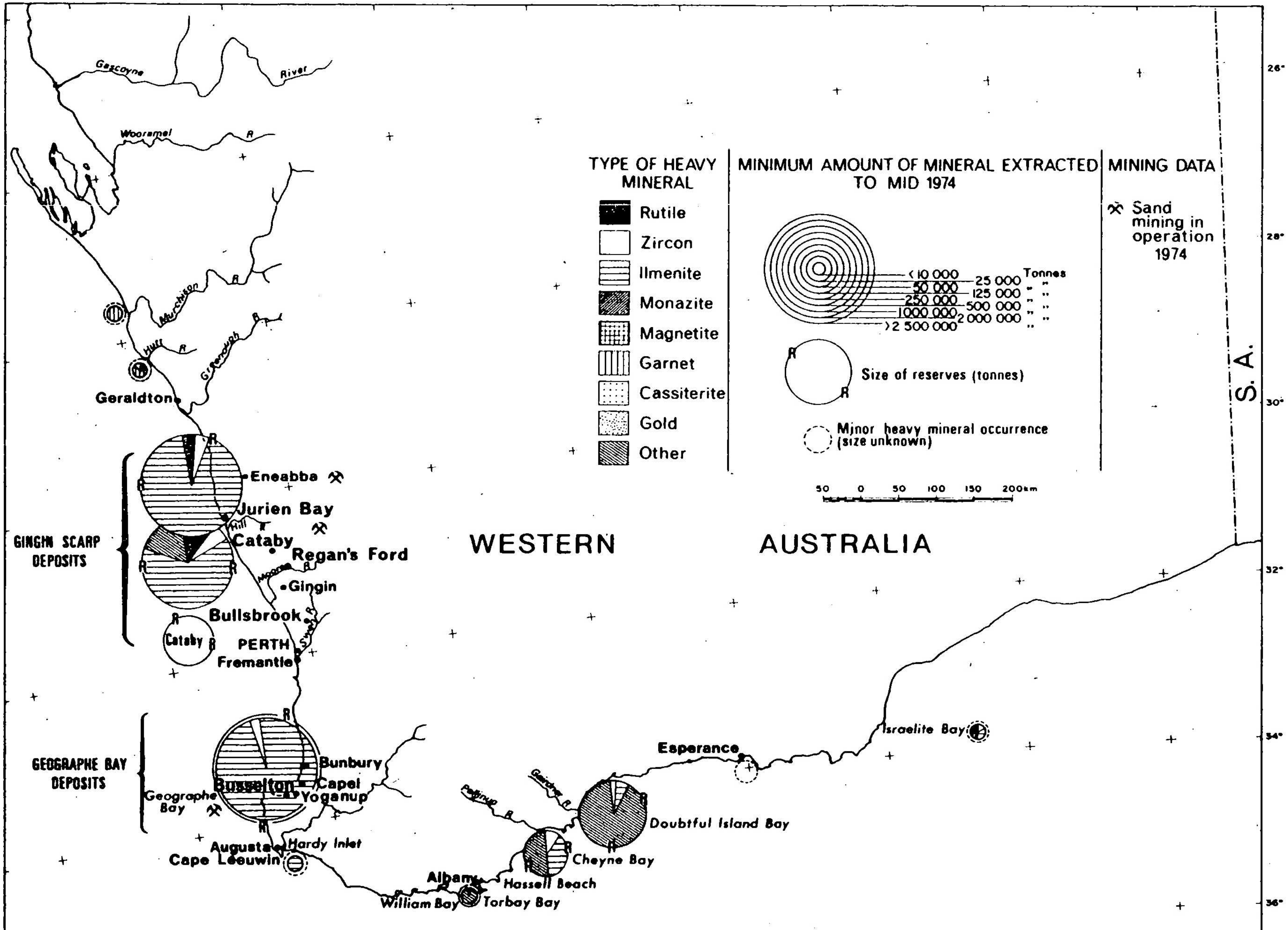

Fig 1B Distribution of heavy mineral deposits along the Western Australian coastline

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112° 114° 116° 118° 120° 122° 124° 126° 128°

Calculation of the ore reserves published in company reports is based on various cut-off grades. In areas such as Eneabba, cut-off grades depend on the depth and degree of ferruginisation within the deposit. Problems associated with the use of such figures, particularly the loss of information when combining production figures, are outlined in Gardiner (1975).

2.1 Northwestern Coast

There are no economic heavy-mineral deposits along the northwest coast of Western Australia, but a few small concentrations have been noted between James Price Point and Coulomb Point (Brunnschweiler, 1957), on Gibbings Island (Farrand, 1965), and in the Robinson and Ord River estuaries (Fig. 1A).

2.1.1 Deposits between James Price Point and Coulomb Point

The significance of these deposits has not been assessed, but clearly no-one has considered them to be economic. The deposits are reported to be beach washings extending to a depth of 0.3 m (Farrand, 1965) and consisting predominantly of ilmenite and magnetite (Table 3) (Wilkins, 1953; Brunnschweiler, 1957).

2.1.2 Gibbings Island

Like the James Price Point and Coulomb Point deposits, the Gibbings Island deposit is made up of beach surface washings and lenses of concentrate within the beach. The concentrate is composed of ilmenite, rutile, hematite, magnetite, zircon, and riebeckite, and Farrand (1965) suggested that further investigation of the composition and extent of the beach sands would be justified.

2.1.3 Ord and Robinson River

The deposits occur only as thin veneers of black sand at low tide (Gellatly & Sofoulis, 1973) and have formed from the interaction of tidal currents. They are similar to those described by Connah (1961) at Weipa, on Cape York Peninsula. Their composition is unknown.

2.1.4 Cape Leveque, Lombadina Point, Emeriau Point

At these locations the heavy minerals are distributed throughout quartz sand dunes. They occur as disseminated grains, not as seams, and are mainly opaques, zircon, rutile, and tourmaline (Farrand, 1965).

2.2 Gingin Scarp

2.2.1 Eneabba

Prospectors first became interested in the Eneabba area (Fig. 1B) in the late 1960s. Local farmers pegged a number of claims, which were bought by several of the major sand mining companies such as Western Titanium, Allied Minerals, A.V. Jennings, Ilmenite Pty Ltd, and West Coast Rutile. The late discovery of the district was due to both the unusual location of the deposit (30 km inland from the coastline and 240 km north of Perth) and the fact that Western Australia had been regarded as an ilmenite provenance; ilmenite, being a low-priced product, was never tested for in areas which were more than 60 km away from a port (Ward, 1972), and therefore the Eneabba area was not examined. The importance of this new find was in its composition (Table 3), rutile making up between 5 and 10 percent of the concentrate and zircon between 15 and 35 percent (Lissiman & Oxenford, 1973). Both heavy minerals are high-priced products, with rutile selling for $A220-230/tonne at the end of May 1977.

In contrast with other Australian heavy-mineral deposits, the deposits at Eneabba are found in a coastal sequence dating back to the early Pleistocene or Tertiary (Lowry, 1974). The heavy minerals occur in a series of strandlines and associated dunal deposits at heights ranging from 85 m to 170 m above present sea level (Lissiman & Oxenford, 1973; Baxter, 1972). The exact size of the Eneabba heavy-mineral deposit is unknown but conservative estimates by several companies consider that the whole deposit contains 25-30 million tonnes of recoverable heavy minerals (Table 2). Since the discovery of the deposit at Eneabba, exploration along the Gingin Scarp (Fig. 1B) between Perth and Geraldton, has revealed similar deposits at Jurien Bay, Gingin, Bullsbrook, Regans Ford, and Cataby.

The proportion of heavy minerals in the beach and associated aeolian sands varies between 2 and 25 percent, with higher grades in the bedded, well-sorted, water-laid material and lower grades in the upper (aeolian) portion of the deposit (Lissiman & Oxenford, 1973). A detailed investigation of the mineralogy of the Eneabba deposits by Lissiman & Oxenford (1973) revealed that the composition of the heavy-mineral fraction varied between strandlines: older strandlines are high in zircon and low in ilmenite and rutile (Table 3). Although the rutile content of the concentrate is high compared with other areas in Western Australia, it is not as high as some deposits along parts of the east coast of Australia. For example, on North Stradbroke Island rutile constitutes 18 percent of the heavy-mineral fraction and at Norries Head 37 percent of the heavy-mineral fraction (Gardiner, 1975). A fact not often mentioned is that although ilmenite forms a major proportion of the heavy-mineral concentrate at Eneabba, it has a high chrome content and may be unsuitable for use in pigment manufacture. Other heavy minerals found in the suite are kyanite, sillimanite, garnet, spinel, hornblende, pyroxene, brookite, limonite, tourmaline, and traces of staurolite.

The grades of heavy mineral at Eneabba are also influenced by the presence of coffee rock (iron-cemented quartz sand). Three types of coffee rock have been identified (Lissiman & Oxenford, 1973); however, only the honeycomb and columnar types are important for it is within these types that unconsolidated heavy-mineral sand is found. The origin of the coffee rock and its association with the heavy minerals is unknown, but it is believed to be related to past and present water-tables (Baxter, 1976). Similar deposits have been noted in the Geographe Bay area (Welch, 1964).

2.2.2 Jurien Bay

The Jurien Bay heavy-mineral deposit is about 70 km southwest of Eneabba (Fig. 1B). Little information has been published on this area, as companies have only been interested in the region since the early 1970s. The deposit is reported to contain 3.44 million tonnes of heavy mineral. The reserves are subdivided into proved ore reserves - 1.6 million tonnes; probable ore reserves - 0.7 million tonnes; and possible reserves - 1.14 million tonnes (Australian Financial Review 16.7.74). The composition of the heavy-mineral fraction is very similar to that at Eneabba, rutile being a major constituent (Table 3).

2.2.3 Cataby

Alliance Oil and Metals Exploration have recently found this deposit 80 km south of Jurien Bay. Limited drilling has outlined 700 000 tonnes of heavy minerals in two buried strandlines over 11 kilometres longg(The West Australian 8.7.76).

2.2.4 Regans Ford, Gingin, Bullsbrook

These recently discovered deposits abut the Gingin Scarp and are similar in mineralogy and location to the Eneabba, Jurien Bay, and Cataby deposits. They occur in strandlines ranging from 27 m above sea level at Bullsbrook to 86 m at Regans Ford. As in the case of the Jurien Bay and Cataby deposits, little information has been published on these areas.

2.3 Hutt River-Port Gregory, Murchison River

This deposit, unlike the deposits along the Gingin scarp, is located at Port Gregory near the mouth of Hutt River and along the present beach. Garnet is the principal heavy mineral, but the deposit also contains ilmenite, zircon, and rutile (Table 3) (The West Australian, 29.7.75). Garnetiferous sands have also been noted near the mouth of the Murchison River (J.G. Blockley, pers. comm.).

