AUSTRALIA'S NEW ROLE IN WORLD MINERAL SUPPLIES

Senior Thesis

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By

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TABLE OF CONTENTS

TABLE OF CONTENTS

FIGURES

FIGURES

TABLES

INTRODUCTION

In recent years, we have become aware of the limited supply of minerals and commodities. Continued use of raw materials in industrial and growing nations, as well as new applications of minerals, is increasing their demand worldwide.

The use of iron ore and steel has depleted many reserves and caused nations to search elsewhere for supplies.

Applications of aluminum have rapidly increased since 1960. The great strength of aluminum alloys is equivalent to steel yet aluminum weighs roughly one-third as much as steel. Because of this surge in aluminum, the demand for bauxite has equally swelled.

General growth causes titanium demands to rise in its traditional role as a pigment. Use in the areospace industry leaped in the last twenty-five years. Titanium is used in both commercial and military aircraft, and in missiles and space applications.

The past decade cast a new light on coal. The energy shortage of the 70's warned countries of the necessity of alternate sources of energy. Coal currently stands as the best mid-range source of power.

Rapid increase in demand is not limited to these commodities. These materials were selected because of their relative significance to an industrialized nation: as a raw material in industry-aluminum and iron ore, in both commonplace and more exotic purposes-titanium and aluminum, and as an alternate source of energy to petroleum-coal.

The surge in world demand for industrial minerals over the past thirty years enabled Australia to spring towards the top of the world mineral market. This paper describes the major deposits of these minerals in Australia, and it is the purpose of this paper to illustrate Australia's new role in world mineral supplies.

BAUXITE

Bauxite deposits in Australia are of the blanket-type. These deposits are flat lying, or nearly so, and at or near the surface. The ore usually occurs on top of hills, ridges, or plateaus in a dissected area. Most of the deposits are Tertiary age and were formed in situ due to weathering in a tropical climate. Four of Australia's largest Bauxite deposits are outlined below to illustrate their characteristics.

Gove Deposit, Northern Territory

The Gove Deposit is a series of caps on several plateaus. These plateaus consist of Mesozoic sediments deposited in a lacustrine enviornment. These sediments lie unconformably on Precambrian basement rock. After deposition a peneplain formed and then the bauxite began to form. Further uplift and differential erosion created the plateaus. Continued erosion causes the bauxite to thin or pinch out upon crests and increase in low areas. Often the increase in the low areas is enhanced by the redeposition of loose pisolitic ores.

The ore chiefly consists of gibbsite and goethite and occurs in three different horizons. The upper horizon contains a loose pisolitic ore and is underlain by a cemented pisolitic ore with vary little matrix. The lowest horizon is a tubular ore that occurs in secondary solution channels.

The deposits average four meters thick but range widely. Reserves are roughly 250 million tons with 51% Al_2O_3.

Weipa, Queensland

Weipa is located on the west side of Cape York Peninsula .(Fig. 1). It is the world's largest bauxite exporter. The deposit ranges up to ten meters thick and covers over 11,000 sq. kms. The overburden is simply soil. Al_2O_3 content ranges from 45-60%.

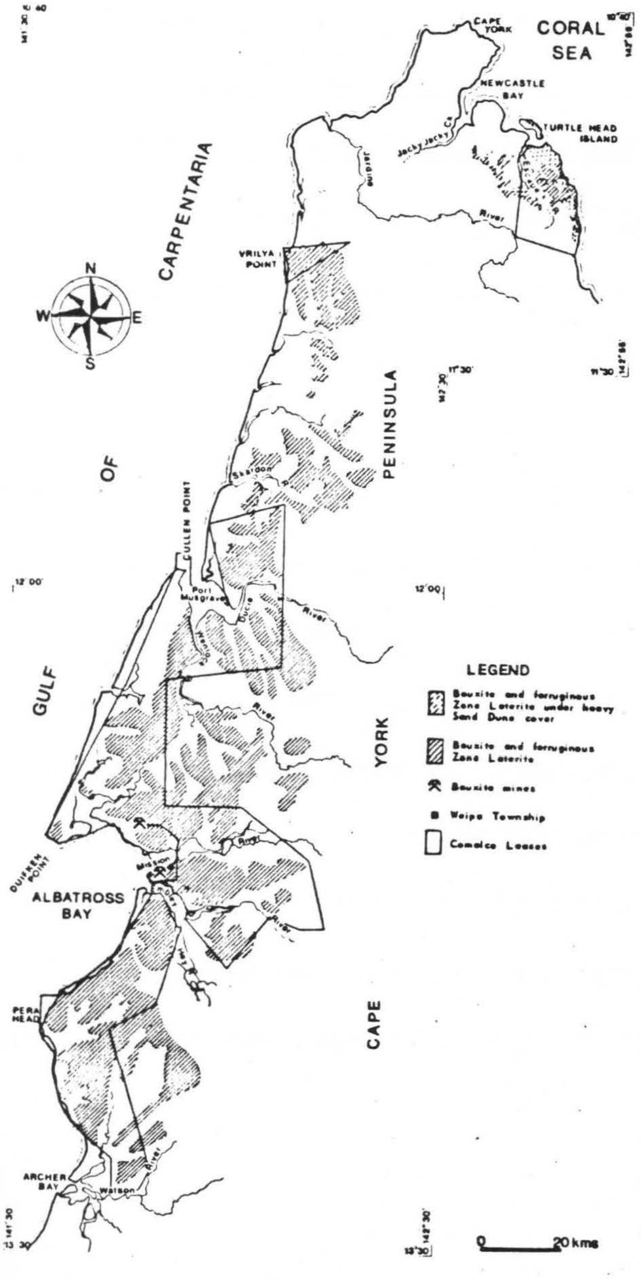


Figure 1. Geologic map of York Peninsula.

(from Evans,1975)

Mesozoic and younger sediments deposited on arched basement rock forms the structure at Weipa. The sediments are sand, silt, and clay . Bauxite developed in the Tertiary and although laterites formed in the Cretacious and Jurassic sediments none were bauxitic. There is an increase in silica eastward and a change to nonbauxitic sediments coincides with this pattern. This seems to result from a decrease in the amount of laterization inland.

Tilting of the Tertiary peneplain caused the level of the water table to lower inland and this decreased the amount of leaching could occur.

The most important control of the bauxite seems to be the age of the sediments. The thick Tertiary sediments contain the aluminous laterites while the Jurassic and Cretacious laterites are ferruginious.

The selective development in Tertiary sediments is a result of having higher porosity and permeability than the older rocks. These sediments were deposited in coastal areas. The high permeability and low lying topography of the Tertiary sediments allowed for increased water flow and weathering. This is the main factor in the selective bauxite development.

The deposits are nearly horizontal, but do appear to be gently folded.(See figure 2,3,4). The crests of the folds have been eroded varying the thickness of the bauxite (Figure 3).

Except for the transportation of this eroded material, the deposit is the result of in situ weathering. Evidence of this includes preservation of the original sedimentary structure in the bauxite and the similiarity of the bauxite and underlying sediments.

EAST-WEST PROFILE AT WEIPA SHOWING VARIATION OF THICKNESS OF BAUXITE DUE TO EROSION AFTER FOLDING OF LATERITE

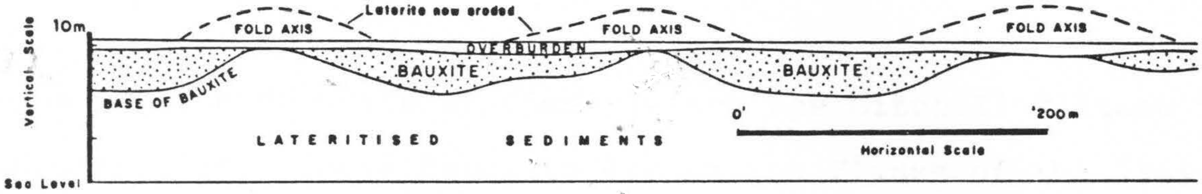


Figure 2

EAST-WEST PROFILE ACROSS BROAD FOLD WEST ANDOOM AREA SHOWING EROSION OF LATERITE FROM CREST AND FLANK OF FOLD

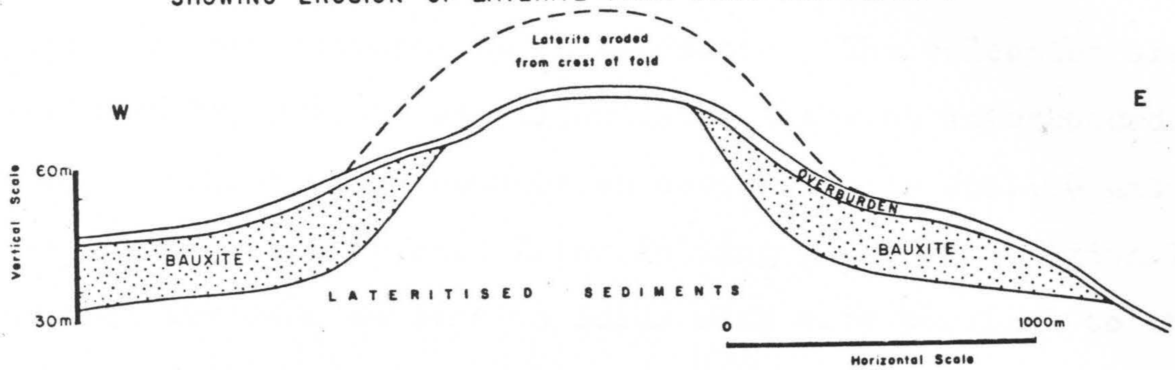


Figure 3

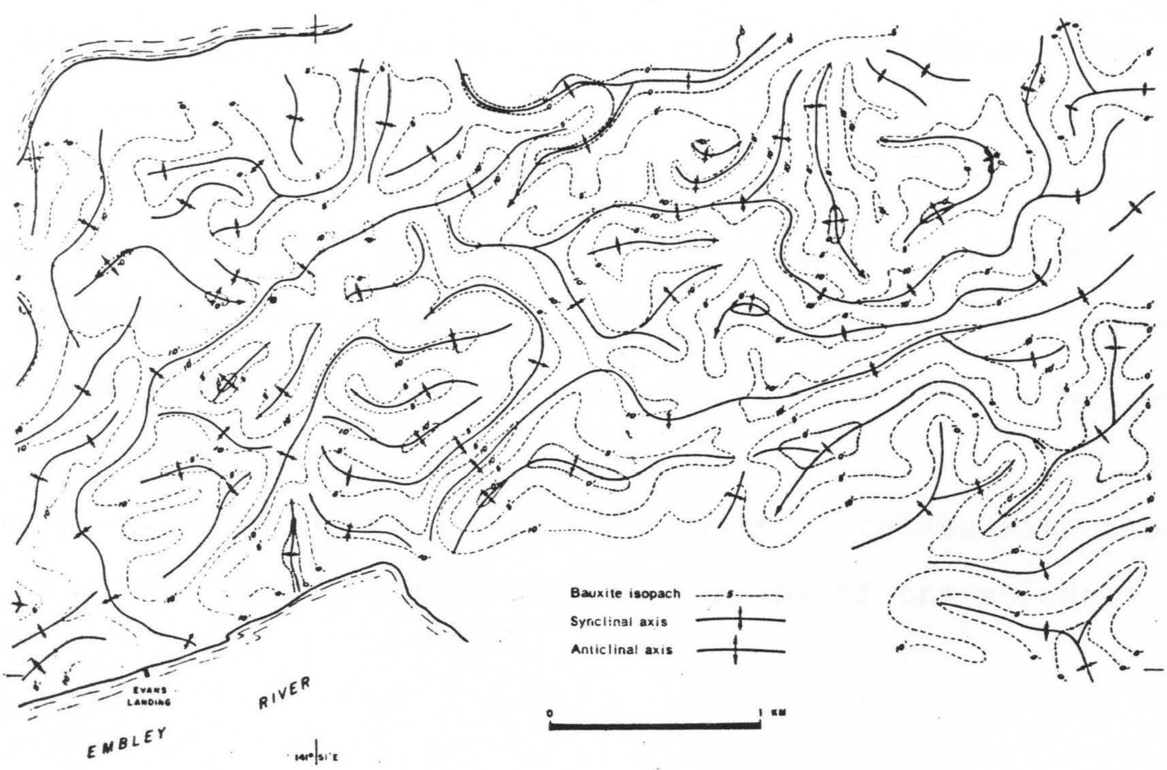


FIG. 4—Part of the West Weipa bauxite area showing trends in laterite.

