Heavy Mineral Deposits in the Yoganup Formation

by B.K. Masters

INTRODUCTION

This paper describes the Yoganup Formation within the southern Perth Basin of Western Australia, from Busselton in the south to Gingin, some 350 km to the north.

Mining of heavy mineral deposits within the Yoganup Formation commenced in 1959 at the Westralian Sands Limited mine at Yoganup, near Capel (Fig. 1). Although mining ceased at this site in 1974, development of further mines within the strike extensions of this original site occurred in 1971 at the Yoganup Extended deposit, and in 1987 at Yoganup North. Cable Sands (WA) Pty Ltd began mining from this formation in 1985 at Waroona North, 90 km north of Capel and from the Waroona South deposit, some 7 km south, in 1988. Westralian Sands Limited has announced an economic evaluation of deposits 60 km further north at Munjidong, while the Gingin deposit, 110 km north, has also been the subject of renewed investigation.

Overall, the Yoganup Formation has produced in excess of 10 Mt of combined ilmenite, rutile, leucoxene, zircon and monazite. Reserves are estimated at a further 13 Mt, valued in 1988 at approximately $A1500 million.

Younger shoreline deposits in the Capel area occur to the west of the Yoganup Formation. Exploitation of these deposits commenced in 1954 and two companies (Associated Minerals Consolidated Limited and Cable Sands (WA) Pty Ltd) continue to mine from Quaternary shorelines contained within the Safety Bay Sand and Bassendean Sand (Baxter, 1977).

REGIONAL GEOLOGY

DEPOSITIONAL FEATURES

The Yoganup Formation is a siliciclastic deposit of probable Pliocene age (Collins and Baxter, 1984), laid down along palaeo-shorelines during periods of elevated sea level. Typically, erosion during these periods of high sea level initially produced sea cliffs and wave cut platforms in the pre-existing sedimentary Leducville Formation, volcanic Bunbury Basalt and Precambrian granitoids of the Yilgarn Block. A reduction of shoreline energy conditions combined with an influx of heavy mineral bearing, medium grained, feldspathic and quartzose sands allowed wind, waves and currents to concentrate the heavy minerals into a series of shoreline placer deposits (Macpherson and Masters, 1983). Subsequent movements in sea level preserved these sediments. Post-depositional weathering and erosion have modified the volume and mineralogy of the Yoganup Formation.

The heavy minerals were brought into the shoreline environment by a combination of coastal erosion of pre-existing sediments, and detritus introduced by rivers under flood conditions. However, evidence from the Capel area supports fluvial sources as being locally dominant. This evidence includes:

1. a definite spatial association of deposits with palaeo-river mouths,
2. increasing clay and trash mineral contents to the north of the palaeo-rivers, and
3. decreasing zircon and monazite contents and physical reduction in the size of the deposits to the north of river mouths.

Sea level fluctuated during deposition of the Yoganup Formation. Hence, accumulations of heavy minerals are present at varying heights from 24.4 to 63.5 m above present day sea level. A typical deposit comprises up to seven distinct shoreline sequences. Individual economic deposits (here defined as having a cutoff grade of 4% heavy minerals) are developed only locally within the formation. For example, within the Yoganup North deposit of Westralian Sands Limited, there are three distinct shorelines or strands up to 4.5 km long. Individually, they may reach 400 m in width and be mineralised over a vertical depth of 20 m.

REGIONAL VARIATION

The Yoganup Formation overlies two broad basement types. North of Perth and south of Bunbury, basement consisted primarily of poorly lithified, feldspathic sandstones. Erosion by the advancing, and then temporarily static, shoreline mostly produced gently sloping beaches, with shallow water (less than 5 m) extending considerable distances offshore. Between Bunbury and Perth, however, the basement was a combination of the same sediments and a series of granitic sea cliffs, where comparatively deep water (5 to 10 m) was present at the base of the cliffs.

The individual heavy mineral accumulations reflect the regional differences in basement geology. With a predominantly sedimentary basement, the deposits consisted of quartzose sands, with feldspars, silt, clay and 'light heavy' minerals such as garnet tending to be removed. With pre-dominantly granitic basement, the greater water depth resulted in less winnowing, so that silt, feldspathic and lower grade heavy mineral deposits were formed. From an economic viewpoint, these latter deposits are more difficult to develop. However, in places, accumulations up to 35 m thick occur, compared with less than 20 m for the higher grade type of deposit formed above sedimentary basement.

LOCAL STRATIGRAPHY

At operating mine sites, the stratigraphy and associated sedimentary structures are well displayed. Since each deposit is a combination of overlapping shoreline accumulations of
heavy minerals, a description of a typical strand or shoreline deposit is appropriate (Collins, Hochwimmer and Baxter, 1986).

Immediately overlying the basement is a 10 to 30 cm bed of conglomerate composed of quartzite and feldspathic quartzite granules to boulders. A clay-free, coarse to very coarse grained quartz sand with low heavy mineral content overlies this, with a thickness of up to 20 cm, before grading into a fine to medium grained quartz sand that displays small scale (up to 10 cm) ripples and cross stratification structures. These are interpreted as having formed immediately off-shore from the palaeo-beach between the bar and backwash zones (Conybeare and Crook, 1968).

The highest concentration of heavy minerals occurs next, in a layer up to 3 m thick. Here essentially horizontal planar laminations which contain up to 95% heavy minerals and attain individual thicknesses of 35 cm represent deposition on the beach surface during the waning phases of a high energy storm event. The heavy minerals are fine grained, while the enclosing sand is fine to medium grained.