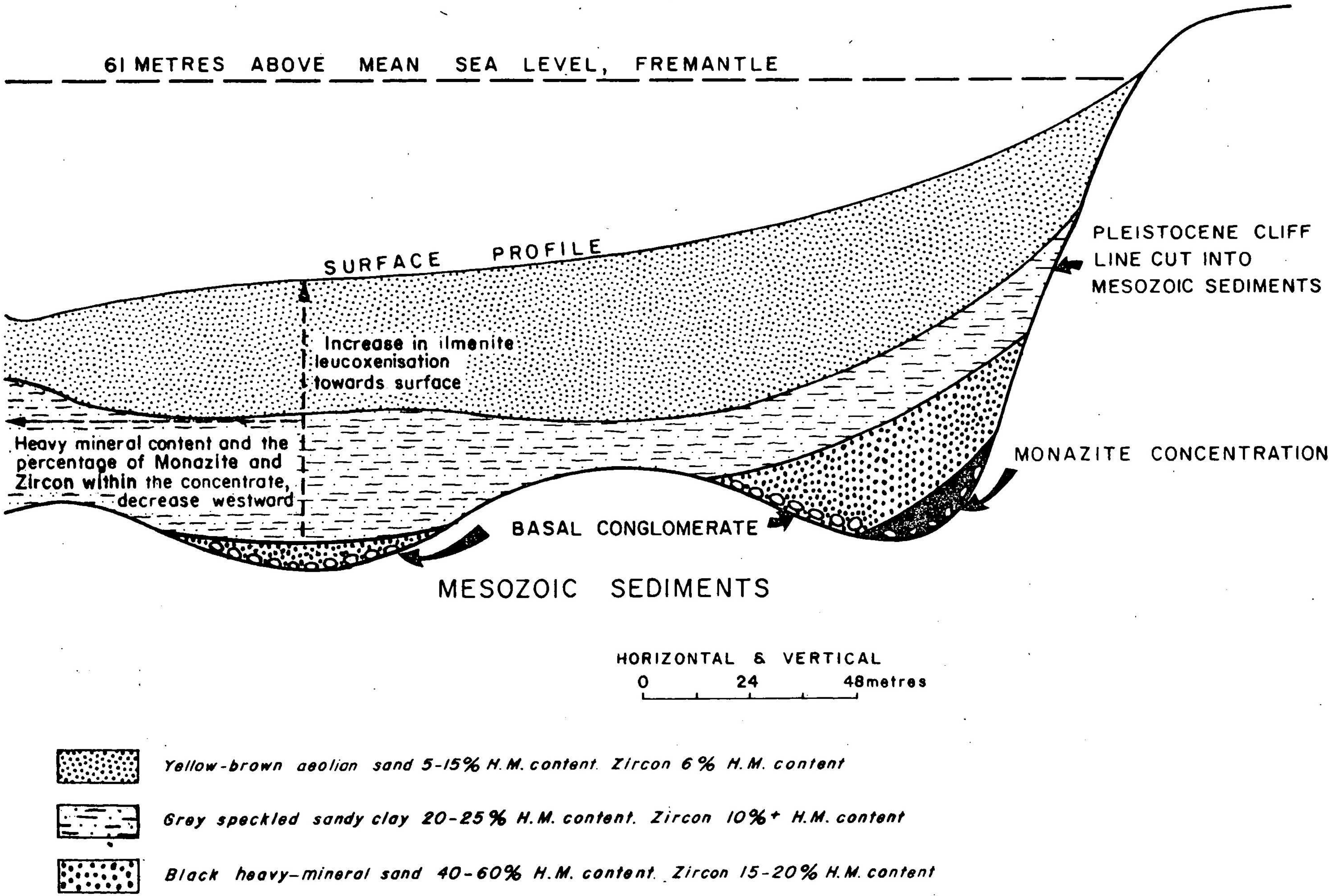

Fig 2 Diagrammatic cross section of beach ridge system at Yoganup, Western Australia (Adapted from Westralian Sands Ltd. Prospectus, 1973).

2.4 Geographe Bay

To date the Geographe Bay area has produced the greatest tonnage of heavy minerals in Australia. Deposits extend from Bunbury to Busselton (Fig. 1B), along a series of ancient shorelines, with major concentrations at Boyanup, Capel, Yoganup, Ludlow, and Wonnerup (Fig. 8B). Five companies namely Western Titanium NL, Westralian Oil Pty Ltd, (now Westralian Sands Ltd), Western Minerals Pty Ltd, Cable (1956) Ltd, and Ilmenite Pty Ltd have produced over seven million tonnes of heavy minerals in the period 1957-1974 (Table 1). Ilmenite has formed the bulk of the heavy minerals produced.

The heavy-mineral fraction in the Geographe Bay area is dominated by ilmenite; there are minor amounts of rutile and zircon (Table 3). As at Eneabba, the mineralogy of the deposits changes across the beach ridges. The most notable changes are: (1) the increase in heavy-mineral content with distance from the coast; and (2) an increase in the percentage of monazite and zircon with distance from the coast (Morgan, 1964). A cross-section of an ancient beach ridge system at Yoganup (at Yoganup (Fig. 2) shows this change in heavy-mineral content within the deposit.

Heavy minerals constitute up to 60 percent of the sand at Geographe Bay, but the grade depends on the origin of the sand deposits. As at Eneabba, the highest grades of heavy minerals are found in water-laid deposits and the lower in aeolian deposits (Fig. 2). Higher grades are also associated with coffee rock (Welch, 1964).

Other characteristics of the heavy minerals at Geographe Bay, are: (1) low chromic oxide content of the ilmenite (McMath, 1950b), and (2) abundance of clay, associated with the highest grades of heavy-mineral deposits (Welch, et al., 1976).

2.5 Southern Coast

Since the 1940s scattered heavy-mineral deposits have been noted along the southern coast of Western Australia (McMath, 1950a, 1951; Low, 1957). In recent years interest has been renewed in the deposits, particularly those at Agusta, Doubtful Island Bay, and Israelite Bay (Fig. 1B) However, the deposits are too far from ports to make their mining profitable at the present time.

2.5.1 Augusta Area

Around Augusta, heavy mineral deposits occur in the Warren and Milyeaanup fossil shorelines (Fig. 3), modern dune sands, and the channels of the Blackwood and Scott Rivers (Hodgkin, in preparation). Ilmenite is the major heavy mineral, but minor amounts of zircon, rutile, and monazite are present. The total reserves in the area are unknown.

2.5.2 Williams Bay to Doubtful Island Bay

This section of coastline contains seven beaches on which heavy minerals have been reported (Fig. 1B). During winter storms the beaches are eroded and some of the heavy-mineral deposits are destroyed (McMath, 1950a). Cheyne Bay and the coast of Doubtful Island Bay (between Doubtful Island and the Gairdner River) appear to be the only too areas containing substantial heavy-mineral deposits (Table 2). At Cheyne Bay ilmenite commonly constitutes about 40 percent of the heavy-mineral fraction. Like the ilmenite at Geographe Bay, that along the south coast is practically chrome-free (Low, 1957). Apart from the ilmenite, the concentrate is composed of up to 1 percent monazite, 3-12 percent zircon, 1 percent rutile; tourmaline, epidote, cassiterite, staurolite, kyanite, garnet, zoisite, corundum, and spinel make up the remaining 38 percent (McMath, 1950a, McMath & de la Hunty, 1951a, b; Low, 1957; Overstreet, 1967).

2.5.3 Israelite Bay

Several companies have been interested in the deposits at Israelite Bay because they have a high content of leucoxene in the concentrate. Zircon and ilmenite are also present (Table 3). Estimated reserve figures have not been published for this area, but Lowry & Doepel (1974) considered the deposits uneconomic, possibly because they felt that they were too far from port facilities.

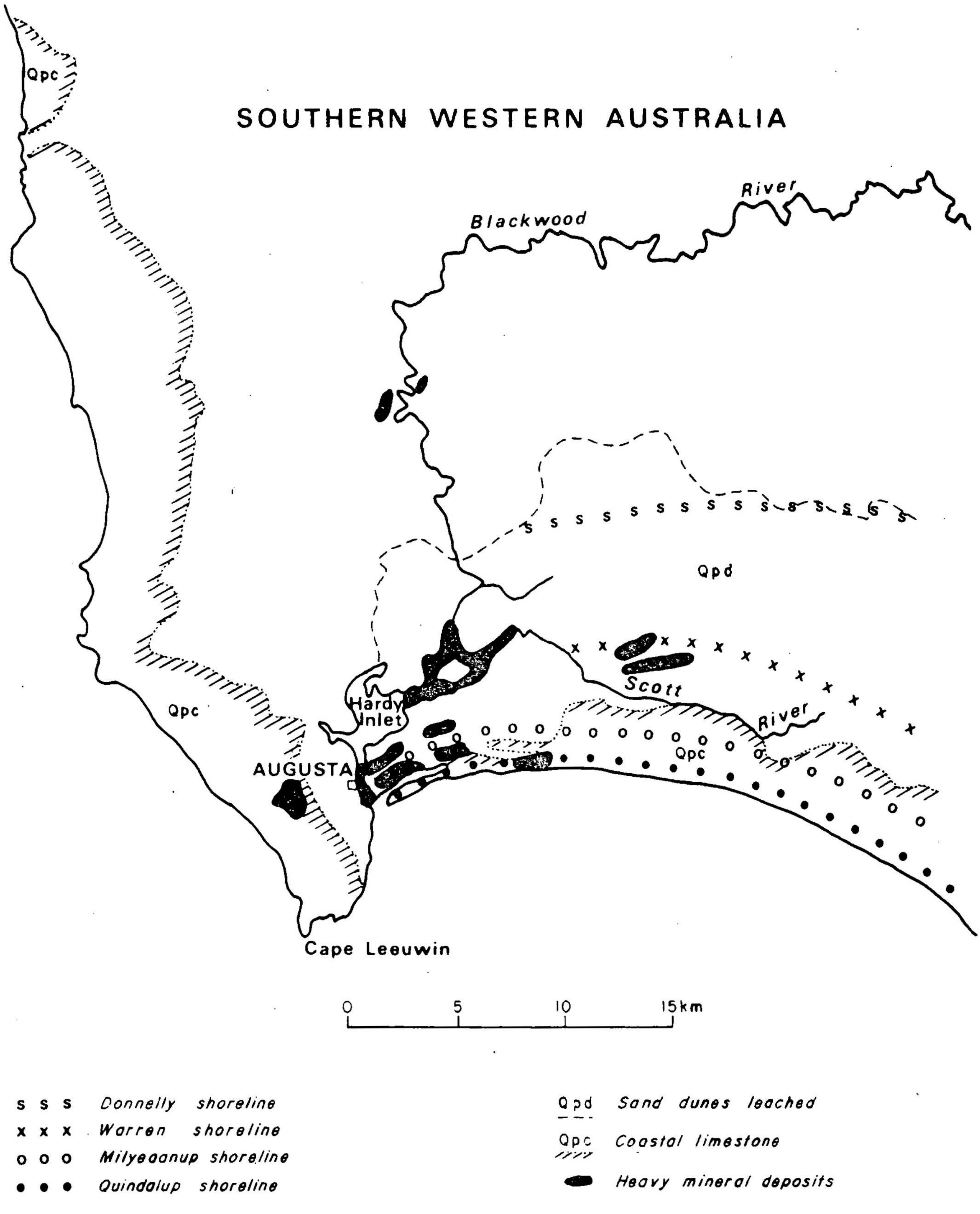

Fig 3 Location of heavy minerals in the Augusta Area
(Adapted from Hodgkin, in preparation)

3. GEOLOGICAL PROVENANCE

3.1 Introduction

Distribution of the major rock types in each drainage basin adjoining the western coast of Australia is shown on Figures 4A and 4B. Geological information was taken from the Tectonic Map of Australia (1960) and 1:250 000 Geological Series maps. Few basins consist wholly of one major rock type and it is therefore difficult to deduce the influence of each drainage basin on the detrital heavy-mineral suites.

3.2 Origin of the heavy-mineral Sands

3.2.1 Northwestern coast

Farrand (1965) is the only author to have suggested a source for the detrital heavy minerals in this area. He suggested that the deposits on Gibbings Island (Fig. 4A) resulted from the erosion of rutile-bearing schists. The origin of the heavy-mineral deposits between James Price Point and Coulomb Point is unknown, but the coastline in this area is bordered by Quaternary and Mesozoic sediments (mainly continental and marine sandstone, siltstone, etc). Elsewhere in Western Australia, Mesozoic sediments have been cited as the source of heavy minerals (Baxter, 1972; Lissiman & Oxenford, 1973). It is also possible that the heavy-mineral sands are derived from the Great Sandy Desert (Canning Basin). Analysis of desert dune sands has shown that their total heavy-mineral content, however, is less than 1 percent (Brown, 1959).