(taken from Evans, 1975)

Kimberly, Western Australia

The bauxite deposits at Kimberly are the Mitchell Plateau and Cape Bouganville. These deposits lie on the flanks of the Admirality Gulf (Fig. 5). The deposits contain roughly 45 sq. km. of bauxite each.

Volcnaics rest conformably on sandstone. The volcanics are laterized basalts, present as pillow lavas and with interbedded sandstone and siltstone. Precambrian deposition in shallow water is suggested for this series. Later folding produced a regional syncline that contains en echelon folds with axes parallel to the synclinal axis. This fold pattern is reflected in the analysis of the weathering products.

Subsequent faulting uplifted the area and exposed it to erosion. By the Cenozoic a peneplain had formed and was laterized. Further erosion occurred in the Tertiary..

The prescence of faults and both horizontal and vertical joints has a direct effect on the thickness and grade of bauxite at Mitchell Plateau. The joints allow for increased leaching which enhances the laterite processes. The end product is not only thick deposits, but deposits of a high grade.

The structure and content of the bauxite corelate with those of the volcanics suggesting in situ weathering of the volcanics.

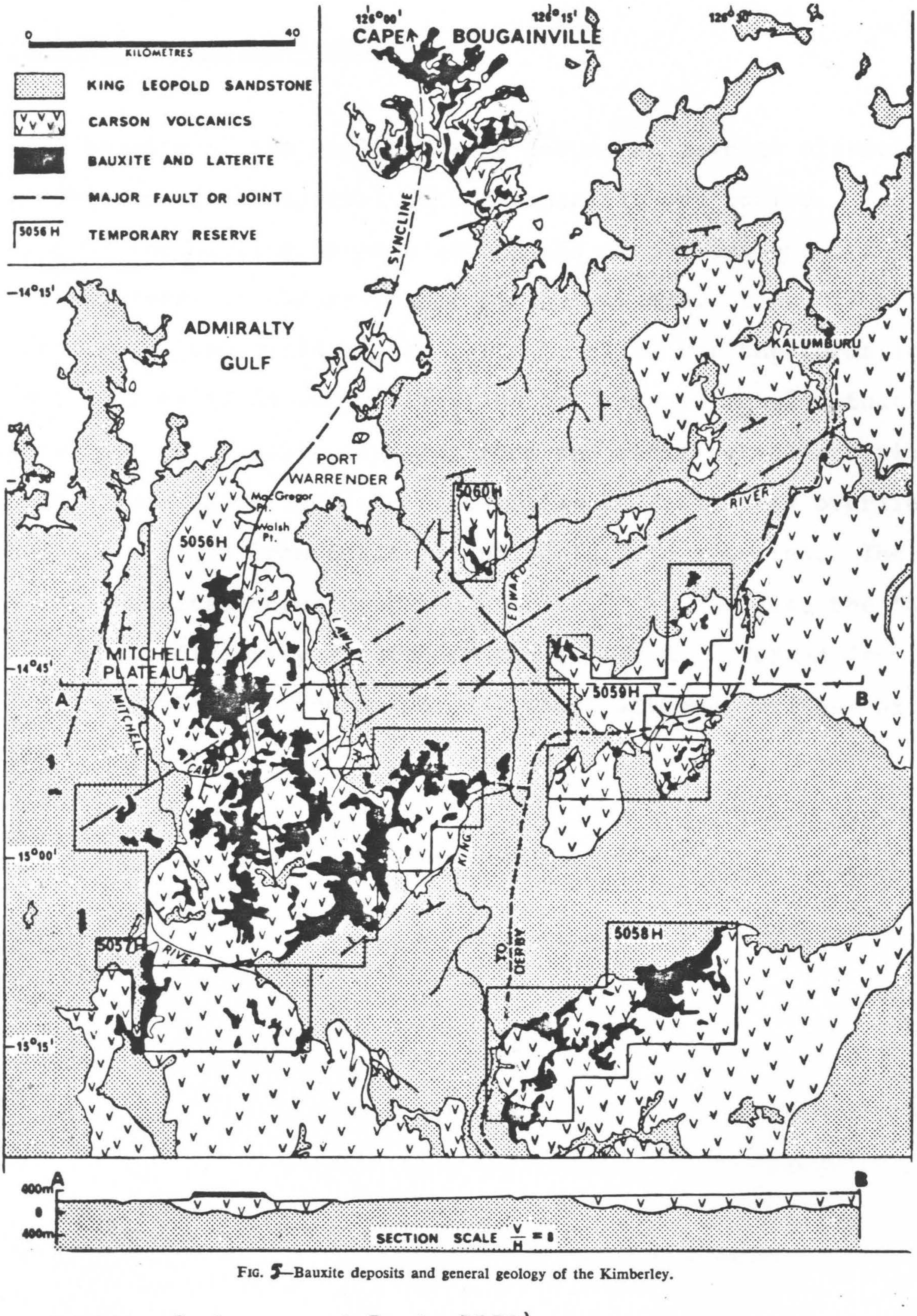


FIG. 5—Bauxite deposits and general geology of the Kimberley.

(from Joklik, Jackson, and Zani, 1975)

Darling Range, Western Australia

The bauxite of the Darling Range occurs at several elevations rather than one as is typical of the peneplain ore bodies. The deposits of the Darling Range occur on the slopes but are not generally present on the crests or in the valleys.

Erosion is too rapid on the peaks to allow for the formation of a residual soil. In the valleys the drainage is so slow that it would degrade any bauxite that may form and cause rekaolinization.

The orebodies reflect the Precambrian bedrocks they overlie. The bedrock changes from gneisses and schists to granites. The most economical bauxites occur over the granite. One deposit, the "Seldom Seen", shows sedimentary structures and it may have formed from Proterozoic shales or Permian glacial beds, although neither exists locally.

BAUXITE PRODUCTION

Although some other deposits of bauxite were known to exist, the first important discovery of bauxite in Australia was in 1955. The Cape York Peninsula delievered its first bauxite shipments from Weipa in 1963, a time when bauxite production was rapidly increasing.

Also, in 1961, shipments from the Darling Range to Japan began. This was the beginning of Australia's dominance in the world bauxite market.

> In 1962 total world bauxite production was 31 million tons and by 1972 production had increased to 66mt. Total production for the 10 year period, 1963 through 1972, was 463 million ton which amounted to 55% of the total amount produced from 1900 to 1962 (Shaffer, 1975).

The world-wide surge in demand furnished Australia the chance to capture part of the bauxite market. Bauxite exports from Australia before 1962 were none existent. In 1962 Australia exported six thousand long tons ; by 1967 Australia was exporting approximately 902,000 long tons and had become the the third largest producer in the free world.

> World bauxite production increased 12%...Australia accounted for 86% with an individual increase of 132%..
> (Griffith, 1975)

This full throttle development of the bauxite deposits was illustrated when the Gove facility was opened in 1965. Only ten years had passed since the first major discovery of bauxite and now a new port and mining facility was being opened with a capacity of 1.25 million ton per year. This was accompanied by the construction of a 500,000 ton per year alumina plant and smelter, and also a township for 3,000 people.

Expansion of facilities was the rule in the late 1960's and an integrated aluminum market was being developed. The Australian bauxite was being converted to alumina before shipment,,which decreased the transportation costs. Australia maintained its position as the world leader in bauxite exports and was also rising swiftly in the alumina market. Australia's growth and growth potential was well recognized by 1969.

> ...Australia appears headed for the world lead in alumina production and should overtake the United States lead...
> (Lewis, 1969)

In only fourteen years, Australia went from a non-exporting country to one of the top producers of bauxite and alumina. The nation gave no indications of slowing down:

> In late 1969...Australia was planning what would be by far the worlds largest alumina plant, eventually capable of producing five million tons per year (Lewis, 1969).
>
> A Swiss Australian consortium...began development of its large (250 million long tons) bauxite holdings at Gove.
> (Lewis, 1969)

The plans included a 1 million ton per year treatment plant and a town to house 4000 people. Growth at such a pace,resulted in the overload of recently completed facilities.

> Weipa is the largest bauxite-shipping port in the world, and the port facilities are being expanded (Kurtz, 1970).

Alcoa of Australia announced expansion plans including a second alumina refinery and a 15-20 mile conveyor to transport ore from a new mine.

> Production of bauxite throughout the world made a 14 percent annual gain in 1969,...Australia took most of the high-performance honors by by increasing its output from 4.9 million tons in 1968 to 7.8 million tons in 1969, an increase of 59 percent...Australia thus edged Surinam out of second place...(Lewis,1969).

This rapid growth is illustrated best in Figure 6. This diagram shows the total bauxite production of selected leading nations. (Guinea is the only country of any significance excluded. Guinea's production curve is approximately equal to Jamicia's.) Total production is used rather than exports because of the difficulty in comparing exports by weight. These difficulties arise from bauxite being exported in concentrated forms. Other weight factors such as moisture content are important.

> ...some crude bauxite may contain 10 to 30% free moisture, drying can result in a decrease in shipping costs, that offsets drying costs. Surinam bauxite, for instance, is dried to 3 to 6% moisture while Jamacian bauxite is shipped with about 15% moisture (Banks, 1979).

Considering that all of these nations export the majority of their production and the Al_2 contents are comparable, (Table 1) production curves of these nations are good indicators of the exports of each country.

Australia has discovered such large reserves that further exploration is sometimes considered not feasible. Banks calculated that current reserves of bauxite will last until 2020, allowing for the recent 9% growth rate. He also demonstrated the vast discoveries in Australia.

> World bauxite reserves were estimated at 1 billion L-T in 1945, 3 billion in 1955, 6 billion in1965, and 25 billion in 1977. The jump between 1965 and 1977 can be accounted for by the growing attention paid Australia, Brazil...(Banks, 1979).

Australia has enough reserves to maintain its export lead for many years. Guinea is the only country with similiar reserves.(Table 2) "Australia has approximately one-third of the worlds known bauxite reserves" (Kurtz, 1970). It is safe to conclude that Australia's dominance of the export market will not be hampered by short supply.