In places a bioturbated zone up to 1 m thick occurs above the high grade beach layers. It contains lower-heavy mineral concentrations and possibly represents the vegetated transition zone between the beach and fore dunes. Then follows broad scale, cross-stratified dunal sand which attains a thickness of up to 10 m, with a 5 to 10 cm cap of clay which marks the shoreward advance of interdunal swales and associated estuarine/lacustrine sediments.

Complex variations of this generalised sequence are common. Bioturbated, high grade heavy mineral sands are recorded from beneath the plane laminated beach layer at the Yoganup North mine, while repetitions of two or three high grade beach layers may occur within one strandline/shoreline sequence. Variations of energy conditions, sediment input and sea level determined the complexity of individual deposits.

MINERALOGY

From south to north within the Yoganup Formation, a number of trends are present (Table 1). Re-interpretation of the Table 1 data shows that variations in ilmenite and monazite are not significant. However, there is a marked increase in rutile content from south to north, and markedly lower zircon in the Bunbury to Perth region. When the 'others' content is considered, there is also a major increase in the presence of 'light heavies' (mainly aluminosilicates) from south to north.

ALTERATION

Circulating acidic ground waters were responsible for the leucoxenisation of ilmenite. In general, in the less deeply buried deposits, iron oxide was removed from the contained ilmenite, such that FeO decreased, Fe₂O₃ increased, total Fe decreased and TiO₂ increased. Mineralogical changes relate to the loss of the ilmenite molecular structure and increases in the proportion of pseudo-rutile and rutile structures (M. Frost, I. Grey, I. Harrowfield, C. Li and K. Mason, unpublished data, 1982).

Induration or lithification within heavy mineral deposits is also attributed to circulating ground water. At the air-ground water interface, iron sesquioxides were deposited from solution, as dry summer conditions caused evaporation and high solute concentrations. Although maximum thicknesses of 3 m are known, this induration is typically only sparse and thin (1 m) within the more sandy deposits. Where the deposits or their overburden horizons are high in clay, the zone of winter-summer water table fluctuation and the overall hydraulic permeability are low, and ironstone or similar induration is rare.

In places further lithification occurs within the high grade heavy mineral deposits. Here, even weakly acidic ground water can affect the more reactive ilmenite grains, causing the heavy mineral grains to be bound together. Such lithification is weak and loss of recoverable heavy minerals from this cause is very low.

Feldspars within the Yoganup Formation have been completely converted to clay minerals, typically of kaolinitic composition. Since most of the deposits have obtained their sediment from fluvial sources, and with feldspar seemingly more easily transported along shore by currents, most deposits show an increase in clay-silt content from south to north, away from the ancient river mouths.
### TABLE 1
Trends in heavy mineral concentration, Yoganup Formation

<table>
<thead>
<tr>
<th></th>
<th>South of Bunbury</th>
<th>Bunbury to Perth</th>
<th>Perth to Gingin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>82.4 (86.9)³</td>
<td>81.0 (90.0)</td>
<td>59.7 (83.7)</td>
</tr>
<tr>
<td>Zircon</td>
<td>10.9 (11.1)</td>
<td>6.9 (7.2)</td>
<td>9.5 (11.0)</td>
</tr>
<tr>
<td>Altered ilmenite</td>
<td>1.4 (-)</td>
<td>3.5 (-)</td>
<td>8.3 (-)</td>
</tr>
<tr>
<td>Leucoxene</td>
<td>2.4 (1.2)</td>
<td>4.8 (2.5)</td>
<td>8.4 (4.9)</td>
</tr>
<tr>
<td>Monazite</td>
<td>0.5 (0.5)</td>
<td>0.3 (0.3)</td>
<td>0.4 (0.5)</td>
</tr>
<tr>
<td>Others</td>
<td>2.2 (-)</td>
<td>3.5 (-)</td>
<td>13.7 (-)</td>
</tr>
<tr>
<td></td>
<td>99.8 (99.7)</td>
<td>100.0 (100.0)</td>
<td>100.0 (100.1)</td>
</tr>
</tbody>
</table>

1 Also called magnetic leucoxene; represents partly weathered ilmenite.
2 Also called non-magnetic leucoxene; at Westralian Sands Limited, this historically has contained 50% rutile and 50% highly weathered ilmenite. Figures in brackets refer to rutile only.
3 The unbracketed figures neglect the effects of post-depositional weathering on the ilmenite. The figures in brackets are recalculated heavy mineral assemblages in which the altered ilmenite and 50% of the leucoxene contents are added back into the ilmenite on a pre-weathering "others free" basis.

### FUTURE DEVELOPMENTS
The majority of the Yoganup Formation is held under mining or exploration tenements by Westralian Sands Limited. The known deposits (about 20) are certain to be supplemented by further discoveries, and recovery of heavy minerals from this geological unit will continue well beyond the year 2000.

However, the Yoganup Formation occurs at the foot of community valued hills, which are partly urbanised. Mining in these instances will need to be carried out with full consideration for the social and natural environment. The future challenges therefore lie less in exploration and geological understanding, and more in the fields of mine planning, social interaction and post-mining rehabilitation.

### ACKNOWLEDGMENTS
Numerous unpublished Westralian Sands Limited reports have been consulted in the preparation of this paper. Sincere thanks are expressed to B. Hochwimmer for detailed geological mapping and mineralogical analysis, L. Collins and J. Baxter for mapping, thought provoking discussion and conceptual evaluations, and L. Grey for exhaustive investigations into ilmenite characteristics.

### REFERENCES