3.2.2 Gingin Scarp

Published articles have concentrated on the origin of the heavy minerals at Eneabba rather than on other deposits along the scarp, such as Jurien Bay, Regans Ford, Gingin, and Bullsbrook. Several authors (Baxter, 1972; Lissiman & Oxenford, 1973; Lowry, 1974) have concluded that the Mesozoic sedimentary rocks are the immediate source of the heavy minerals at Eneabba. The Mesozoic sequence includes the Cockleshell Gully Formation, Yarragadee Formation, and South Perth Formation (Baxter, 1972). They are

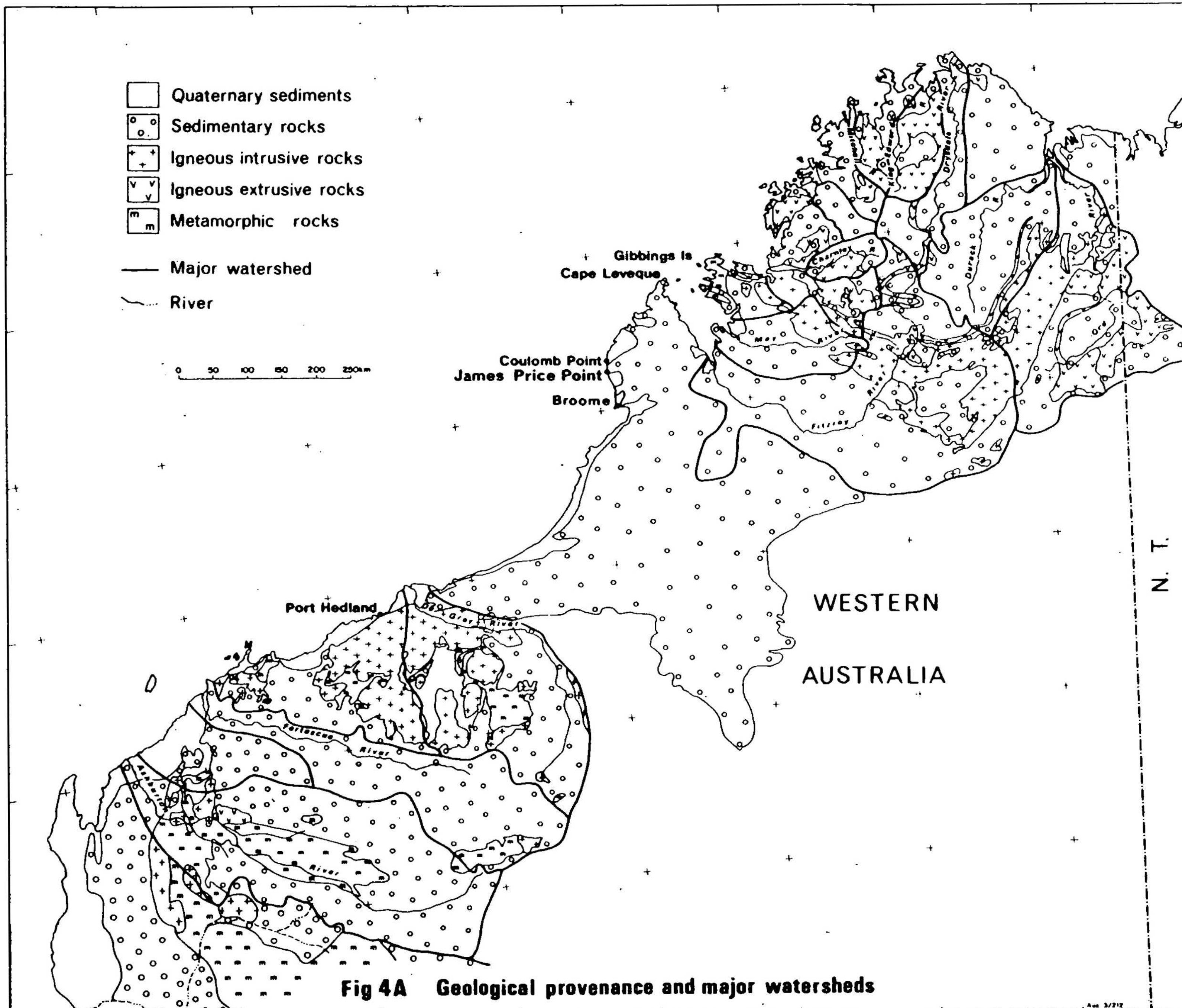

Fig 4A Geological provenance and major watersheds

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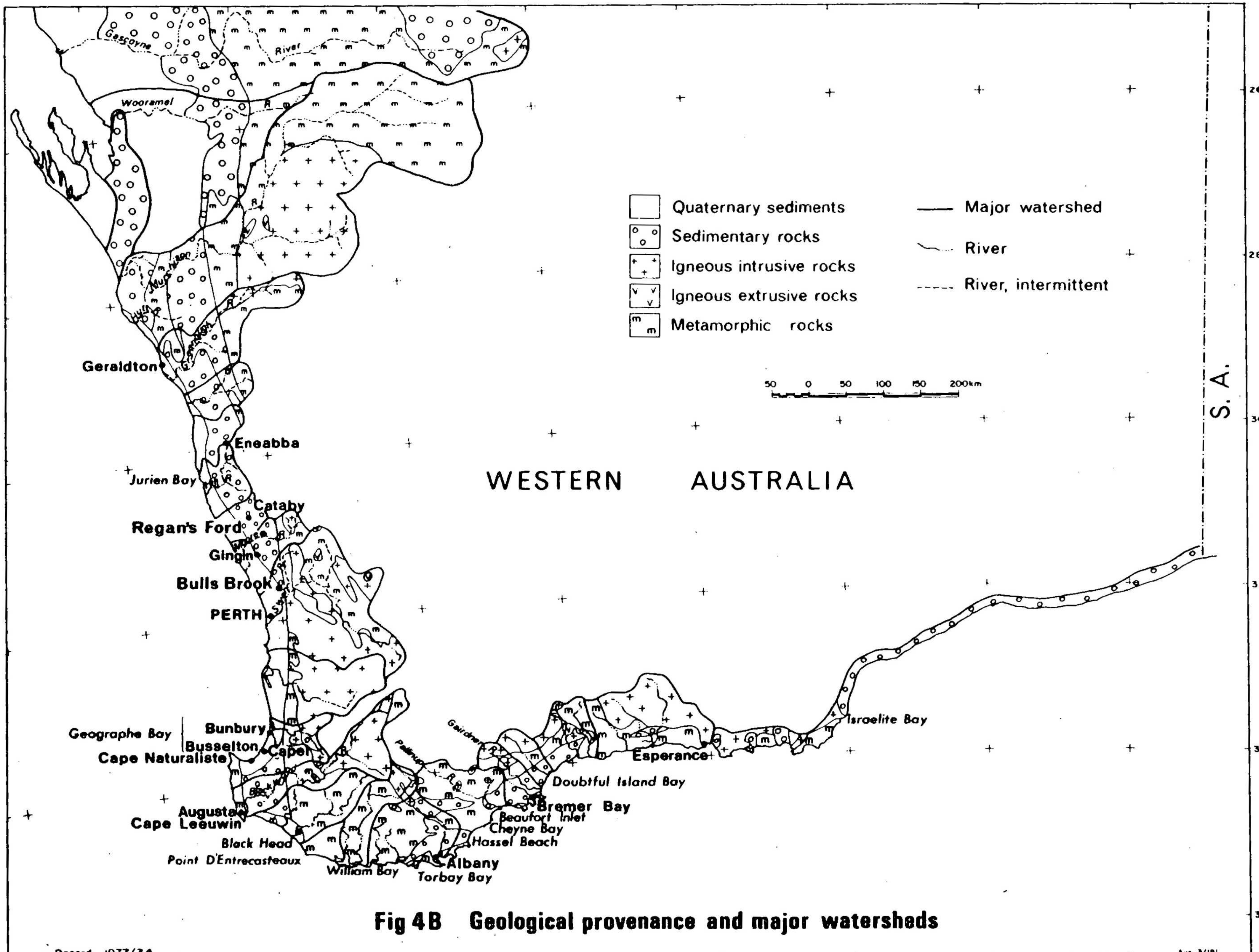

Fig 4B Geological provenance and major watersheds

composed of sandstone, siltstone, and claystone with small amounts of conglomerate, shale, and coal and all have a low heavy-mineral content. Lissiman & Oxenford (1973) have studies these formations in great detail and consider that the South Perth Formation* is the most likely source of the Eneabba heavy minerals. They have calculated that the erosion of 5 km^3 of these rocks containing 0.5% percent heavy minerals would release about 60 million tonnes of heavy minerals.

3.2.3 Geographe Bay

Carrol (1939) was the first author to suggest the probable sources of heavy minerals at Geographe Bay. She listed six possible sources, but of these, the tholeite flow underlying Bunbury, the Permian sandstones near the Darling Scarp, and Precambrian gneisses of the Cape Naturaliste area seem the most likely. Since Carrol's paper most authors have considered that the heavy minerals originated from granulites and associated granite gneisses forming the exposed portion of the Precambrian complexes in the Leeuwin-Naturaliste ridge, together with similar rocks exposed east of the Darling Fault (Welch, 1964; Overstreet, 1967; Welch and others, 1976).

The immediate source of the heavy minerals, as in the case of the deposits along the Gingin scarp, is thought to be the Mesozoic sediments west of the Darling Fault (Welch and others 1976). Although there is little surface outcrop of the Mesozoic sediments in the region of Geographe Bay, it has been suggested (Cope, 1972) that the greatest thicknesses of Mesozoic sediments were formerly deposited in the Geographe Bay area.

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* The South Perth Formation consists of interbedded very fine to very coarse sandstone, shale and siltstone with minor conglomerate. It is considered to have formed mainly in a continental environment, but contains minor intercalations of marine and paralic sediments (Baxter, 1972, p. 61).

Wise (1972) studying present-day accumulation along Minninup Beach at Geographe Bay (Fig. 11), concluded that ilmenite, zircon, and monazite come directly from the Precambrian shield via the now abandoned Minninup River, and from reworking of sediments on the Swan Coastal Plain. Garnet and hornblende, he stated, came directly from the Leeuwin-Naturaliste Block via littoral drift.

3.2.4 Southern Coast

Granite/gneiss complexes and metamorphosed sediments are cited as the source of the ilmenite-rich heavy-mineral deposits along the southern coast from Point D'Entrecasteaux to Doubtful Island Bay (McMath, 1950a; McMath & de la Hunty, 1951b; Low, 1957). It is thought that the heavy minerals are currently being brought to the coast by rivers draining metamorphic and granitic country, such as the Gairdner River entering Doubtful Island Bay (McMath & de la Hunty, 1951b), and the Pallinup River which enters the sea near Beaufort Inlet (Low, 1957). Augen gneiss crops out to the east of Israelite Bay, where concentrations of ilmenite and leucoxene are found (Lowry & Doepel, 1974). The gneiss, like the gneiss to the west, is probably the source of the heavy minerals. The predominance of ilmenite in deposits at Augusta, Hardy Inlet, and Scott River (Fig. 3) suggests that the heavy mineral originated, like the Geographe Bay deposits, from the erosion of Mesozoic sediments which filled the Bunbury Trough.

In the Esperance area, the very small uneconomic concentrations of heavy mineral are low in ilmenite (Morgan & Peers, 1973). This is difficult to explain, as migmatite, a source of ilmenite, is common in the area.