BAUXITE PRODUCTION CURVES OF SELECTED COUNTRIES

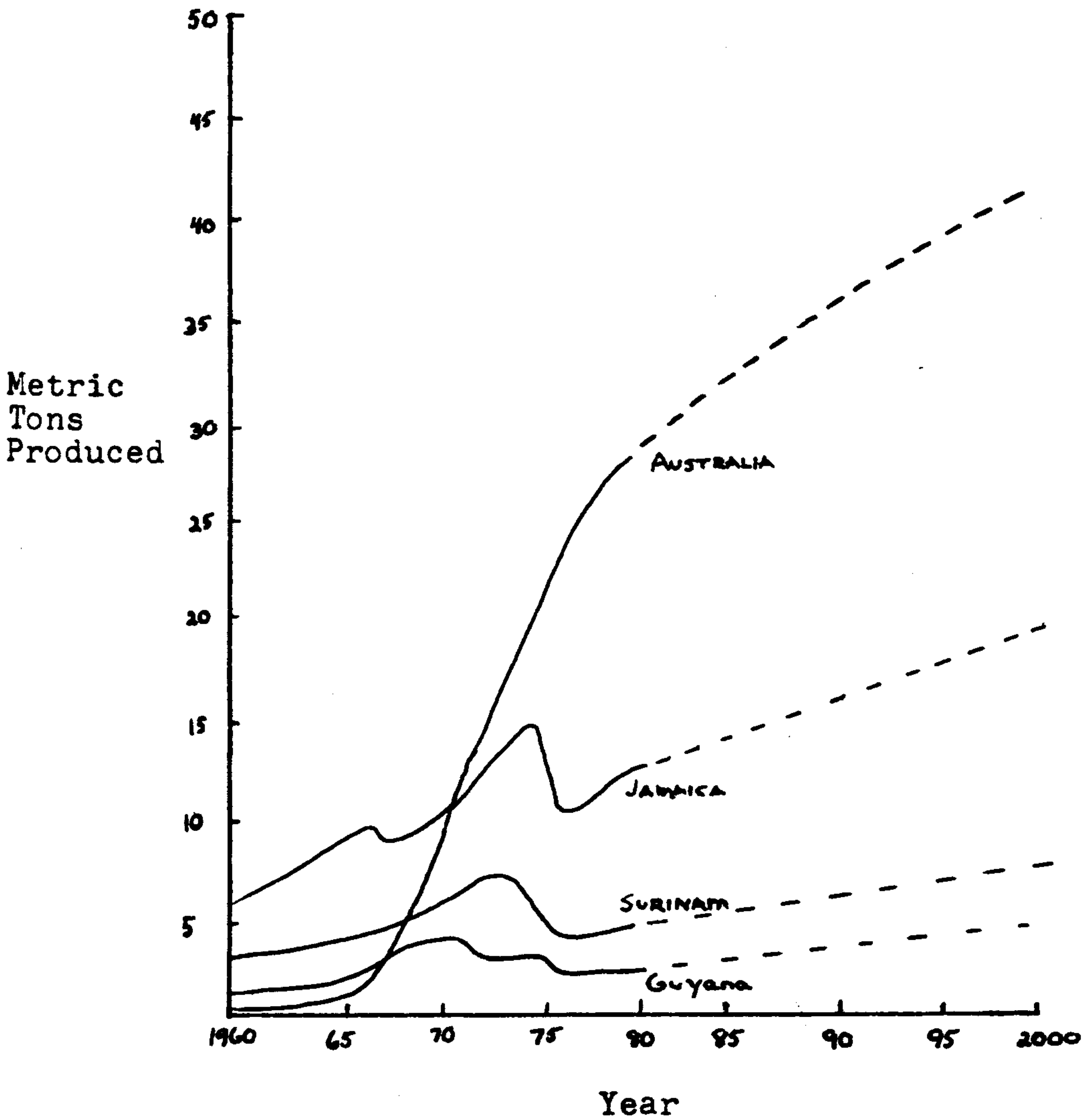


Figure 6

Table 1 RANGE OF MAJOR CHEMICAL CONSTITUENTS OF BAUXITES

	Al_2O_3, %	SiO_2, %	Fe_2O_3, %	TiO_2, %	Loss On Ignition, %
Australia					
Cape York	52-60	2-10	5-13	2.1-3.1	21-29
Gove	48.7	3.6	17.0	3.4	26.3
Darling Ranges	30-48 available				
Kimberly Region	47-50	2.5-3.5			
Brazil					
Minas Gerais	55-59	1.6-5.6	6.9-9.6		
Amazon	50-61	3.7-9.0	1.7-14	1.1-2.0	25-30
China	50-70	9-15	1-13	2	
Dominican Republic	46-49	1.6-5.2	19-21		
France	55-70	3-16	4-25	2-3.5	
Ghana					
Yenahin	41-63	0.2-3.1	1.2-30.9	1.5-5.3	20-29
Awaso	48-61	0.4-2.4	4-22	0.8-2.1	26-33
Kibi	32-60	0.3-2.9	6-45	2.0-6.2	13-30
Greece	35-65	0.4-3.0	7.5-30	1.3-3.2	
Guinea	40-65	0.5-5	2-30	3-5	22-32
Guyana	51-61	4-6	1-8	2-3	25-32
Haiti	46.8	3.4	21.9	2.8	24.1
Hungary	50-60	1-8	15-20	2-3	13-20
India	45-60	1-5	3-20	5-10	22-27
Indonesia	53	4-5	12		
Jamaica	49-51	0.7-1.6	19-21	2.5-2.7	25-27
Malaysia	38-60	1-13	3-21	1-2	
Sierra Leone	51-55	1.5-2	10-18	1.5	27-31
Surinam	50-60	2-6	2-15	2-3	29-31
United States					
Arkansas	45-57	5-24	2-12	1.6-2.4	22-28
Oregon and Washington	31-35	5-11	33-35	5-6	16-20
Southeastern States	51-56	12-15	1-5	1.5-3.5	22-30
USSR	26-52	2-32	1-45	1.4-3.2	
Yugoslavia	48-60	1-8	17-26	2.5-3.5	13-27
Romania	55	5	22	1-2	
Turkey	55-60	5-7	15-20	2-3	12-14

from Shaffer, 1975

Table 2 ESTIMATED RESERVES PLUS POTENTIAL RESOURCES OF BAUXITE

(Millions of Mt)

North America	
United States	
Arkansas	55
Southeastern states	5
Hawaii	100
Total rounded	160
Central America	
Costa Rica	150
Panama	10
Total rounded	160
Caribbean	
Dominican Republic and Haiti	70
Jamaica	1000
Total rounded	1070
South America	
Brazil	3200
French Guiana	170
Guyana	290
Surinam	500
Venezuela	100
Total rounded	4260
Europe	
Austria	1
France	240
Greece	500
Hungary	150
Italy	24
Northern Ireland	3
Romania	20
Spain	100
USSR and Soviet Asia	300
Yugoslavia	300
Total rounded	1640
Africa	
Cameroon	2100
Chad	30
Ghana	380
Guinea	3740
Malagasy	150
Malawi	60
Mali	550
Mozambique	2
Portuguese Guinea	10
Rhodesia	2
Sierra Leone	30
Zaire	100
Total rounded	7150
Asia	
China	1000
India	250
Indonesia	400
Malaysia	30
Pakistan	15
Philippines	28
Turkey	130
Total rounded	1850
Oceania	
Australia	
New South Wales	20
Northern Territory	260
Queensland	3660
Tasmania	1
Victoria	1
Western Australia	1075
Total rounded, Australia	5020
Admiralty Islands	0.6
Babelthuap	5
Fiji	6
New Zealand	20
Solomon Islands	
New Georgia	11
Rennell	20
Wagina	20
Total rounded	80
Total rounded, Oceania	5100
World total rounded	21,400

from Shaffer, 1975

The possesion of large reserves and the ability to produce them does not necessarily make a world-wide supplier. The production of the resources at a relatively low cost does. Table 3 illustrates the cost for the U. S. to buy bauxite from different countries.

Table 3

Typical Bauxite Costs (1974)[a]
(In Dollars/Tonne)

	Jamaica	*Guyana*	*Guinea*	*Brazil*	*Australia*	*Average*
Variable cost	3.00	3.00	3.00	3.00	4.00	3.20
Capital costs	1.07	3.20	3.20	3.20	3.20	2.77
Domestic transport	2.00	2.00	2.00	2.00	2.00	2.00
Infrastructure cost	–	2.50	2.50	2.50	2.50	2.50
Ocean transport	3.00	5.60	6.00	10.00	13.50	7.62
Subtotal	9.07	16.30	16.30	20.70	25.20	
Tonnes bauxite per tonne alumina	2.50	2.0	1.9	1.8	2.2	
Bauxite cost/tonne alumina	22.68	32.60	31.73	37.26	55.44	

Source: United Nations documents.
[a]These costs apply to just before the imposition of a production levy on bauxite by Jamaica, which increased the cost of bauxite in a tonne of alumina by $33.0. For more on this matter, see chapter 4.

from Banks, 1979

This table suggests Australia has the most expensive ore, but there are additional considerations. Note that Australia's largest cost is ocean transport. Remember that this ore is being transported to the United States, and other countries are closer and have less transportation cost. The fact that Australia only pays $3.50 per ton more than Brazil in transport to the United States demonstrates the relative inexpense of ocean cargo. This low-cost transportation works to Australia's benefit when shipments overall are considered. The short distance to Japan makes Australian ore a great buy for the Japanese. Japan is the largest importer of Australian bauxite.

When the International Bauxite Association was formed in 1974, Australia was a member along with Jamacia, Surinam, Guinea, and others.

> Although Australia is the largest producer of bauxite in the world, that country has pursued a price policy that is markedly different from most of the other producers. In fact Australia, which was one of the original member of the IBA, announced in January 1979 that it was no longer prepared to follow IBA operational outlines because of its rather special geographic situation. (Banks, 1979)

In 1974 after the table was constructed, the nations of the IBA, except Australia, levied taxes:

> ...that raised bauxite prices by an average of $10 a ton in 1974 and about $25 a ton in January 1976...as a relatively painless manner of augmenting their income (Banks,1979).

These increases caused the price of Australian ore to become more competitive, if not the cheapest ore.

As Australia increases output with little cost increase,

> ..Australia eats into the market share of others. Or, conversely, the countries moving their price up the most rapidly suffer a declining market share, as seems to be the case of the Caribbean countries today(Banks, 1979).

> ...Thus to summarize on recent trends:...the imminent appearance of Australia as a major producer have brought about a revolution in the sources of supply of bauxite.
> (Brubaker,1967)

Figure 7 LOCATION OF BAUXITE ORES

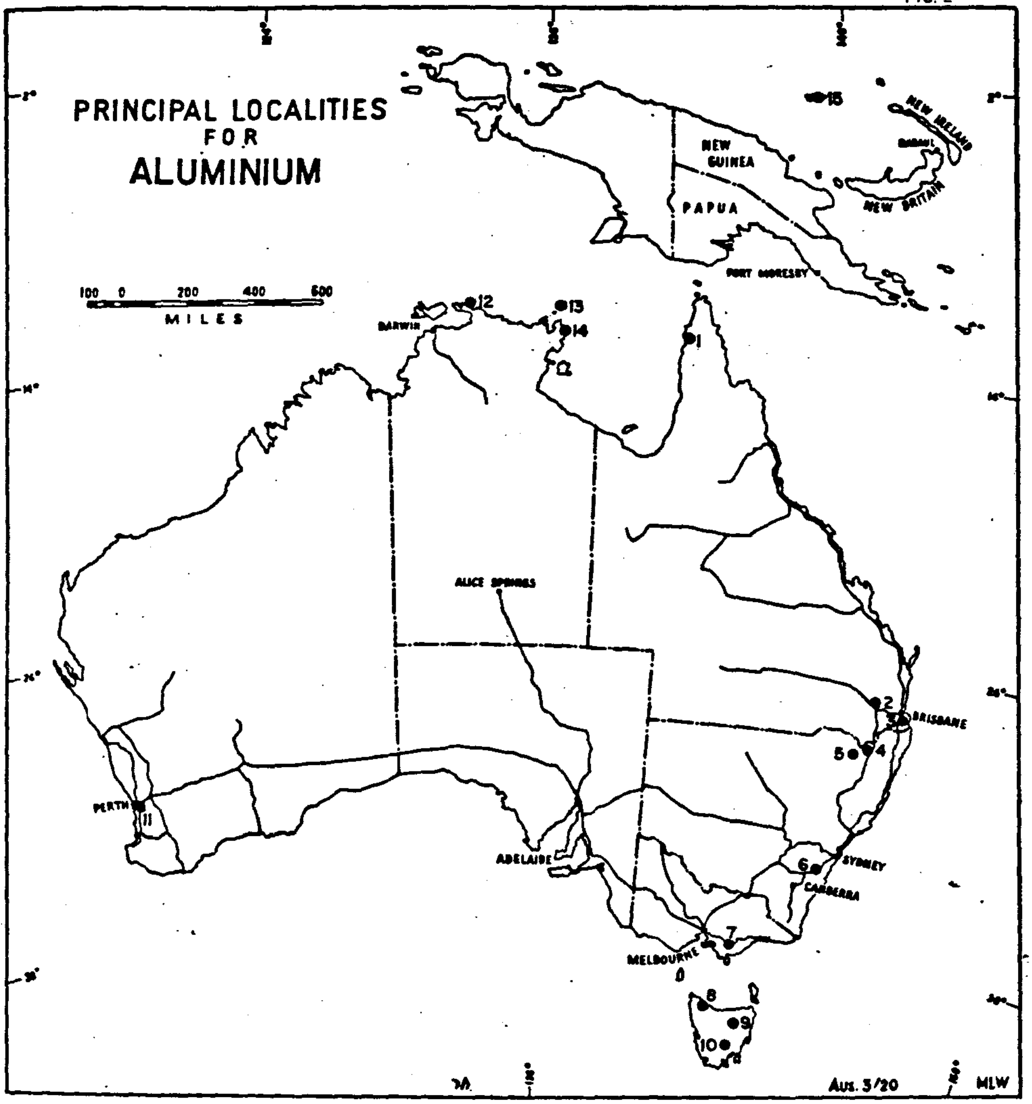


Fig. 2–2.