4. CLIMATIC AND OCEANOGRAPHIC DATA

4.1 Introduction

Published articles provide the main source of information for the maps of climatic and oceanographic factors (Figs. 5A, 5B). Climatic data (rainfall and wind) are from the Commonwealth Bureau of Census and Statistics (1972) and de la Hunty & Low (1958). Tidal data were adapted from Easton (1970), and wave height analysis was taken directly from a world wide study

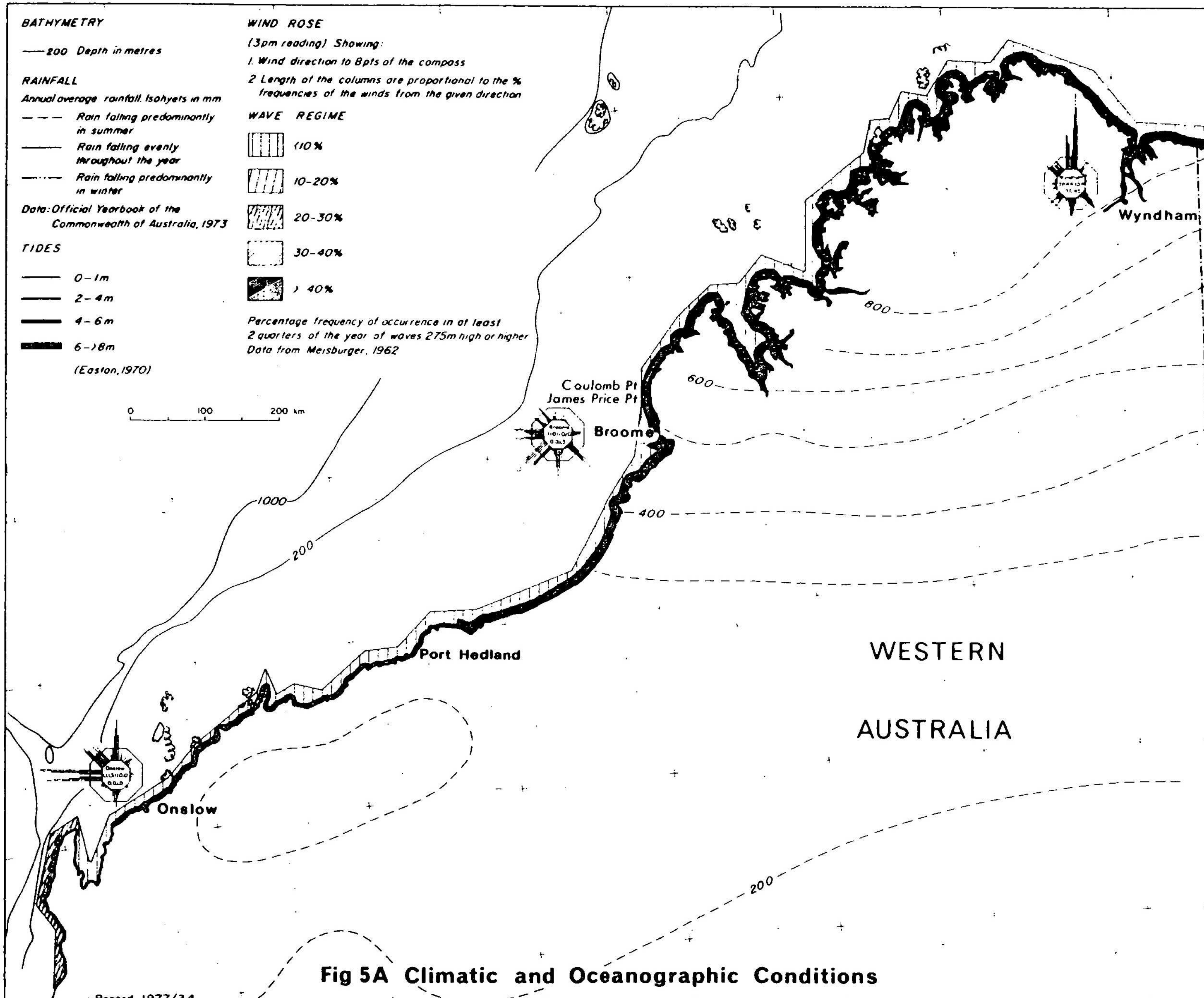

Fig 5A Climatic and Oceanographic Conditions

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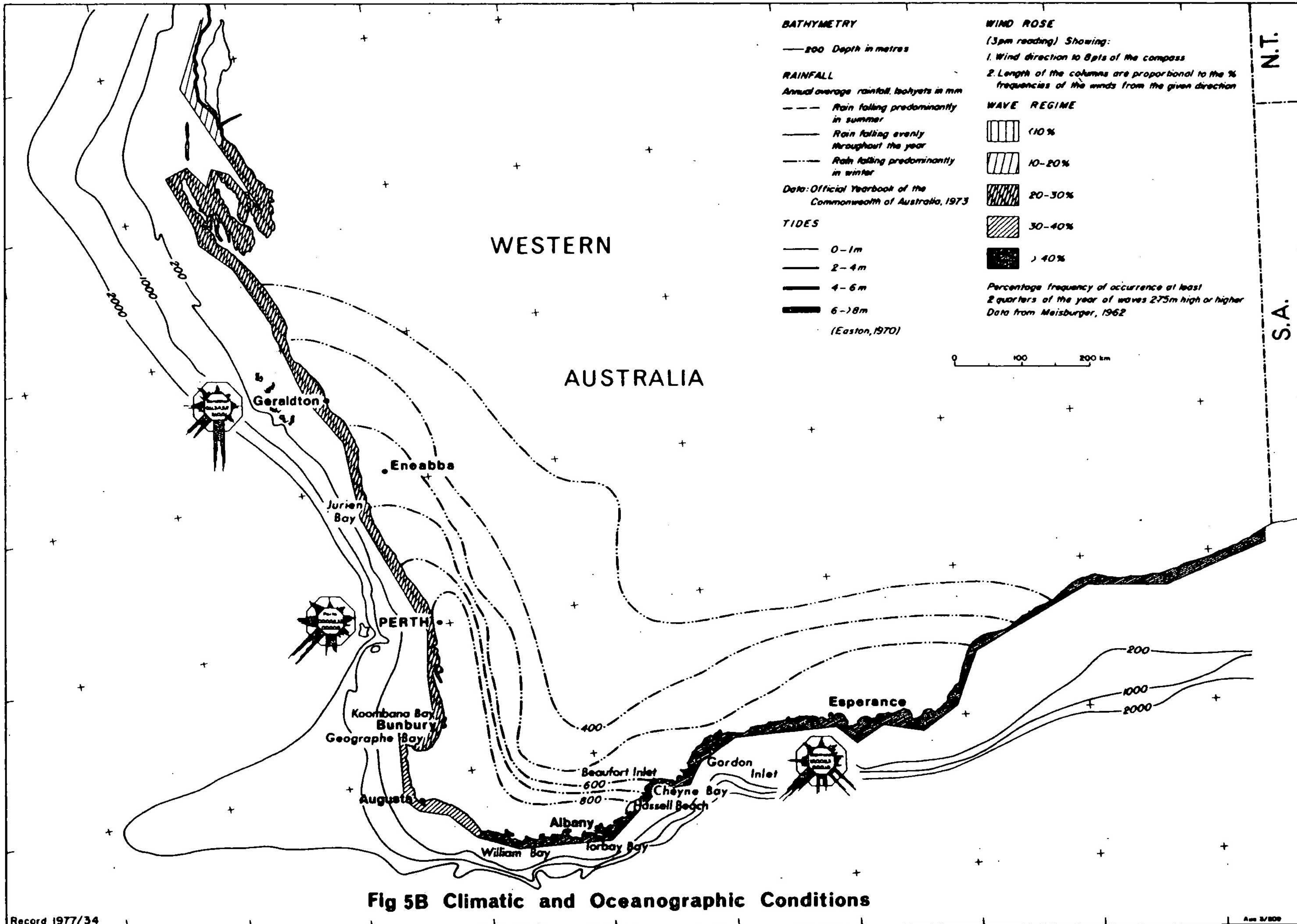

Fig 5B Climatic and Oceanographic Conditions by Meisburger (1962). The bathymetry is from both the Australian 1:2 500 000 and 1:250 000 Topographic Map series.

4.2 Northwestern Coast

The coastline between James Price Point and Coulomb Point is smooth, with few headlands or rivers changing its trend, and it is exposed to direct (unrefracted) wave and wind activity. For most of the year, waves reaching this part of the coast are less than 2.75 m high and are from the southwest, but between November and April cyclones - with their associated storm surges and extreme winds - are common. On the east coast of Australia, cyclonic storms have been recognised as playing a major part in the formation of heavy-mineral deposits (Harrison, 1949; Connah, 1961; Winward, 1975). Cyclonic systems increase turbulence in the surf zone and hence the quantities of sand in suspension, and produce accumulations higher on the beach than are produced under normal conditions.

It is concluded that the concentration of heavy-minerals along this section of the coast is aided by the exposed nature of the coast and cyclonic activity.

4.3 Gingin Scarp

The influence of climatic and oceanographic factors on the formation of the Eneabba heavy-mineral deposits is difficult to determine as the Eneabba deposits are over 30 km inland from the present coastline and are of early Pleistocene or late Tertiary age. However, both Lissiman & Oxenford (1973) and Baxter (1972) have postulated the oceanographic and climatic conditions at the time of heavy-mineral deposition. These authors agree that the Eneabba deposits formed in a northward-facing bay (Fig. 10), resembling the outline of Geographe Bay, and that the bay was exposed to strong southwesterly wind and wave activity. Evidence to support the theory that southwesterly winds predominated comes from the northeasterly trend of the dunal deposits. Baxter (1972) has also claimed that currents were important in aiding the deposition of heavy minerals at Eneabba. He suggested that currents diffracted by 'Rocky Spring Cape' (a northern extension of the wave-cut platform at the southern end of the bay) sorted the sediments and concentrated the heavy minerals.

Climate, particularly rainfall and temperature, has been more important in the weathering of the Eneabba deposit than in its deposition. Lissiman & Oxenford (1972) and Baxter (1972) have stated that after heavy-mineral deposition, a period of deep weathering reduced the feldspars in the beach deposits to clay and leached some of the iron from the ilmenite. Today, the area receives an average of 400 mm of rainfall per annum, but of course the rainfall may have been different in the past.

4.4 Geographe Bay

Because the strandlines which contain the heavy-mineral deposits of Geographe Bay are parallel to the present outline of the coast (Fig. 11), it is thought that oceanographic factors operating in the past were similar to those operating at present (Welch, 1964; Low, 1957). Carrol (1939), working in the vicinity of Koombana Bay (Fig. 5B), concluded that where wave action set up longshore drift, sorting of the sand occurred and heavy minerals were concentrated. She also concluded that tides had little influence on sand movement, and further more that most longshore currents were ineffective in moving sand.

At Minninup Beach (Fig. 11), Wise (1972) noted that local variations in mineralogy were due to oceanographic factors. On a very local scale, ilmenite, zircon, and monazite tended to concentrate in the highest parts of the wave-wash area of the beach, and garnet, hornblende, and kyanite in the lower parts. On a larger scale, Wise, like Carrol, noted differential sorting by waves and littoral drift. For example, with increasing distance northwards along the beach there was a decrease in mean grain size of the sand and an increase in the amount of garnet, hornblende, and kyanite. Welch (1964), like Carrol and Wise, stated that the role of longshore drift was important in heavy-mineral deposition, although on a large scale he found no significant change in the longitudinal distribution of the heavy-mineral suite.

At least some of the deposits in the Geographe Bay area were deposited within aeolian dunes formed presumably by southwesterly winds (Fig. 6). The deposit at North Capel, for example, has been attributed to aeolian processes (because of its uniform distribution of heavy-minerals) (Welch and others, 1976).

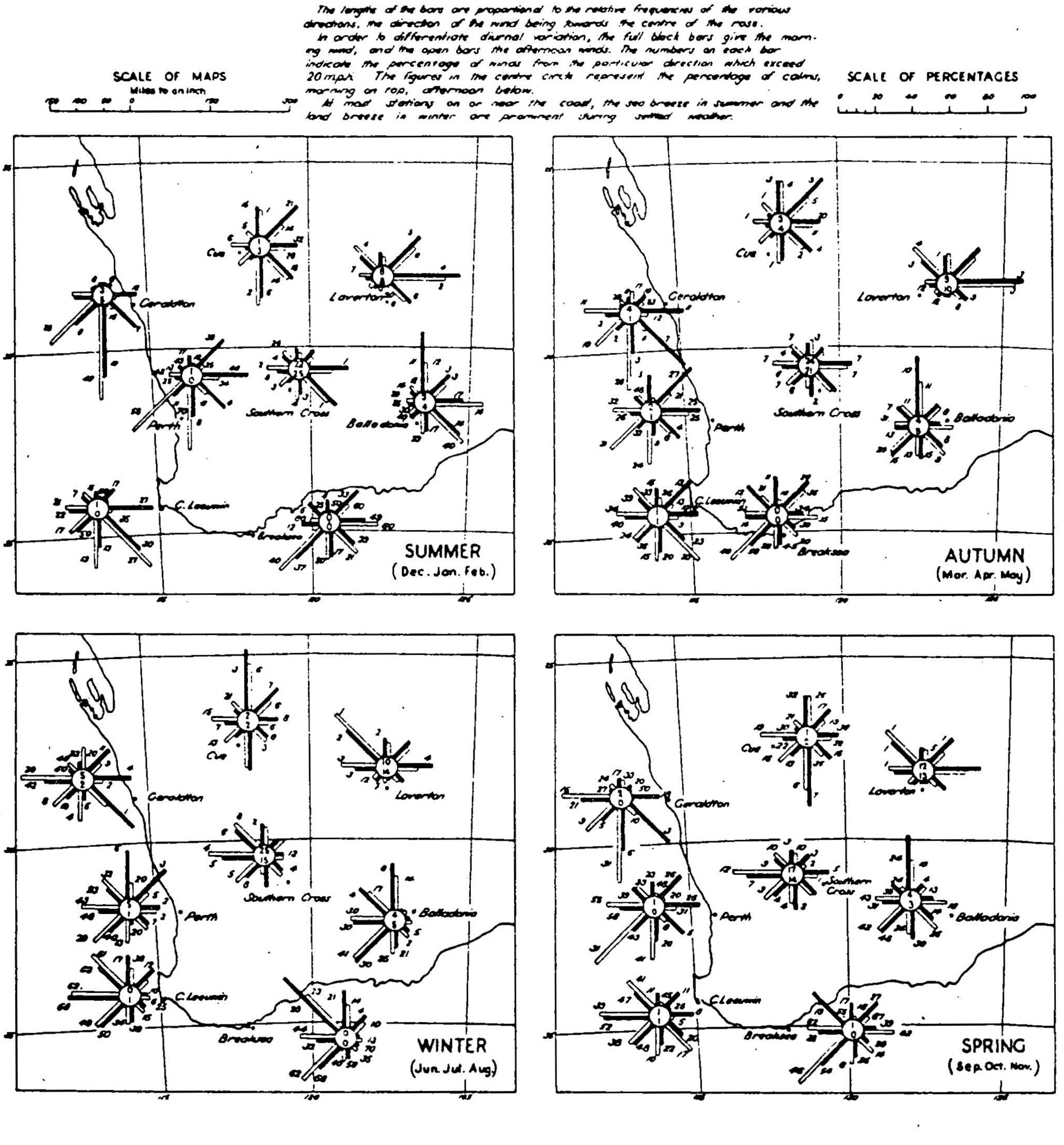

Fig 6 Seasonal and diurnal wind roses for selected southern stations in Western Australia

(From de la Hunty and Low, 1958)

As at Eneabba, rainfall has been important at Geographe Bay in the weathering of the beach deposits and in the process of lateritisation (Lowry, 1967) within the Pleistocene and Recent beach and dunal sands. The present rainfall in the area averages 800 mm/year and occurs mainly in the winter months.

4.5 Southern Coast

The southern coastline of Western Australia is exposed to a high wave energy environment (Davies, 1972), over 40 percent of all waves reaching the coast are greater than 2.75 m high. This, coupled with severe storm activity during winter, has resulted in many of the beaches being ephemeral. For example, at Beaufort Inlet, Gordon Inlet, Hassel Beach, and Port Harding (in Torbay Bay), the beaches have been reported as being severely eroded during winter (McMath & de la Hunty, 1951a and b; Low, 1957). Thus there is little opportunity for the concentration and preservation of heavy minerals. Exceptions to this occur where the coastline receives abundant sediment by longshore drift in protected east and southeast-facing bays (Morgan & Peers, 1973). On these beaches minor heavy-mineral deposits have been noted (Fig. 7).

5. COASTAL GEOMORPHOLOGY

5.1 Introduction

Figures 8A and 8B have been compiled to show the distribution of coastal landforms. Seven categories of coastal landforms have been plotted from a study of aerial photographs (RC9; 1:80 000 scale), 1:250 000 maps (geological and topographical), and references. The seven landforms used to characterise the coastal geomorphology are described in Gardiner (1975).