1. WEIPA.
2. Hampton.
3. Tamborine.
4. Emmaville.
5. Oakwood.
6. Moss Vale.
7. Boolarra.
8. Myalla.
9. St Leonards.
10. Ouse.
11. DARLING RANGES.
12. Croker Island.
13. MARCHINBAR.
14. GOVE.
15. Manus Island.

from McLeod, 1965

Figure 8 WORLD BAUXITE PRODUCTION BY COUNUNTRIES 1972

Country	Production Rank	Production, 1,000 Mt	% of World Total
Australia	1	14,430	21.9
Jamaica	2	12,540	19.0
Surinam	3	6,910	10.5
U.S.S.R.	4	4,670	7.1
Guyana	5	3,730	5.7
France	6	3,250	4.9
Guinea	7	2,640	4.0
Greece	8	2,440	3.7
Hungary	9	2,360	3.6
Yugoslavia	10	2,200	3.3
United States	11	1,840	2.8
India	12	1,660	2.5
Indonesia	13	1,280	1.9
Dominican Republic	14	1,230	1.9
Malaysia	15	1,080	1.6
China	16	740	1.1
Sierra Leone	17	690	1.0
Haiti	18	690	1.0
Brazil	19	610	0.9
Ghana	20	340	0.5
Romania	21	300	0.5
Turkey	22	260	0.4
Others combined†		110	0.2
		66,000	100.0

* Based on preliminary World production figures for 1972 rounded to nearest 10,000 mt.
† Includes Italy, Spain, West Germany, Mozambique, and Pakistan.

Source: Kurtz, 1973.

from Shaffer, 1975

IRON ORE

Although all the states and the Northern Territory have some quantity of iron ore, Western Australia has, by far, the majority and the most significant of these deposits. In an attempt to cover the variety of deposits in Western Australia, a representative group of the more profitable mines has been chosen.

There are three major ore types in Western Australia. Hematite enrichment ores occur in the Precambrian banded iron formations. The other types are pisolitic ore and sedimentary iron ore. "These are presently (1970) being mined 20:2:1, while the equivalent reserves are, very approximately 200:70:1" (Trendall, 1975). Description of the hematite enrichment ore is given for its three major occurences: the Hammersly Basin, the Pilbara Block and the Yilgarn Block. Robe River is used as an example of the pisolitic ore and the Kimberly Basin deposit, in particular Yampi Sound, illustrates the sedimentary iron ore. Description of the Middle Back Range of Southern Australia is included because it too is a substantial iron ore development, Australia's largest outside of Western Australia. Although each deposit is somewhat different from the others of its type, on a large scale similarities outnumber the differences. Substantial development took place in the other states over the last thirty years but these deposits are not of the same magnitude as those mentioned earlier.

Hammersly Iron Province

> . The Hammersly Basin was an ovoid intracratonic depositional basin in which some 15,000 m of mixed sedimentary and volcanic rocks accumulated during Lower Proterozoic times. It probably covered about 150,000 km^2...(Trendall, 1975).

The lowest section of the Hammersly Basin is the Fortescue Group. This group varies from explosive volcanics and conglomerates of a turbulent enviornment to quiet basalt flows and shales. It is conformable with the Hammersly Group above.

The Hammersly Group is characterized by the large scale and continuity of its banded iron formations. The section is illustrated in Figure 9.

Figure 9 HAMMERSLY GROUP

Boolgeeda Iron Formation	(215)
Woongarra Volcanics	(730)
Weeli Wolli Formation	(460)
Brockman Iron Formation	(640)
Yandicoogina Shale Member	(60)
Joffre Member	(365)
Whaleback Shale Member	(60)
Dales Gorge Member	(155)
Mt. McRae Shale	(90)
Mt. Sylvia Formation	(30)
Wittenoom Dolomite	(150)
Marra Mamba Iron Formation	(185)

thicknesses in meters

in Trendall, 1975; from Trendall and Blockley, 1970

The banded iron formations (BIF) are marked by alternating iron-rich and iron-poor bands. The iron-poor bands commonly consist of chert. In addition, there is further microbanding in the chert resulting from seasonal variance of the silica and iron content.

There are some local unconformities, but the Wyloo Group generally follows the Hammersly Group conformably. The Wyloo Group contains graywackes and lesser amounts of both dolomite and basalt.

Hematite enrichment orebodies occur in the Marra Mamba Iron Formation and the Dales Gorge and Joffre Members of the Hammersly Group (Figure 9). The orebodies occupy the position of the host BIF and have sharp boundaries against the overlying shale and adjacent BIF. Transition from BIF to ore occurs from 0-30 meters, a small distance compared to the size of the ore.

> This lateral transition from host BIF to ore is normally accompanied by a reduction in stratigraphic thickness of about 50 per cent, so that the ratio of BIF:ore thickness is about 2:1...(Trendall, 1975).

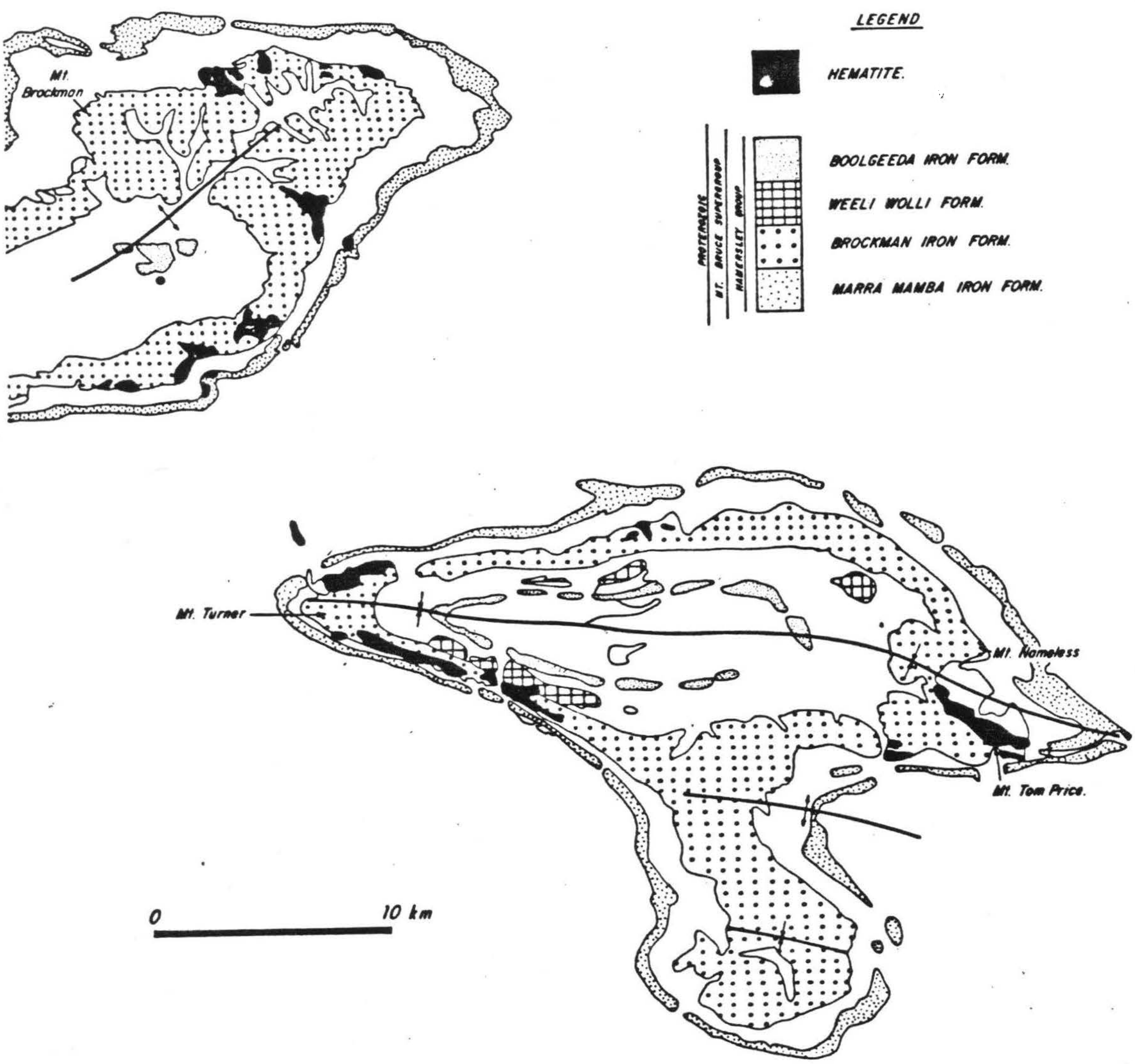
Orebodies tend to be elongate, parallel to the basin axis, and are sometimes associated with faults. They tend to be several kilometers long and hundreds of meters wide. A typical deposit consists of "70 hematite, 23 goethite, 5 kaolin, and 2 quartz..." (Trendall, 1975). Phosphorus is often present as an economically important trace, especially within the goethite.

Mount Tom Price Orebody

Mount Tom Price represents the western end of a ridge formed by the Mount Turner Syncline. The orebody lies within the limbs of this synclinoriun.

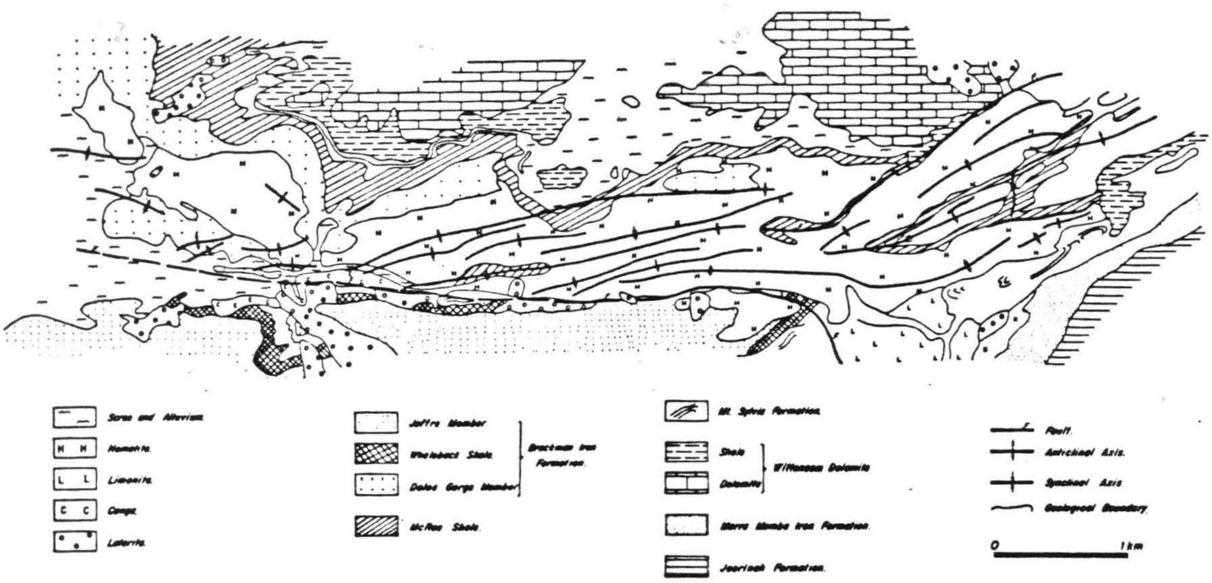
> Within the synclinorium, limbs dip around 30° in accord with in accord with the general dips of the limbs of the Mt. Turner Syncline. Anticlines and synclines within the orebody individually show little persistence and are commonly arranged en echelon... (Gilhome, 1975).