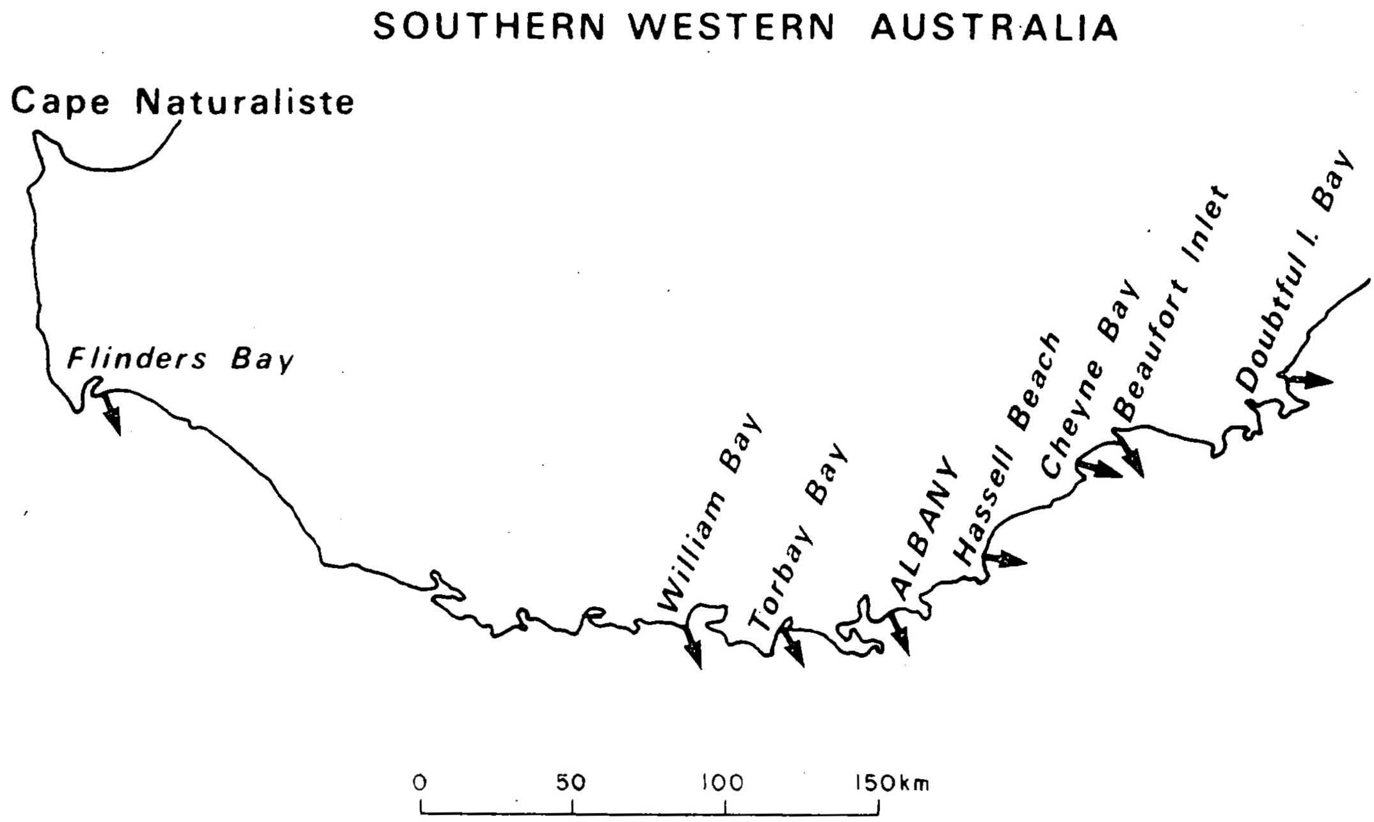

Fig 7 Orientation of beaches containing heavy minerals along the southern coast

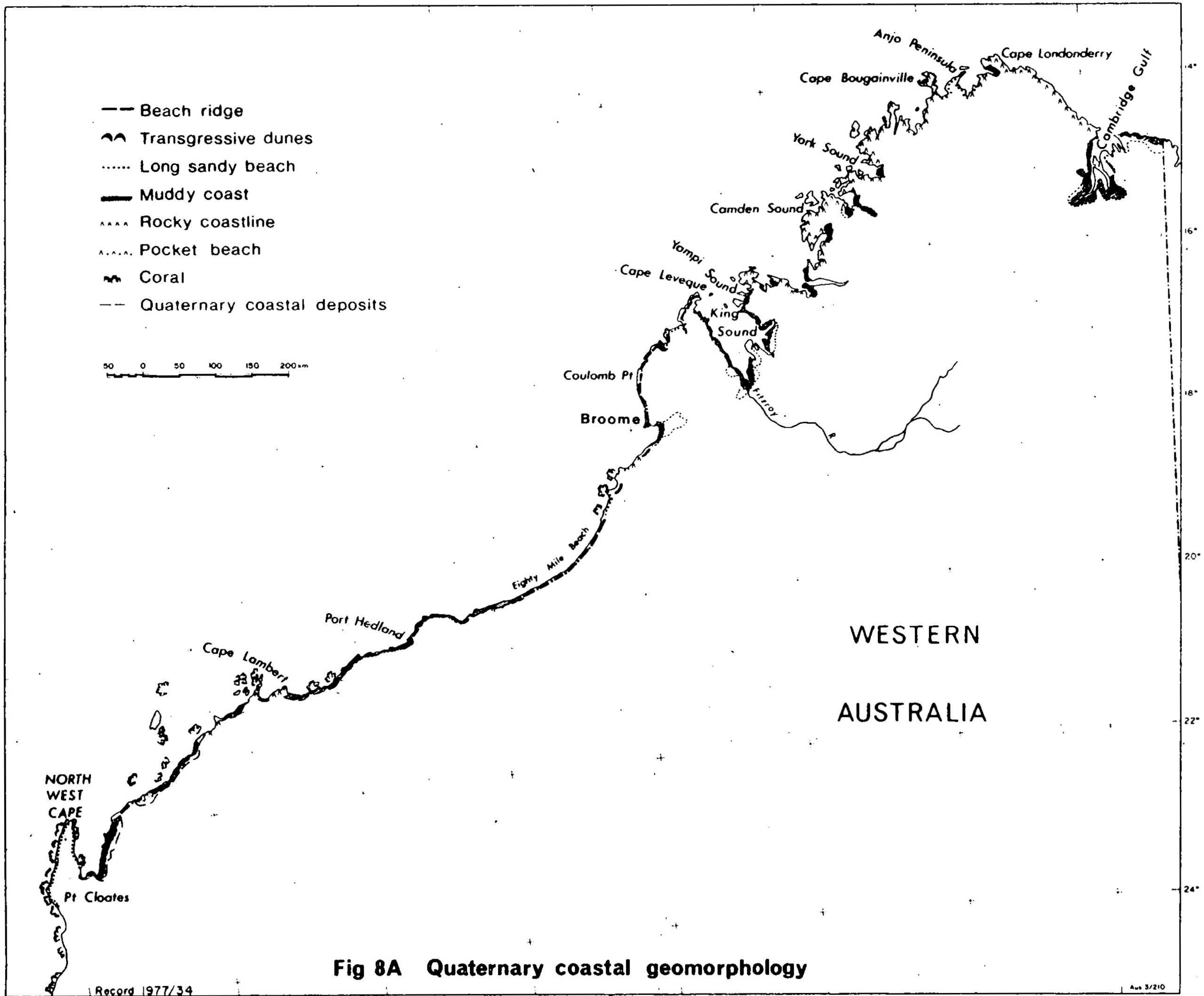

Fig 8A Quaternary coastal geomorphology

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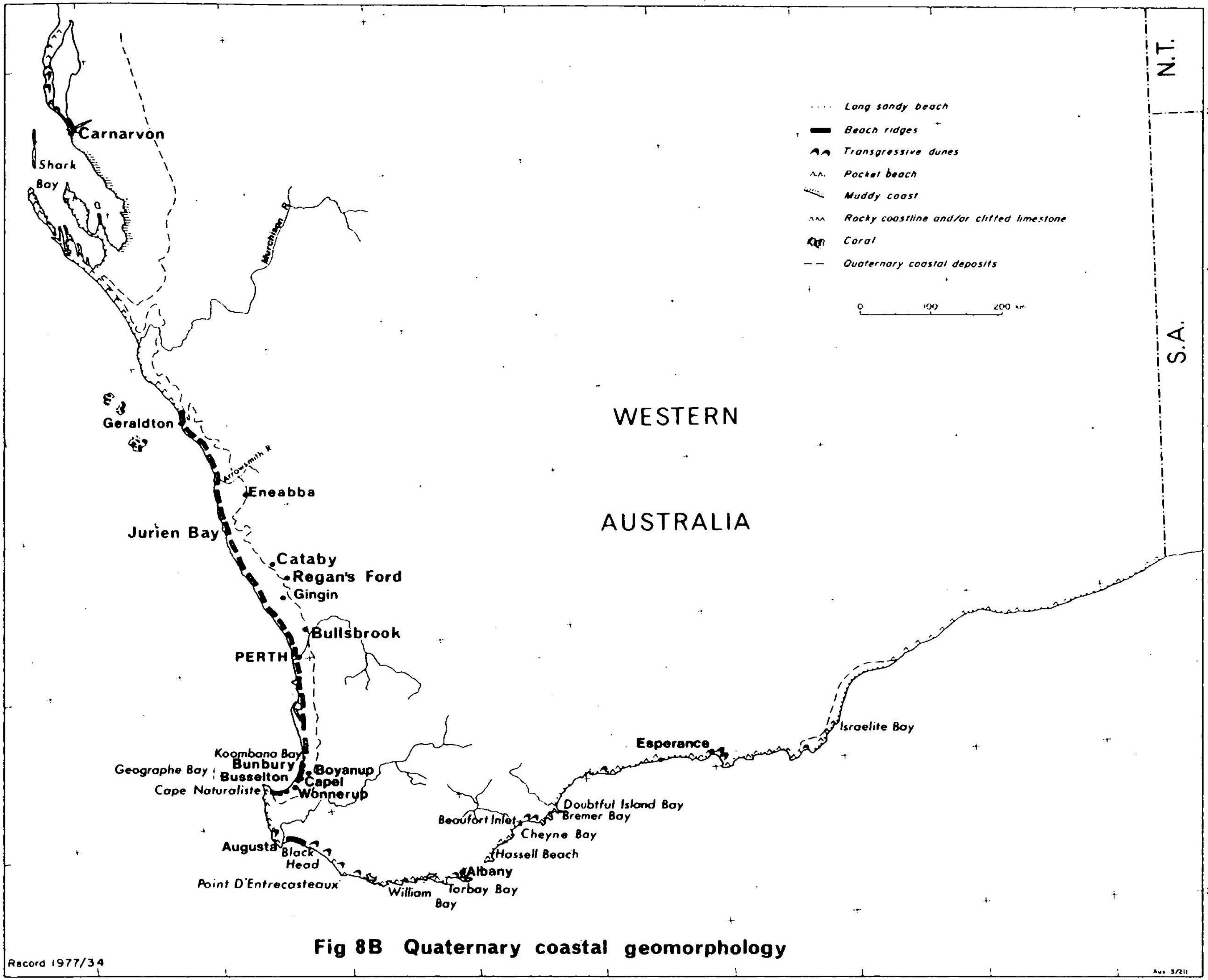

Fig 8B Quaternary coastal geomorphology

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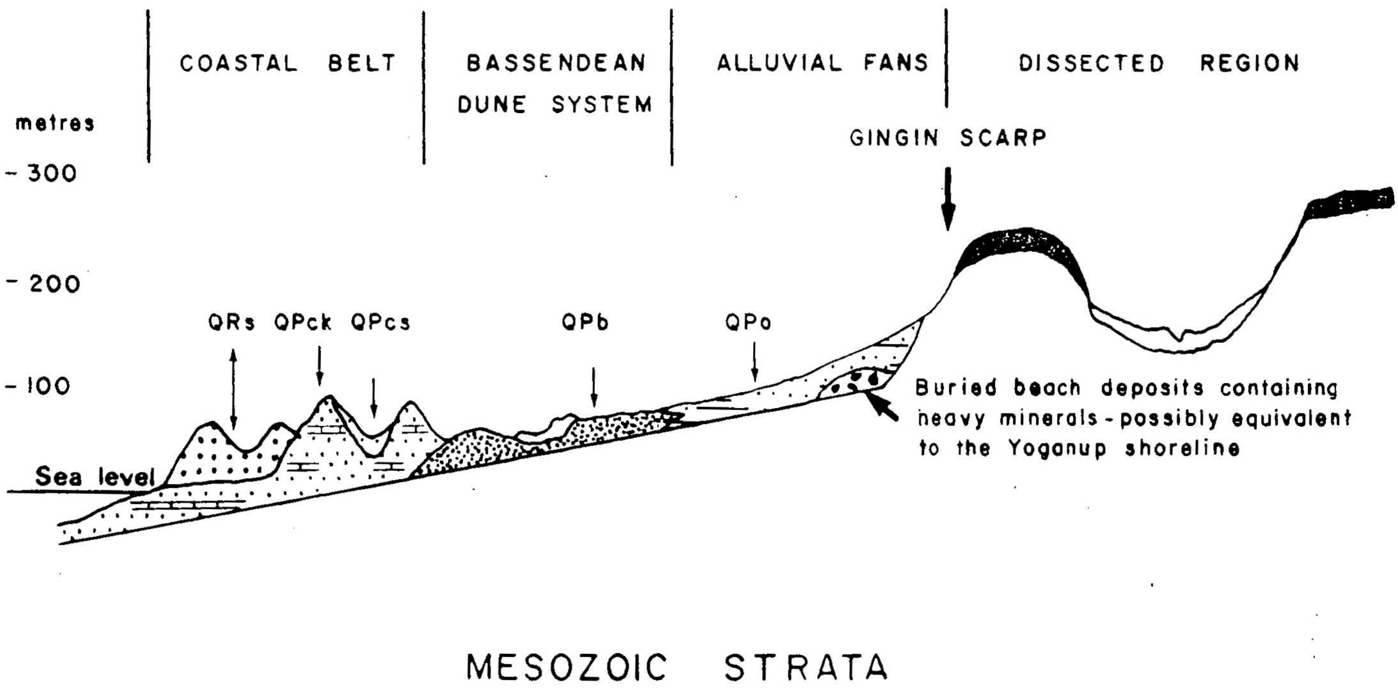
5.2 Northwestern Coast

Coastal Quaternary Sands from Cambridge Gulf to King Sound (Fig. 8A) contain only traces of heavy minerals, whereas coastal Quaternary sands from Cape Leveque to James Price Point contain discrete, though small, heavy-mineral deposits. This lack of heavy minerals along certain sections of the coast may be due to the differing nature of the coastal sands themselves. For example, along the coast from Cambridge Gulf to King Sound the sands have been shaped by the Holocene transgression. The transgression produced an indented, rocky coastline with many islands, e.g. around Yampi Sound and Cape Bougainville (Wright, 1964; Gellatly & Sofoulis, 1969), or else flooded the major river estuaries (Plumb & Perry, 1971). Aggradation followed the rise of sea level and mud flats formed in many of the bays and estuaries (Wright, 1964); in fact almost half of the coastline now consists of tidal flats. Only in places like the Fitzroy estuary, where the transgression resulted in the partial drowning of a desert dunefield, did sandspits and barrier islands develop (Jennings & Coventry, 1973). Thus the coastline is characterised by a high percentage of tidal flats, a lack of sandy deposits, and a lack of heavy-mineral deposits.

South from Cape Leveque to Port Hedland the character of the coast-line changes to one bordered by sandy beaches, beach ridge systems, and coastal aeolianites (Veevers & Wells, 1961). The change can be attributed to the the Great Sandy Desert, which backs this section of coastline for over 400 km. Quaternary eustatic sea-level changes have probably reworked the desert sands and redeposited them to form the coastal plain. The character of this section of coastline is similar to parts of the east Australian coast where heavy-mineral deposits are common.

5.3 Gingin Scarp

Unlike the coastal formations containing heavy minerals in the northwest of Western Australia, the Eneabba heavy minerals are found in a coastal sequence (Fig. 9) dating back to the early Pleistocene or Tertiary (Lowry, 1974). The youngest members of this sequence, namely the Safety Bay Sand, the coastal limestone, and the Bassendean Sand do not contain heavy minerals. The sequence which contains the heavy minerals comprises a set of



RECENT	QRs	*Unconsolidated to weakly lithified calcareous sand (Safety Bay Sand)*
PLEISTOCENE	QPck QPcs	*Calcarenite, kunkar and quartz sand (coastal limestone)*
PLEISTOCENE	QPb	*Bassendean Sand (quartz)*
PLEISTOCENE TO TERTIARY	QPo	*Colluvium, quartz sand*
		Laterite capping

Fig 9 Diagrammatic cross section of the coastal sequence at Eneabba (Adapted from Lowry, 1974)

ancient strandlines which range from 85 m to 170 m above present sea level (Lissiman & Oxenford, 1973; Baxter, 1972) and abut the old cliff-line which forms the Gingin scarp. The sequence has been correlated with the Yoganup shoreline at Geographe Bay (Baxter, 1976). Only five of these strandlines, at 91, 97, 103, 115 and 128 m, are mineral bearing. A detailed investigation by Lissiman & Oxenford (1973) has revealed a hiatus between the deposition of the 135-m and 115-m strandlines. It is postulated that during the hiatus a period of lateritisation occurred and the heavy-mineral deposits were cemented to form coffee rock. With rejuvenation following a further withdrawal of the sea, some of the coffee rock was eroded and redeposited as boulders and pebbles in the strandlines to the west.

Sea level changes at Eneabba have been important in preserving, and reworking heavy minerals between the 135-m and 115-m strandlines. However, unlike the eastern Australian heavy-mineral deposits, there has been no major reworking of the strandlines and hence there has been only one period of heavy-mineral deposition.

South of Eneabba at Regans Ford, Gingin, Jurien Bay, and Bullsbrook (Fig. 8B) the heavy minerals are also associated with shorelines well above present sea level. J. Baxter (Geological Survey of WA, pers. comm.) has recognised five shorelines, the oldest being the Eneabba, Coffee Line, Cataby, and Gingin shorelines, and the youngest, the Munbinea shoreline. Baxter correlates the oldest shorelines with the Waroona and Yoganup shorelines at Geographe Bay, and the younger Munbinea shoreline with the Capel shoreline, also at Geographe Bay.

The coastal geomorphology, particularly the actual configuration of the coast, may be of importance in heavy-mineral deposition; however, it is difficult to reconstruct the prior geomorphology of the Gingin Scarp area. Most authors have concluded that a 'zetaform bay'* (see Davies, 1972), similar to Geographe Bay, existed at 'Eneabba Bay' (Fig. 10) at the time of heavy-mineral deposition (Lissiman & Oxenford, 1973; Baxter, 1972; Lowry, 1972). At Jurien Bay, Regans Ford, Gingin, and Bullsbrook (Fig. 8B), however, deposits seem to have formed on a straight section of coastline.