Figure 10 IRON FORMATIONS IN THE MT. TURNER SYNCLINE



from Gilhome, 1975

Figure 11 GEOLOGICAL MAP OF THE MT. TOM PRICE OREBODY



from Gilhome 1975

Figure 12 CROSS SECTION OF MT. TOM PRICE

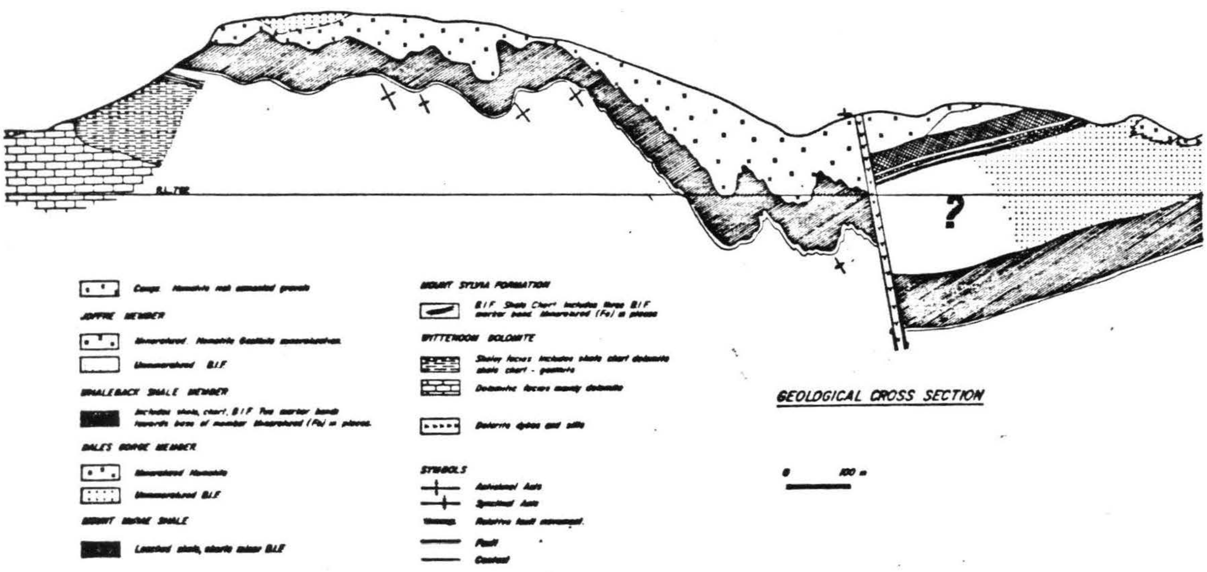


FIG. 3—Geological cross section.

from Gilhome 1975

> ...Folding is of a large scale chevron style. Generally folding is competent, but isoclinal and overturned folds have been mapped in the more intensely folded southern portions of the orebody...Major faulting within the orebody is restricted to an east-west normal fault dipping south. The southern block has been downfaulted approximately 100m bringing the barren Joffre Member into contact with the Dales Gorge Member (Gilhome, 1975).

The orebodies are a direct result of this structure. The folding of the brittle BIF caused jointing, fracturing, and faulting. These fracture planes allowed for increased flow of groundwater. The groundwater dissolved and transported the chert away from the orebody. Recrystallization of the remaining minerals formed the hematite. This is supported by the continuity of the bands from the hematite into the chert. The reduction of the stratigraphic thickness by 50% also implies such a formation.

The main ore is present only in the Dales Gorge Member and one local ore occurs in the Joffre Member.

The major mineral is hematite, both crystalline and specular forms are present. Goethite caps the orebodies to a depth of 20 m. Goethite appears in widely varying forms and amounts. The borders of the orebody usually have higher quantities of goethite than the interior.

Canga wash deposits are found in the drainage of the Hammersly Range. These deposits consist of detached hematite and BIF cemented by goethite.

Typical analysis of the different ore types is given in the table below.

Table 4 SHORT ANALYSIS OF ORE TYPES

	Fe	SiO_2	Al_2O_3	P	LOI
Hematite	68.0	1.07	0.47	0.024	0.94
Goethite	58.2	4.90	2.79	0.064	8.36
BIF	32.1	48.90	0.71	0.024	1.42
Shale	44.9	15.91	12.16	0.136	6.3

LOI= Loss on Ignition

from Gilhome 1975

Mount Whaleback Orebody

Mount Whaleback is located at the southeastern end of the Hammersly Iron Province. The orebody here occurs in the Brockman Iron Formation of the Hammersly Group (Figure 9).

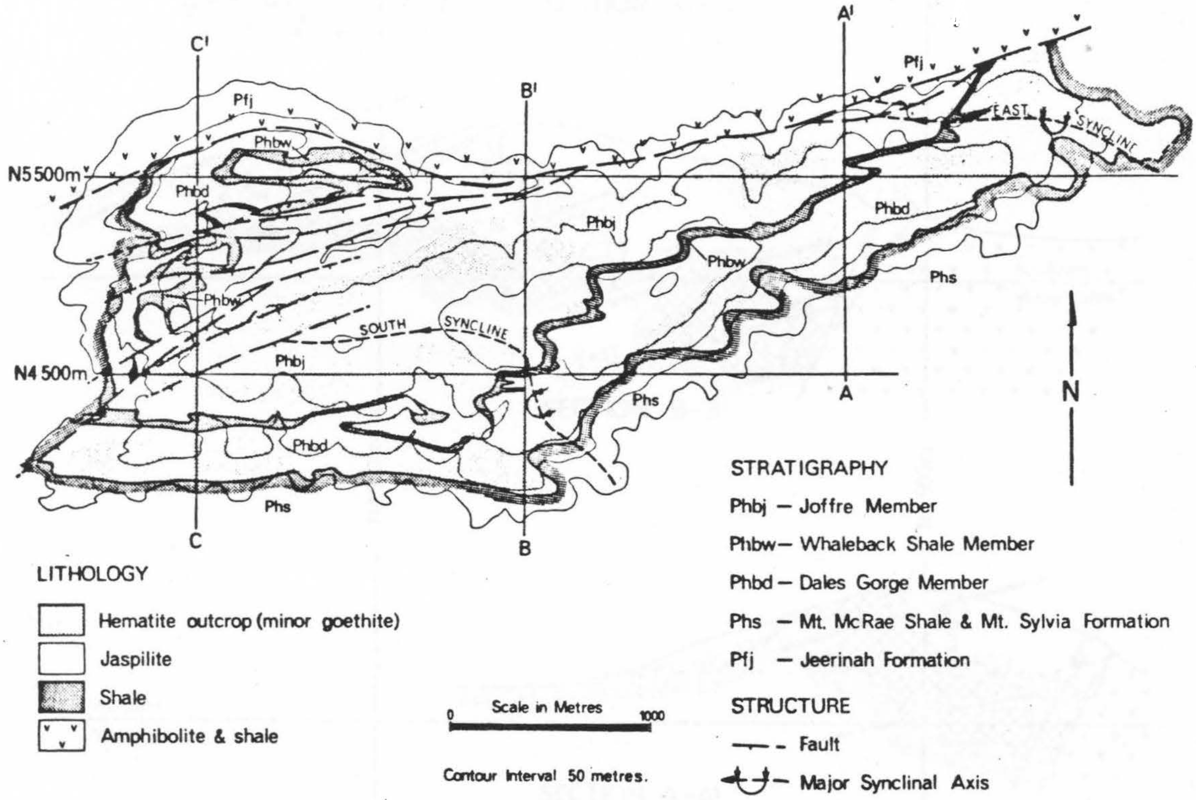
The Dales Gorge member encompasses the ore which consists of alternating hematite,jaspilite and shale layers.

> The shale macrobands are 0.1 to 2 m thick and the ore macrobands are 1-7 m thick. True thickness of the enriched member is approximately 65 m...(Kneeshaw, 1975).

The structure at Mt. Whaleback consists of two east-west trending overturned synclines. These synclines have en echelon parasitic folds on their limbs. The folds increase the ore thickness on the nearly vertical southern limb and decrease thickness in the horizontal northern limb.

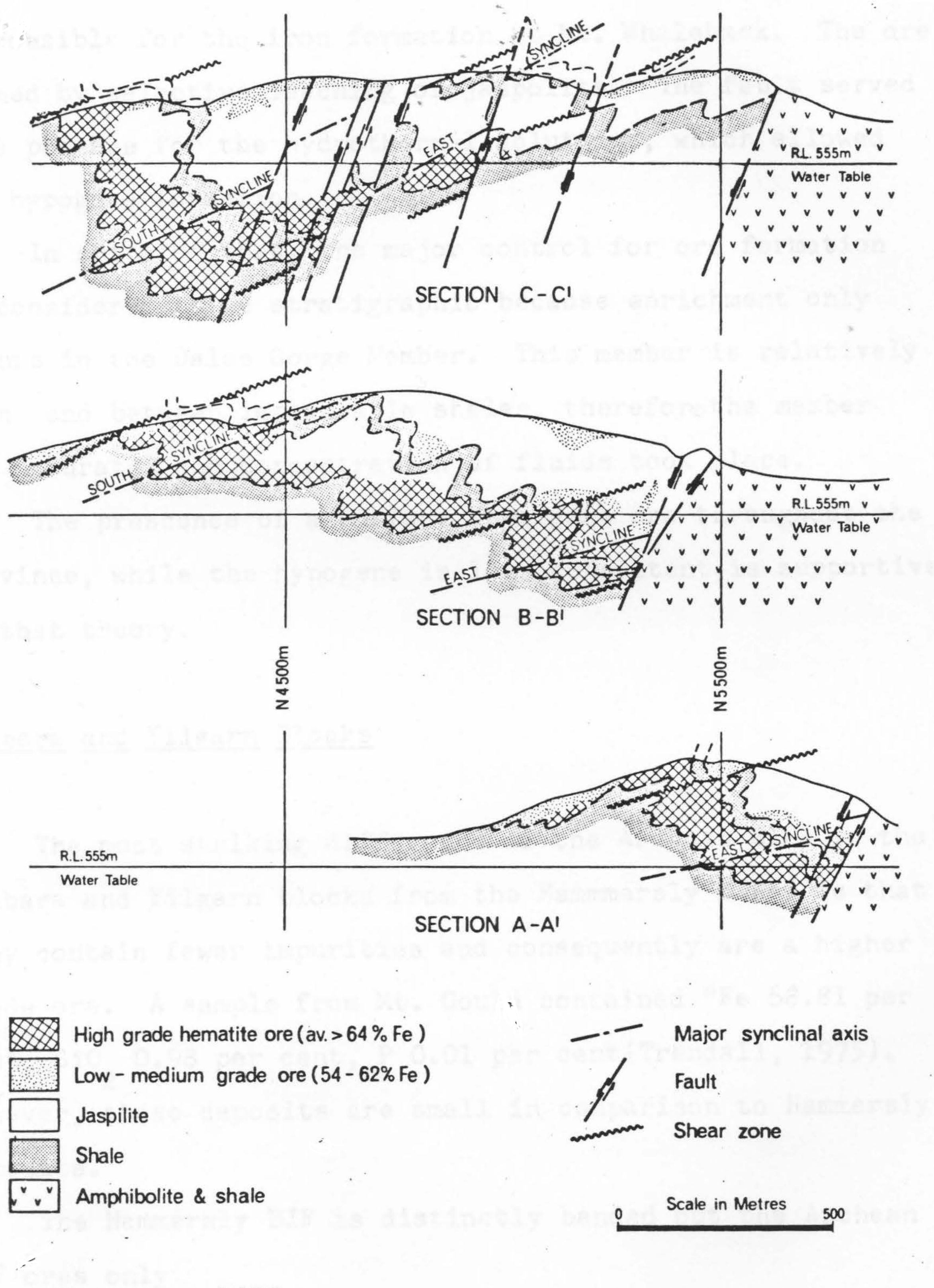
The horizontal limbs of both synclines contain parallel shear zones. These zones are the result of compression from the south and from gravity sliding. See Figure 13 and 14.

Figure 13 GEOLOGICAL MAP OF MOUNT WHALEBACK



from Kneeshaw, 1975

Figure 14 CROSS SECTIONS OF MOUNT WHALEBACK OREBODY



from Kneeshaw, 1975

The major fault which runs along the north flank is responsible for the iron formation at Mt. Whaleback. The ore formed by selective leaching of jaspolite. The fault served as a passage for the hydrothermal solutions, which allowed for hypogene formation.

In spite of that, the major control for ore formation is considered to be stratigraphic because enrichment only occurs in the Dales Gorge Member. This member is relatively thin and between impermeable shales, thereforethe member was saturated and concentration of fluids took place.

The prescence of a surface supergene ore throughout the province, while the hypogene is less consistent,is supportive of that theory.

<u>Pilbara and Yilgarn Blocks</u>

The most striking difference of the Archean BIFs in the Pilbara and Yilgarn blocks from the Hammmersly BIFs, is that they contain fewer impurities and consequently are a higher grade ore. A sample from Mt. Gould contained "Fe 68.81 per cent, SiO_2 0.98 per cent, P 0.01 per cent(Trendall, 1975). However, these deposits are small in comparison to Hammersly deposits.

The Hammersly BIF is distinctly banded but the Archean BIF ores only

> ...reveal a mesobanded structure on polishing, cross-cutting veins of coarsely crystalline hematite commonly conceal this, and larger scale mobilization

of iron has locally produced chaotic brecciated structures; the formation of these structures has everywhere preceded the final crystallization of hematite (Trendall, 1975).

Other than these variances, the Pilbara and Yilgarn blocks are very similiar to each other and the Hammersly Province. Therefore, further general description is minimized to avoid an abundance of repetition.

In the Pilbara and Yilgarn Blocks , the major ore is again hematite enrichment ore. Deposits are usually lenticular, hundreds of meters wide, and up to 2 km. long. The ores are bound by sedimentary and volcanic rock. Ores occur in steeply dipping host rocks with thicknesses in the tens of meters, depending on the corresponding stratigraphic thickness.

As elsewhere, the only structural control is faulting, which allows for ground water flow and ore concentration.

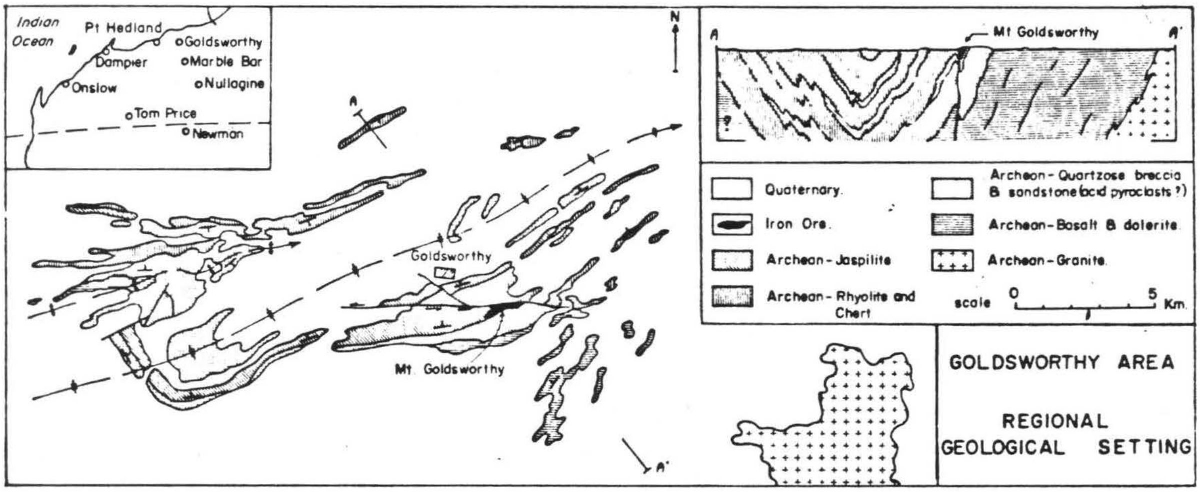
Mount Goldsworthy Iron Ore -- Pilbara Block

The ore deposits of Mt. Goldsworthy are located within the nearly vertical southern limb of a syncline. An east-west transverse fault has displaced the northern limb over 3 km. westward. Other minor faults, with little displacement, are present. The orebodies and synclinal axis are parallel, with the ore adjacent to the east-west striking fault in a jaspilite succession.

The regional structure is the result of Archean orogenesis. Permeability increased due to fracturing and brecciation in the tight synclinal fold, and allowed for the formation of ore.

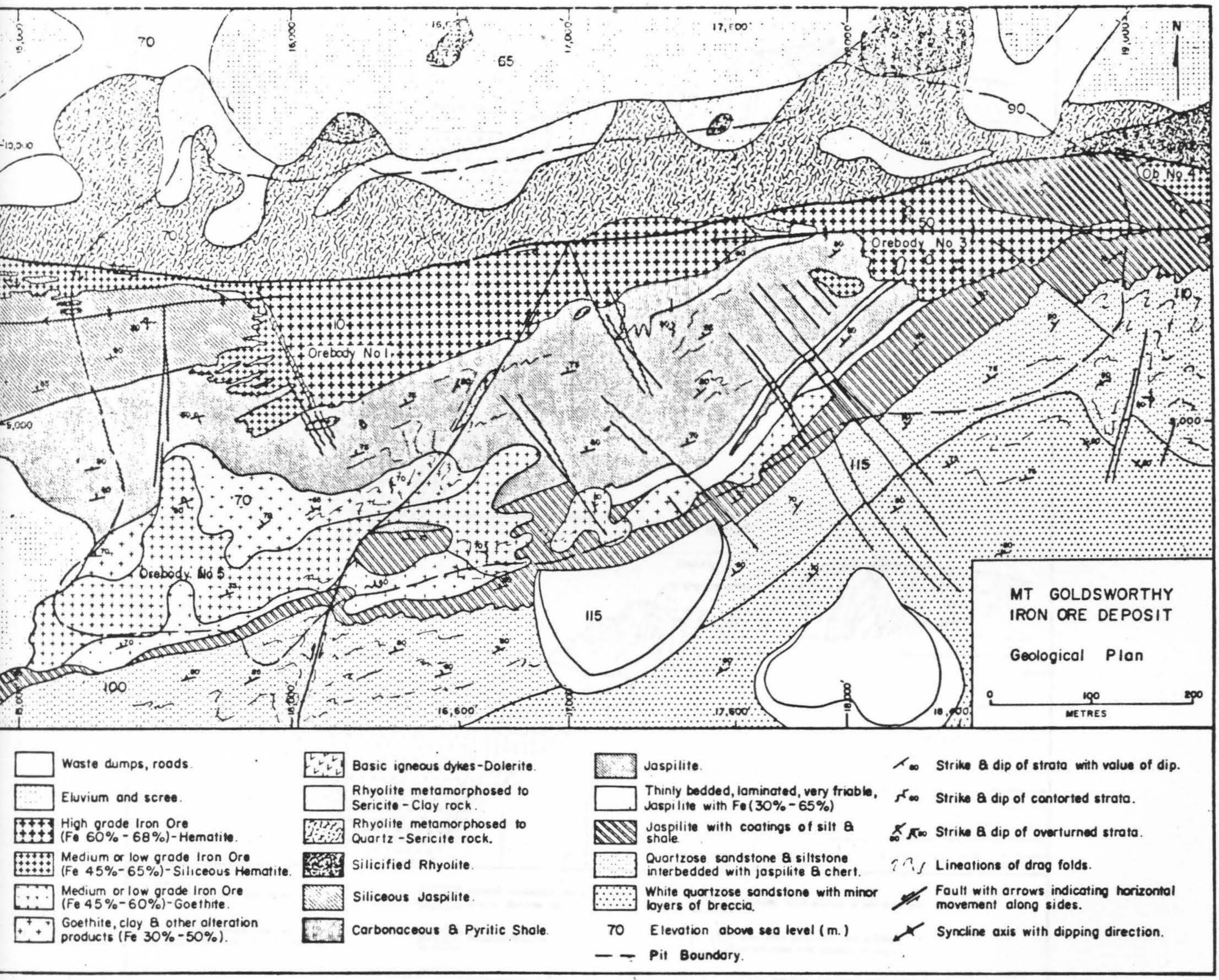
These supergene enrichment ores formed pre-Proterozoic and probably continued to develop with later uplift. The deposits remaining today are only remnants of much larger bodies that have been eroded.