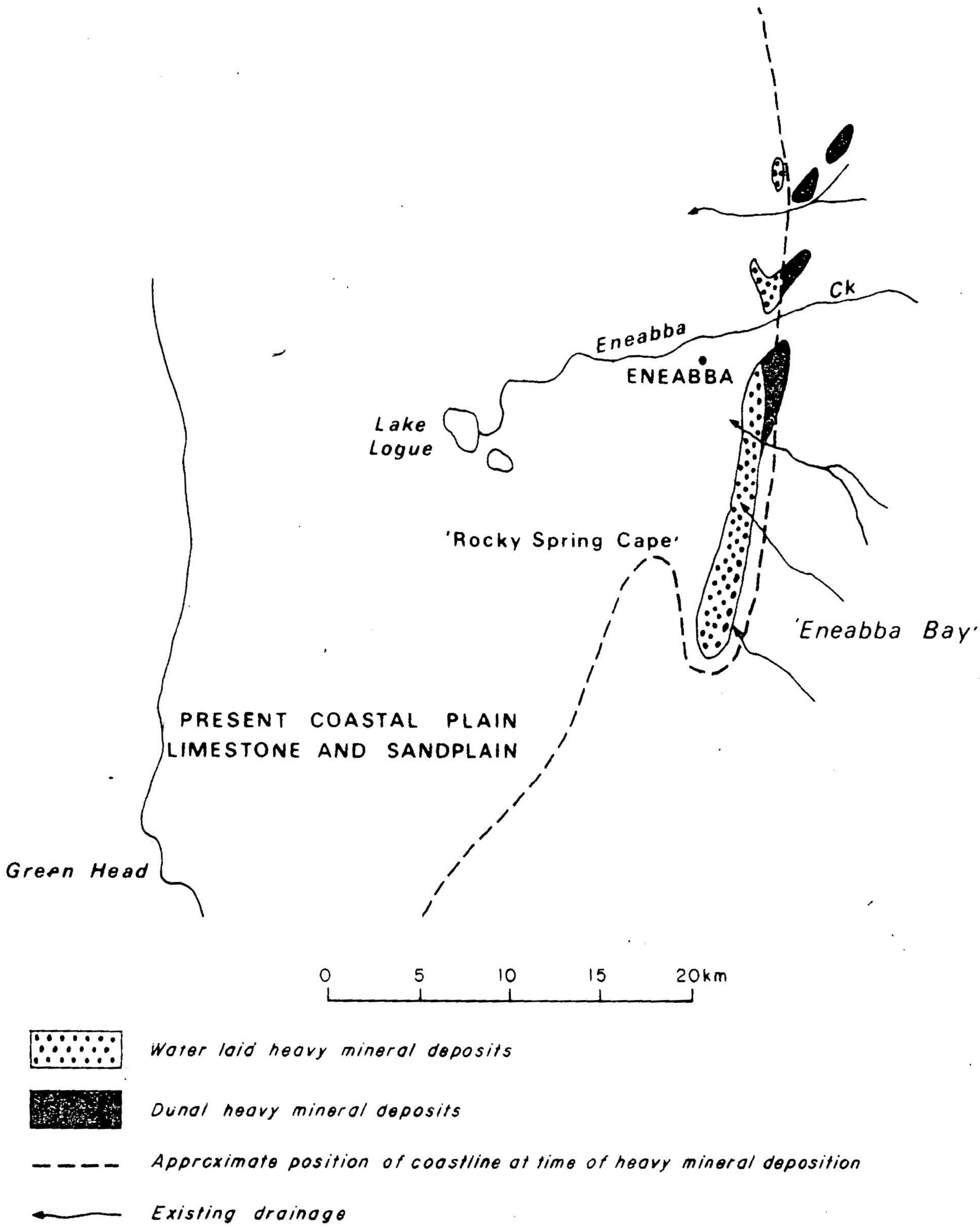


Fig 10 Coastal geomorphology at the time of heavy mineral deposition at Eneabba (Redrawn from Lissiman and Oxenford 1973)

The particular locations of the heavy-mineral deposits seems to suggest that the presence of a river on the coast is a prerequisite for heavy-mineral deposition. At Eneabba, Eneabba Creek and the Arrowsmith River are thought to have brought the heavy minerals to the coast. Further south the Moore River brought heavy minerals to the Regan's Ford area and Gingin Brook supplied material to the Gingin region. Today, many of these rivers are small and it appears that the headwaters have been captured.

5.4 Geographe Bay

Heavy-mineral deposits occur both in recent beaches and associated foredunes, and in ancient strandlines in the Geographe Bay area (Carroll, 1939; Low, 1957; Welch, 1964; Lowry, 1967). Continuous heavy-mineral deposition, from the Pleistocene to Recent is suggested by the presence of heavy minerals in all the shorelines. The seams and their associated foredunes near the present coastline are extremely young, and a study of foredunes in Koombana Bay has revealed the remains of whaling boats, dated at 1840, within heavy-mineral seams (Welch, 1964). Currently the coastline is prograding and, hence, the heavy-mineral deposits are being protected from erosion.

The shorelines have been grouped into five distinctive geomorphic units (Fig. 11), named the Ridge Hill strandlines (67-76 m), the Yoganup strandlines (27-40 m), the Bassendean (or Capel?) strandlines (4.8-6 m), the Spearwood strandlines (3-6 m), and Quindalup* (1-3 m) strandlines (Welch and others, 1976). Only two of these strandlines, the Yoganup and Bassendean (Fig. 12), are currently mined, although small heavy-mineral deposits are known in the Quindalup strandlines.

The Yoganup strandlines spread laterally over about 1.5 km and have been described as beach deposits, located in a 'notch' cut into a wavecut platform of Mesozoic rocks (Welch, 1964; Welch and others, 1976). The heavy minerals occur below an unconsolidated sand layer and are within a compact sand-clay mixture, which may be interspersed with lateritic hard pans. Sometimes the highest grades of heavy minerals are located within these hard pans and are not recoverable (Welch and others, 1976). As there is no material suitable for age determination within these deposits, their exact age is not known.

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* The Quindalup strandlines are also known as the Minninup strandlines (J.L. Baxter. Geological Survey of WA, pers. comm.).

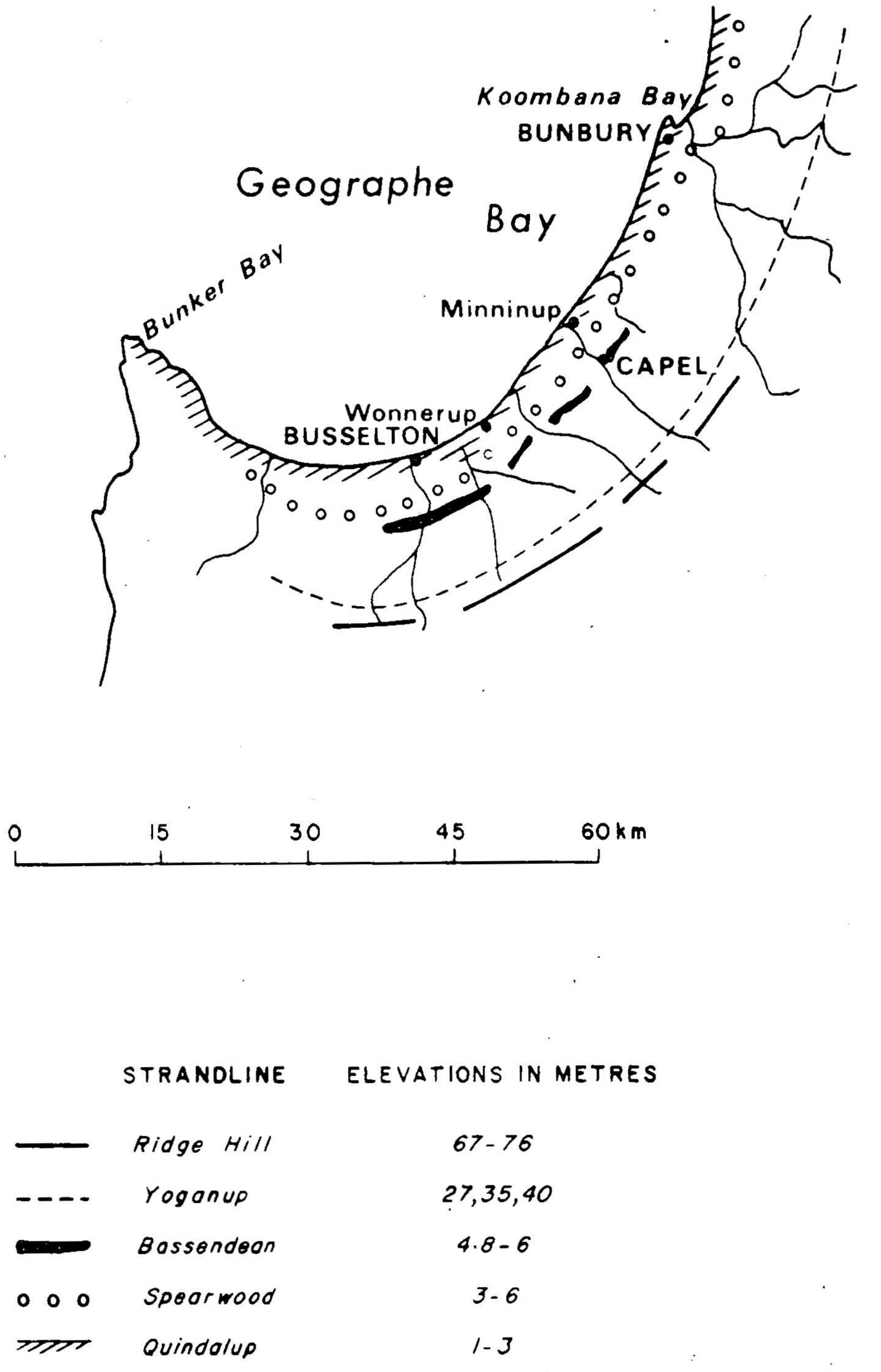
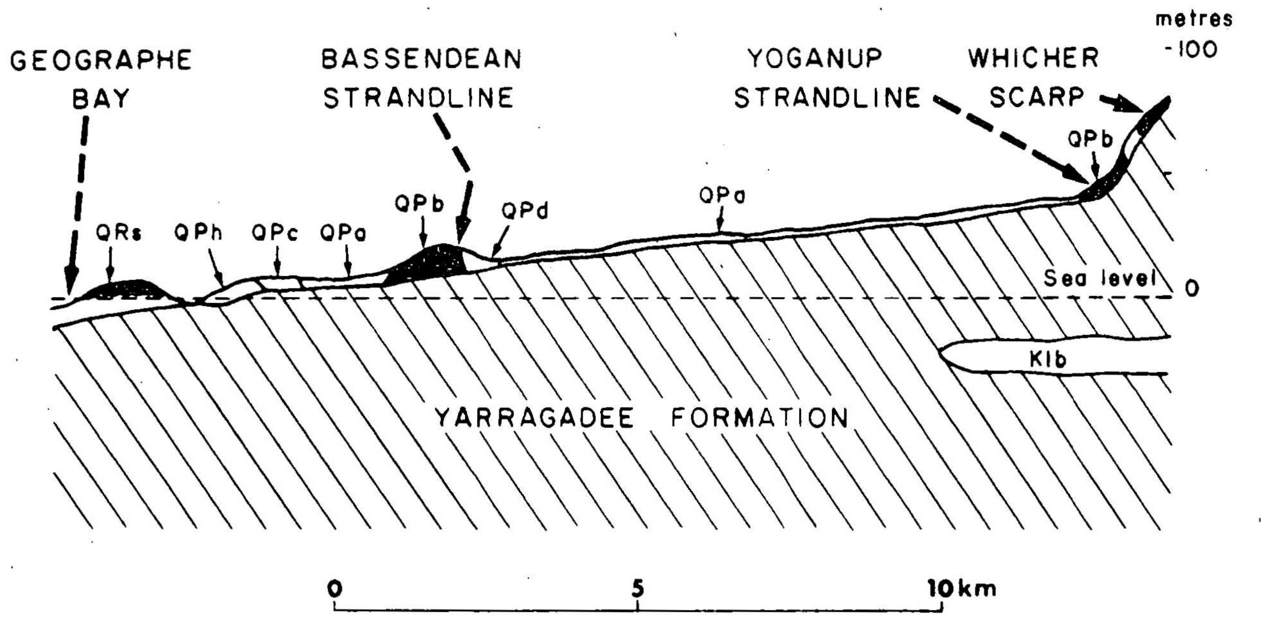


Fig 11 Raised shorelines of Geographe Bay

(Modified from Welch, 1964 and Welch, Sofoulis & Fitzgerald, 1976)



RECENT	QRs	*Sand dunes and beach ridges*	
HOLOCENE TO PLEISTOCENE	QPc	*Coastal limestone*	
	QPh	*Shelly member*	
LATE TO MIDDLE PLEISTOCENE	QPa	*Alluvium*	now podzolised
	QPb	*Beach ridges and foredunes*	now podzolised
	QPd	*Dunes*	now podzolised

Klb	Bunbury Basalt
(shaded)	*Heavy mineral deposit*

Fig 12 Cross section of the coastal sequence at Geographe Bay (from Lowry, 1967)

Dunal deposits are the major constituents of the Bassendean strandlines (McArthur & Bettenay, 1960; Welch, 1964). The deposits were laid down after the Yoganup strandlines and it is thought they were formed in part by the cutting of a lower platform either in Mesozoic or Pleistocene sediments, and in part by the erosion of the Ridge Hill and Yoganup shorelines (Welch and others, 1976).