Figure 15 REGIONAL GEOLOGY--MOUNT GOLDSWORTHY



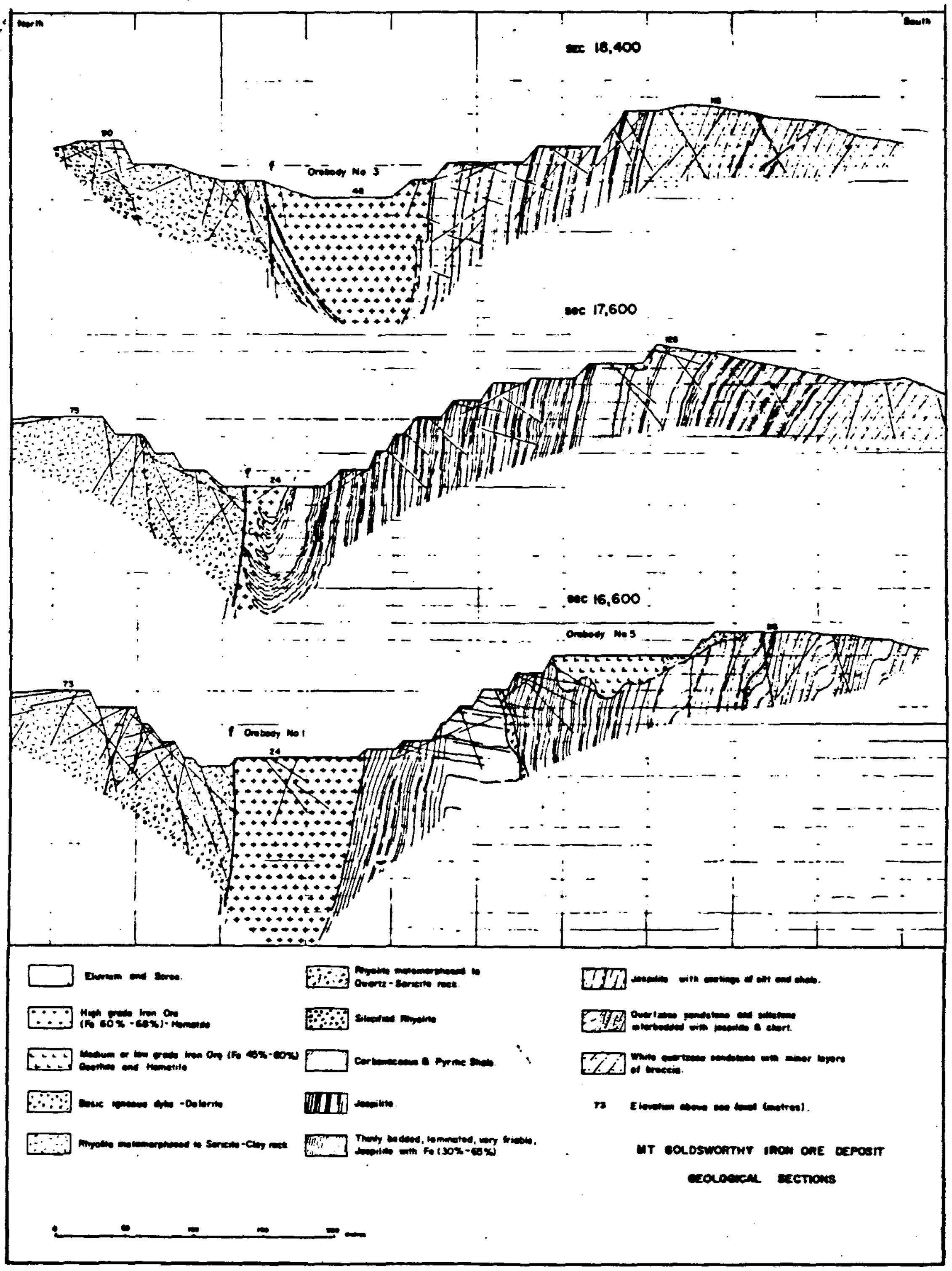
from Neale, 1975

Figure 16 MOUNT GOLDSWORTHY IRON ORE DEPOSIT



from Neale, 1975

Figure 17 MOUNT GOLDSWORTHY CROSS SECTIONS



from Neale, 1975

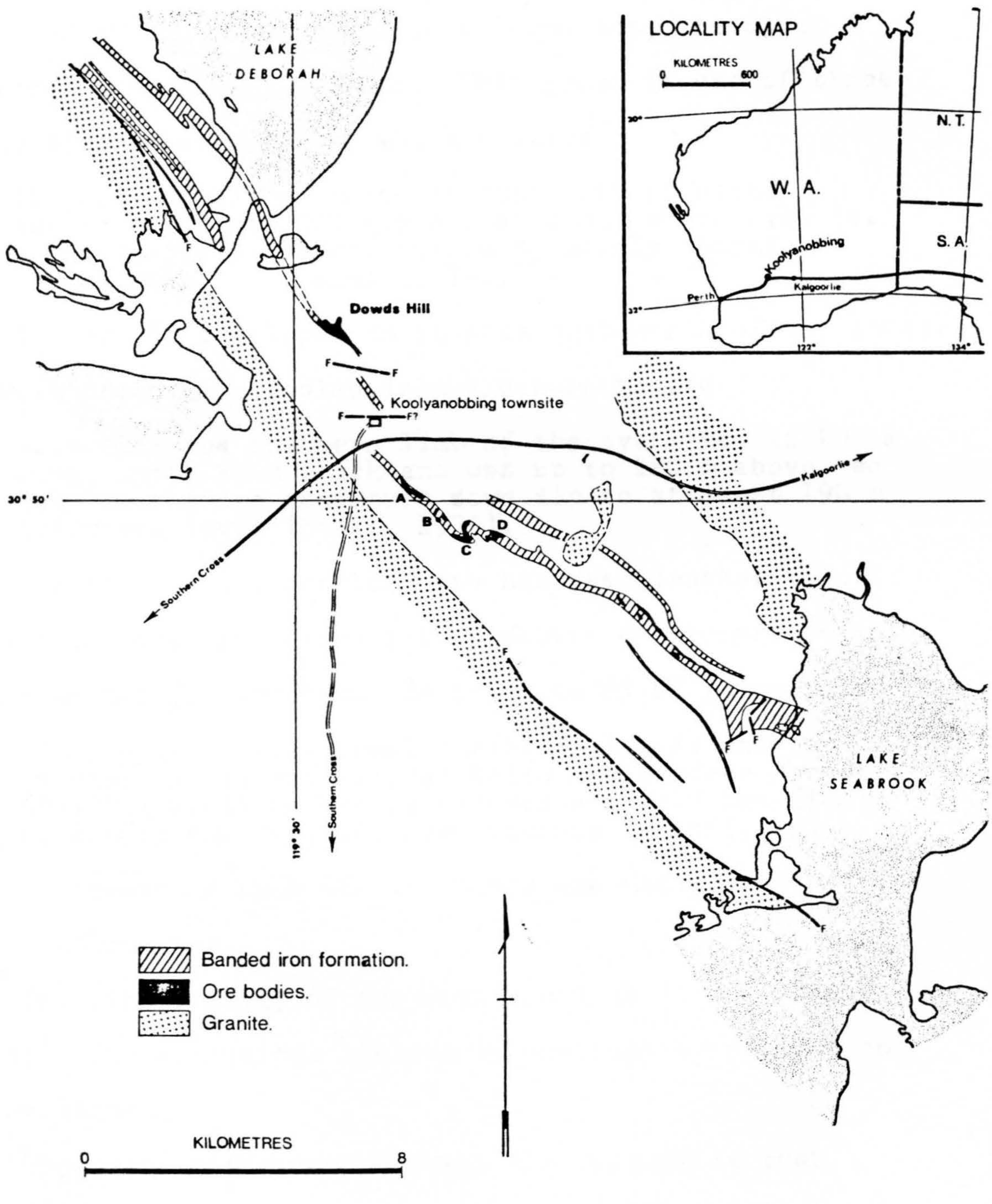
Koolyanobbing Iron Ore -- Yilgarn Block

This greenstone belt runs northwest along the Koolyanobbing Range. The main iron formations occur in isoclinal anticlinal structures that have been folded into a S shape. Granite surrounds and sometimes intrudes the belt along fault planes. Faulting and granite contacts mark the boundary of the greenstone belt in the south and east.

Amphibolites and ultramafics are the major constituients of the greenstone belt. Sedimentary deposits between flows include chert, quartzite, and banded iron formations. Schists usually enclose the iron formations which consist of magnetite-talc schist and quartz magnetite. The ore itself consists of goethite, specular hematite, limonite, and magnetite. Chlorite schist and jaspilite are present in the ores. The Koolyanobbing ore is not as pure as the Pilbara ores.

Supergene alteration formed the hematite and goethite while hydrothermal processes formed the specularite.

Figure 18 KOOLYANOBBING IRON ORE DEPOSITS



from Staff, 1975

Yampi Sound Iron Ore -- Kimberly Basin

Yampi Sound contains the major sedimentary iron ore deposits of Australia. The orebodies occur in the Yampi Member of the Pentecost Sandstone Formation, the upper section of the Kimberly Group. This group is one of three within the Kimberly Basin, which covered

> 120,000 km^2 of the northern most part of Western Australia about 1800 m.y.a., at about which time it was relatively quickly filled by mainly chaotic sedimentation (Trendall, 1975).

The ore is developed on islands just north of the sound. The main orebody on Koolan Island occurs in the

> ...overturned southern limb of the syncline, is 200 m long, up to 30 m thick and was up to 180 m above sea level...the ore continues down dip to at least 190 m below sea level (Staff, 1975).

The hanging wall conglomerate has been leached to ore grade. The orebody grades into hematite conglomerate and sandstone below. The hematite grade is 65-68 percent iron.

> Orebody in the normal northern limb is shorter (1860 m), thinner (17 m) and extends below the surface for only 60-120 m depth before it becomes entirely hematite sandstone and hematite conglomerate (Staff, 1975).

Lesser amounts of this ore are mined and mixed with ore from the southern limb.

Only the orebody of the southern limb is on Cockatoo Island. Its dimensions are nearly duplicates of those on Koolan Island.

The major difference between the islands is that Cockatoo Island has a siltstone hanging wall and footwall. The conglomerate does not exist above sea level. Therefore sea cliffs are formed by the iron.

The iron ore formed as a clastic sediment. Detrital accumulation of hematite is well accepted but an original source of the hematite has not been determined.

> It has been suggested that the original source was... eroded and concentrated near a beach or off-shore bar (Staff, 1975).

Figure 19 YAMPI SOUND IRON ORE DEPOSITS

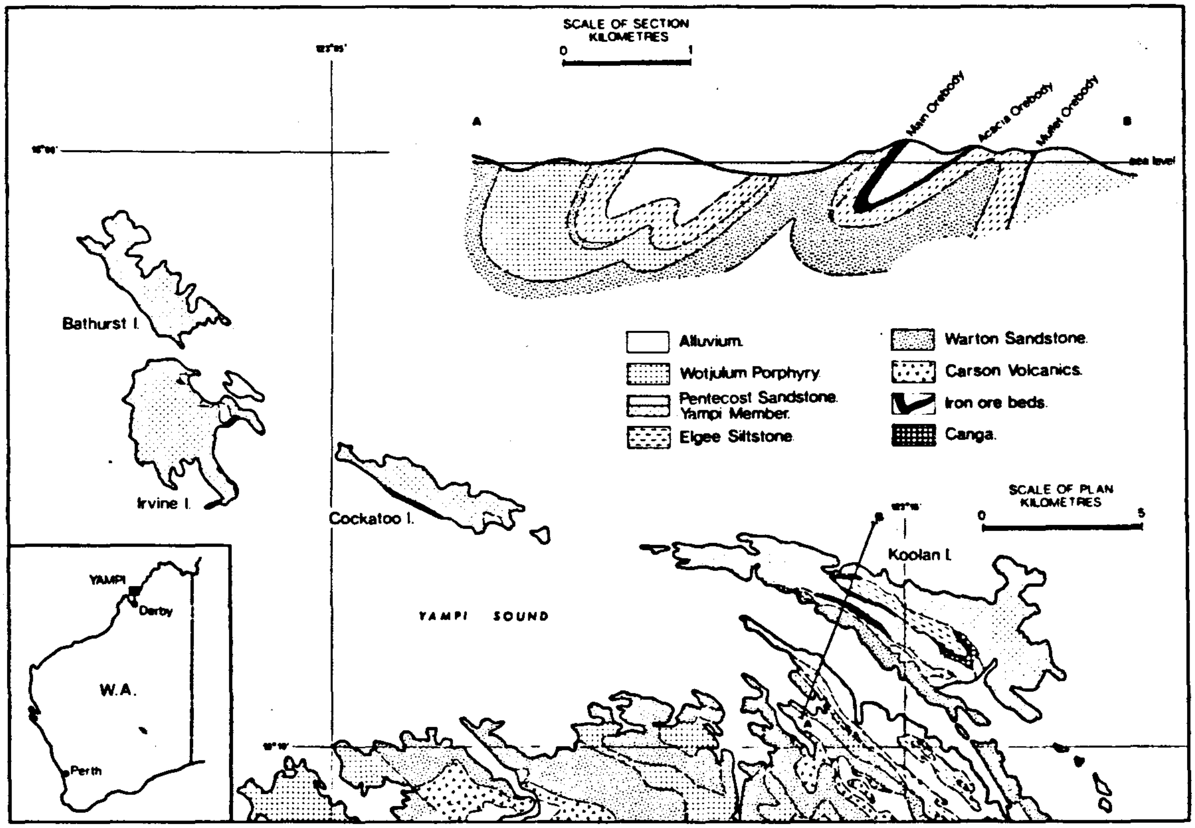


FIG. 19—Iron Ore Occurrences, Yampi Sound. Geology after Bureau of Mineral Resources 1:100 000 geological map, Yampi, preliminary edition.

from Staff, 1975

Robe River Iron Ore

Robe River is an example of the pisolitic limonite ore. The pisoliths are a few mm wide and and the minerals within them are limonite, goethite, maghemite, and hematite. These minerals form concentric layers around a hematite core.