Disseminated heavy minerals occur in all other coastal sands at Geographe Bay, but it is only where the sands have been eroded and the minerals concentrated that substantial heavy-mineral deposits have been found. In the Quindalup strandlines (Fig. 11) the process of erosion and reconcentration to form larger heavy-mineral deposts has been observed (Carroll, 1939; Low, 1957; Welch, 1964; Wise, 1972). The largest of the recent concentrations are at Minninup, Koombana Bay, Wonnerup, and Bunker Bay.

5.5 Southern Coast

Few authors have described the geomorphology of the southern coastline of Western Australia, but topographic and geologic maps show that from Augusta to Black Head (Fig. 8B) there are strandlines, the Donnelly, Warren, and Milyeaanup, which can be recognised by beach deposits (Hodgkin, in preparation).

East from Black Head, many small beaches, backed only by a foredune, border the coast. However, where the beaches are orientated to face the southwest, mobile dune systems have developed. McMath (1950) and Low (1957) have both noted that beaches in this area are so narrow that they are subject to stripping during storms. Also Morgan & Peers (1973) have noted that the irregular nature of the coastline has resulted in little sedimentation or long-shore drifting of sediments. The presence of coffee rock in the beaches at Torbay Bay and Doubtful Island Bay (McMath & de la Hunty, 1951b), however, suggests the extension of these beaches at a time of low sea level.

Heavy minerals are found within the Warren and Milyeaanup fossil shorelines and in the Recent beach deposits, known as the Quindalup shoreline, in the Augusta area. Elsewhere, along this coastline, deposits are found only on the Quindalup shoreline and this is due to the fact that the coastline is actively eroding (Morgan & Peers, 1973) and reconcentrating heavy minerals in foredunes.

5.6 Discussion

As a result of this examination of Quaternary geomorphology along the Western Australian coast it can be seen that heavy-mineral deposits occur in shoreline complexes which are continuous from Geraldton to Cape Naturaliste on the northern coast and from Augusta to Black Head on the southern Coast. The actual number of recognisable shorelines and their elevation above sea level varies from north to south, and shorelines which may contain heavy minerals at one location may not at another. However, the oldest shorelines (Yoganup) bordering the Gingin Scarp (Fig. 1B) and the Whicher Scarp (Fig. 12) always contain large heavy-mineral deposits.

Large heavy-mineral deposits at Geographe Bay and Eneabba have formed within zetaform bays and it is thought that this particular coastal outline may influence heavy-mineral distribution and accumulation. Beaches formed within these bays produce unique sedimentological characteristics and set-up certain current patterns, which may be significant in accounting for the distribution and accumulation of heavy minerals (Davies, 1972).

Between the Eneabba and Geographe Bay deposits, however, there are some marked dissimilarities. The most obvious of these is the lack of heavy minerals in any but the most inland coastal formation (the Bassendean Sands) at Eneabba, as opposed to the abundance of heavy minerals in all coastal formations at Geographe Bay.

6. CONCLUSIONS

Correlation of the distribution of heavy-mineral deposits with provenance, climatic and oceanographic factors, and coastal geomorphology has shown that provenance, sea level change, coastal outline, wave regime, and longshore drift are significant features in accounting for the location, size, and type of heavy-mineral deposits along the Western Australian coast

6.1 Provenance

The Geographe Bay, Gingin scarp, and Augusta heavy-mineral deposits have all been derived from Mesozoic sandstones, which in turn formed from the erosion of the Precambrian shield to the east of the Darling Fault. The differences in mineralogy between the Geographe Bay and Gingin Scarp deposits are due to differences in the composition of the Precambrian shield north and south of the Swan River.

The smaller heavy-mineral deposits along the southern coast are derived directly from granite/gneiss complexes. Those of the northwest of the State are presumably derived from the Mesozoic sediments of the Canning Basin.

The relationship between provenance and river systems is also important in explaining the distribution of heavy minerals in Western Australia. For example at Eneabba the rivers which originally brought heavy minerals into 'Eneabba Bay' have been captured by the Hill River (Lissiman & Oxenford, 1973) and this may explain why heavy minerals are not found in all the coastal formations. At Geographe Bay, the rivers have drained the Darling scarp throughout the Pleistocene to the present and this probably explains the continuous history of heavy-mineral deposition.

6.2 Sea Level Change

Although sea level change has affected the whole Western Australian coastline, it is only where it has resulted in progradation of the coast that major heavy-mineral deposits have been found. Where sea level change has resulted in drowning of the coastline, mud and tidal flats have formed and heavy-mineral deposits are rare. The influence of sea level change however, must be examined with regard to the coastal outline.

6.3 Coastal Outline

The outline of the Western Australian coast varies from straight, along such areas as Eighty Mile Beach (Fig. 8A), to zetaform at Geographe Bay (Fig. 8B), and to irregular alonng thesouthern coast.

Of the three types of coastal outline zetaform bays seem to be most important in aiding heavy-mineral deposition. This type of bay seems to encourage beach ridge progradation and sorting of sediments. Such bays have also been observed on the east Australian coast where heavy-mineral deposits are abundant. As mentioned earlier the Eneabba heavy-minerals appear to have formed in a zetaform bay, similar to Geographe Bay, but on a much smaller scale. It is probable that when progradation at Eneabba resulted in the infilling of 'Eneabba Bay' (Fig. 10) the coastline became straight and heavy-mineral deposition ceased.

Irregular coastlines are unfavourable to heavy-mineral deposition as they inhibit longshore drift and sedimentation.

6.4 Wave Regime

Wave regime, particularly the direction and type of waves reaching sections of the coast, seems important in setting up longshore drift, which in turn sorts the beach sediments and concentrates the heavy minerals. Where waves from the southwest reach an open coast, they set up longshore drift; where the coastline is irregular, waves are often refracted, causing uni-directional drift and, hence, little sedimentation.

6.5 Longshore Drift

Longshore drift is goverened by coastal outline and wave regime and is important in sorting and concentrating heavy minerals.

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TABLE 1. PRODUCTION OF HEAVY MINERALS FROM COASTAL SANDS IN WESTERN AUSTRALIA

Mining Companies	Years of Mining	Tonnes of Heavy Minerals Produced					Total Heavy Mineral Production
		Ilmenite	Monazite	Rutile	Leucoxene	Zircon	
. Perron Bros	1956	3 344					3 344
. Western Titanium NL	1957	27 157					
	1958	49 073					
	1959	46 384	111		280	4 133	
	1960	63 731	245	630	20	4 697	
	1961	62 047	1 021	561	272	6 196	
	1962	112 015	965	887	762	4 198	
	1963	62 647	306	615	395	4 412	
	1964	180 164	612	839	522	16 527	
	1965	149 770	528	228	385	12 625	
	1966	177 046	1 156	585	558	10 461	
	1967	185 126	878	406	514	7 815	
	1968	218 931	1 068	858	934	17 491	
	1969	249 678	1 384	1 425	316	7 801	
	1970	185 105	1 961	1 376	1 130	33 999	
	1971	255 944	1 783	204	1 242	9 036	
	1972	281 801	1 669	2 956	804	25 080	
	1973	295 022	1 648	2 702	1 135	25 049	
	1974	269 573	1 445	2 939	766	23 675	
	Total	2 871 214	16 780	17 211	10 035	213 195	3 128 435
. Westralian Oil Pty Ltd	1959	209					
	1960	9 468					
	1961	29 089					
	1962	52 144			28		
	1963	34 242	758		66	233	
	1964	76 957	725		1 315	3 862	
	1965	70 943	555		106	12 959	
	1966	87 055	622		209	14 109	

	1967	61 162	489			16 707	
	1968	57 515	714		697	10 380	
(name changed to Westralian	1969	141 857	1 052	243	741	16 578	
Sands Ltd)	1970	114 771	1 763	910	3 649	18 885	
	1971	138 845	1 315	18	5 569	20 610	
	1973	175 483	1 265		10 106	37 052	
	Total	1 190 305	9 907	1 171	28 518	174 202	1 404 103
. Western Minerals Pty Ltd	1964	6 923					
	1965	93 145					
	1966	132 213					
	1967	109 717					
	1968	124 690					
	1969	188 695					
	1970	172 110					
	1971	179 378					
	1971	209 403					
	1972	179 378					
	1973	194 230					
	Total	1 410 504					1 410 504
. Ilmenite Pty Ltd	1959	19 070					
	1960	23 121					
	1961	23 217					
	1962	23 045					
	1963	35 288					
	1964	28 778					
	1965	35 267					
	1966	48 031	48			1 609	
	Total	235 817	48			1 609	237 474

. Cable (1956) Ltd	1957	14 530					
	1958						
	1959	9 060					
	1960	20 175					
	1961	11 160					
	1962	21 892					
	1963	6 891					
	1964	43 303					
	1965	50 050	1			2 740	
	1966	34 084	98			740	
	Total	211 145	99			3 480	214 724
Ilmenite and Cable (1956) Pty Ltd	1967	80 487	71		93	5 569	
	1968	70 679	81		90	953	
	1969	112 174	214		5 795	3 335	
	1970	87 483	1 042		7 543	9 107	
	1971	97 247	41		4 298	1 621	
	1972	45 275	413		10 471	3 529	
	1973	137 400	384		4 155	25 017	
	Total	630 745	2 246		32 445	49 131	714 567
Total Heavy Mineral Produced in Western Australia		6 553 074	29 080	18 382	70 998	441 617	7 113 151

TABLE 2. DEMONSTRATED RESERVES

Location	Data Source	Types of Heavy Minerals (Tonnes)			
		Ilmenite	Monazite	Rutile	Zircon
	. Western Titanium NL (1974)		9 800 000		
Eneabba	. Allied Minerals Pty Ltd (1975)		7 756 000		
	. Ward (1972)	9 300 000	51 000	1 500 000	3 500 000
	. Lissiman & Oxenford (1973)		25-30 000 000		
Jurien Bay	. Financial Review 14.5.73		1 160 000		
Geographe Bay	Ward (1972)	21 200 000	119 000	125 000	1 900 000
Cheyne Bay	. McMath (1950a)		77 000		
Gairdner River area	. Mcmath & de la Hunty (1951b)		371 856		

TABLE 3 HEAVY-MINERAL ASSEMBLAGE OF CONCENTRATES - WA

Location	Source	Percentages					
		R	Z	Il	M	Gt	Other
Southern Coasts							
. Cheyne Bay	McMath (1950a)			52	nil		48
	Low (1957)		12	30	nil		58
. Doubtful Is. Bay	McMath & de la Hunty (1951a)	1	3	11	nil		85
. Torbay	McMath & de la Hunty (1951b)	.1	1	2	nil		96
. Israelite Bay	The West Australian (1970)	1	18	25	.6	18	37
Geographe Bay							
. Wonnerup	McMath (1951)	1	2	43	trace		54
	Bayly (1952)	2	5	86	nil		7
. North Capel	Welch (1964)	.4	4.3	90	.3		4
Capel	Low (1957)	1	7	92.5	.5		
	Gardner	1.8	6	91.6	.35		0.2
		1.3	3.8	93.2	.4		1.3

. Minninup	Le Mesurier (1950)	.2	.6	18		3	78
. Koombana Bay	Welch (1964)	.8	6.2	79	1.0	8.5	4.5
. Yoganup	Welch (1964)	.4	9	88	.9	trace	1.5
	Gardner (1958)	1.1	12.1	77.9	.9		8
	Morgan (1964)	.4	9	70	.9		15
Eneabba Area							
. '128-m' Strandline	Lissiman & Oxenford	5	47.1	38			9.9
. '115-m' Strandline	(1973)	6.4	53.2	33	1.2		6.2
. '103-m' Strandline		10.8	20.4	59.4	1.2		8.2
. '97-m' Strandline		10.5	15.4	68.0	.9		5.2
. '91-m' Strandline		8	19.1	62.1	2.4		8.4
. Average	Allied Minerals (1971)	9.5	25.7	39.7	1		24
. Jurien Bay	Financial Review (14.5.75)	10	10	60	1		19
. Cataby	The West Australian (8.7.76)	7	12	70	1.5	nil	8
Northern Coast							
James Price Point	Brunnschweiler (1957)	1.6	11	66			21
Port Gregory (28°12' 114°15')	The West Australian (29.7.75)	.5	1.5	18		79	1

R - Rutile
Z - Zircon
Il - Ilmenite
M - Monazite
Gt - Garnet