The deposits are Tertiary age and lie unconformably on Proterozoic rock. The ore forms cappings on mesas and are usually less than 20 m thick but may be up to 60 m thick.

Figure 20 ROBE RIVER MESAS

The Robe River mesa deposits viewed from the air are identifiable by the dark ore cappings.

In addition to the lack of overburden atop the mesas, Robe River has the added advantage of an excellent seaport.

Anonymous, 1970

The pisolitic ore is the result of past drainage from the Hammersly Iron Province. The iron accumulated by fixation in meandring rivers that drained the province, until post Tertiary rejuvenation took place.

The footwall border of the deposit is fairly sharp, marked by declining iron and increasing iron and increasing silica and aluminum.

A typical mesa section is illustrated in Table 5.

Table 5 CHEMICAL ANALYSIS OF MESA PROFILE

Footage From	To	Fe	SiO_2	Al_2O_3	LOI	P
0	5	56·5	7·6	4·8	8·4	
5	10	56·8	5·9	4·4	9·2	0·03
10	15	58·8	5·2	2·7	8·5	
15	20	5·85	5·3	2·8	8·1	
20	25	59·4	4·7	2·7	7·6	
25	30	59·2	4·9	2·6	8·1	
30	35	59·2	4·8	2·3	8·1	0·04
35	40	57·9	4·5	2·2	10·6	
40	45	57·9	4·5	2·2	10·8	
45	50	58·1	4·3	3·0	10·6	
50	55	58·8	4·0	1·7	10·1	
55	60	56·5	5·9	3·3	9·9	0·05
60	65	53·6	9·1	4·1	10·5	
65	70	52·4	10·0	3·3	12·1	0·05
70	75	51·7	10·0	4·0	12·1	

from Adair, 1975

One advantage of the Robe River ore is that overburden is only rarely present. Occasionally vugs occur sizes of 10 cm. to 5 m. caves. The vugs are formed when iron-poor zones are exposed to surface weathering.

Probably the entire 72 km. Robe Valley was mineralized before rejuvenation. The current mesas show erosion features but are very resistant and form steep cliffs.

Middleback Range

The Middleback Range is located in Southern Australia. It is Australia's largest iron works outside of Western Australia. The Middleback Range is the result of strong north-south folds on much broader east-west anticlinal folds. Major faults occur east of the range and in the plain below. The relief decreases away from the range in a series of fault scarps.

The iron ore lies within folded jaspilite which average about 30% iron and often form resistant ridges. Scree deposits also form in the range, they exist near the high grade hematite deposits.

The jaspilites are banded and range from limonite jaspilites to hematite jaspilites. Further down section are tremolite-actinolite jaspilites containing magnetite. The rest of the Proterozoic section consists of schist,carbonate, sericite and gneiss.

The iron ore formed from hypogene hydrothermal solutions and/or heated supergene waters. These fluids would carry iron from anticlines to synclinal structures. An alternative hypothesis is that supergene enrichment of jaspilite,already in synclinal traps, took place.

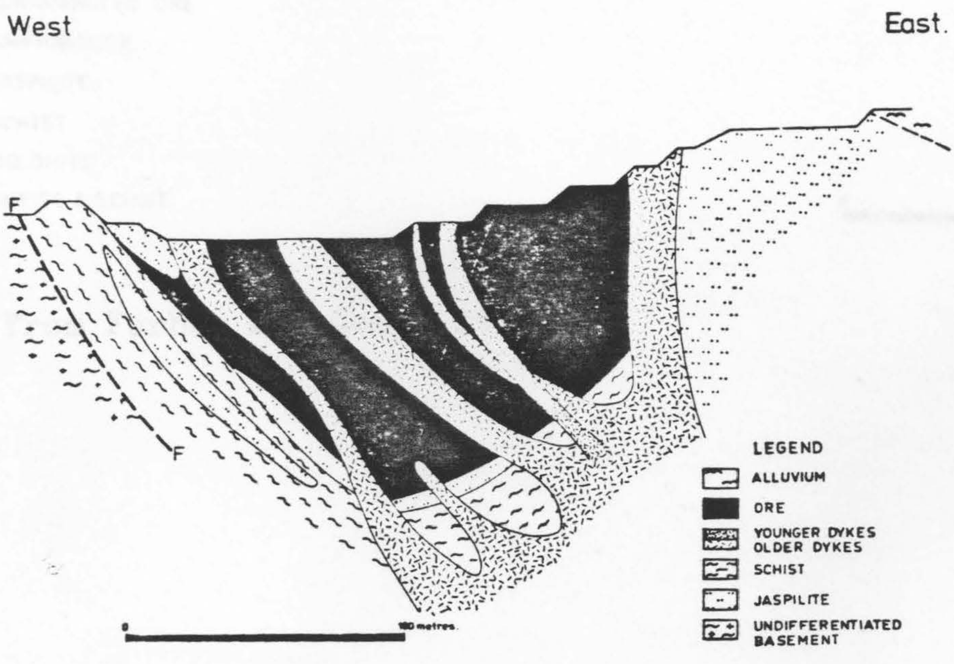
The chief iron ore developments in the Middleback Range are Iron Monarch, Iron Prince, Iron Baron, and Iron Duke.

Iron Monarch Deposit -- Middleback Range

Iron Monarch is part of the Iron Knob development, the most famous in the Middleback Range. The Iron Monarch ore occurs in a hill which is the nose of a syncline. Originally the ore extended 650 m and was 900 m wide. It is truncated by a dike which intruded through a northwest trending fault. Three ages and orientations of faults are present. One group is like the above fault with the dike. There is also a set of both strike slip and dip slip faults. These faults may have been responsible for ore enrichment.

In addition to hematite, the ore also consists of magnetite and manganese. Manganese content increases near the dike. A smaller lens of ore occurs on the east slope of Iron Monarch Hill and scree orebodies are present on both sides.

Figure 21 IRON MONARCH CROSS SECTION



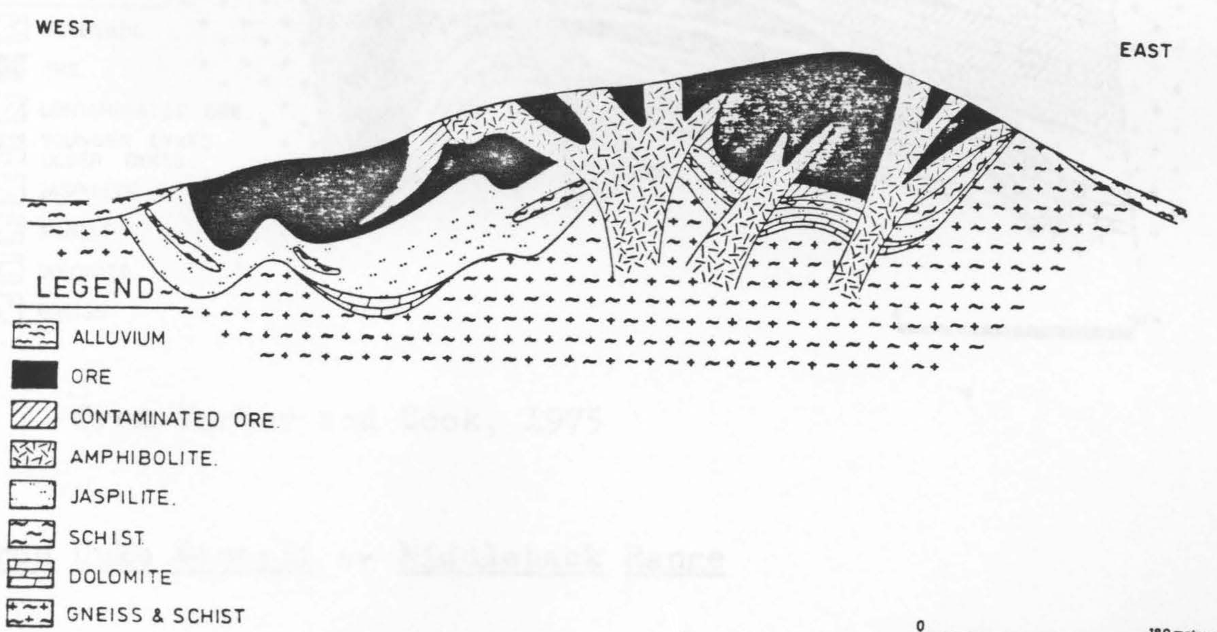
from Furber and Cook, 1975

Iron Prince Deposit -- Middleback Range

This north-northeast trending ore is located in the west limb of a syncline and thin beds of ore occur in the adjacent anticline.

The ore is chiefly hematite, derived from jaspilite. The orebody is nearly 1500 m long and 200 m wide. It contains schistose which was formerly dikes and sills. Faulting in the east terminates the orebody.

Figure 22 IRON PRINCE CROSS SECTION



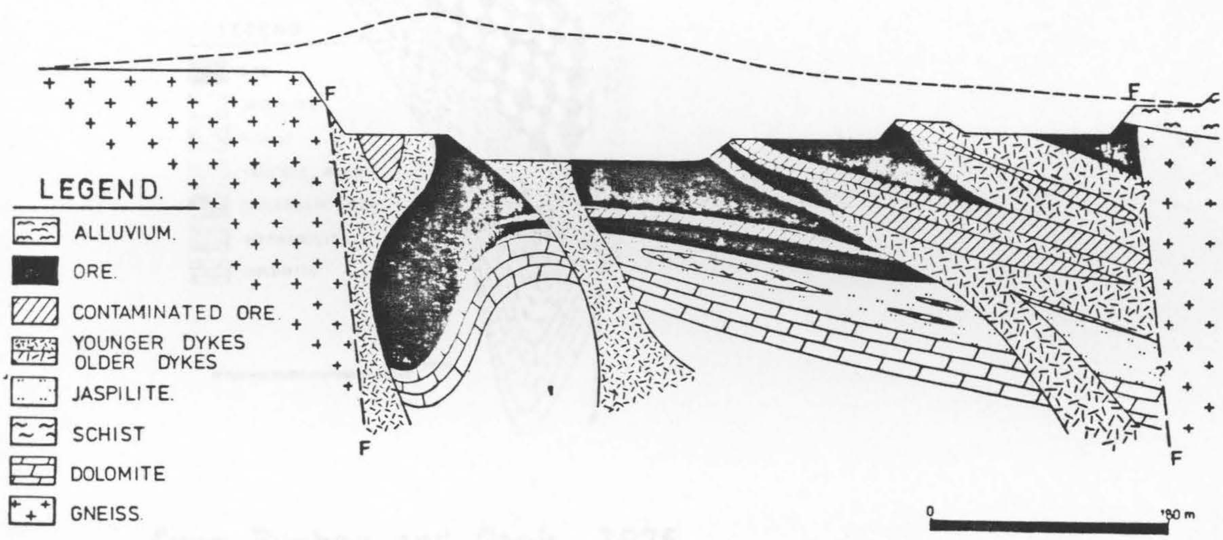
From Furber and Cook, 1975

Iron Baron Deposit -- Middleback Range

This orebody trends north 1500 m and is between 150-600 m wide. The ore occurs in two synclinal traps. The synclines are seperated by intrusive amphibolite. It is cut by transverse faults and plunges north.

Figure 23 IRON BARON CROSS SECTION

West East



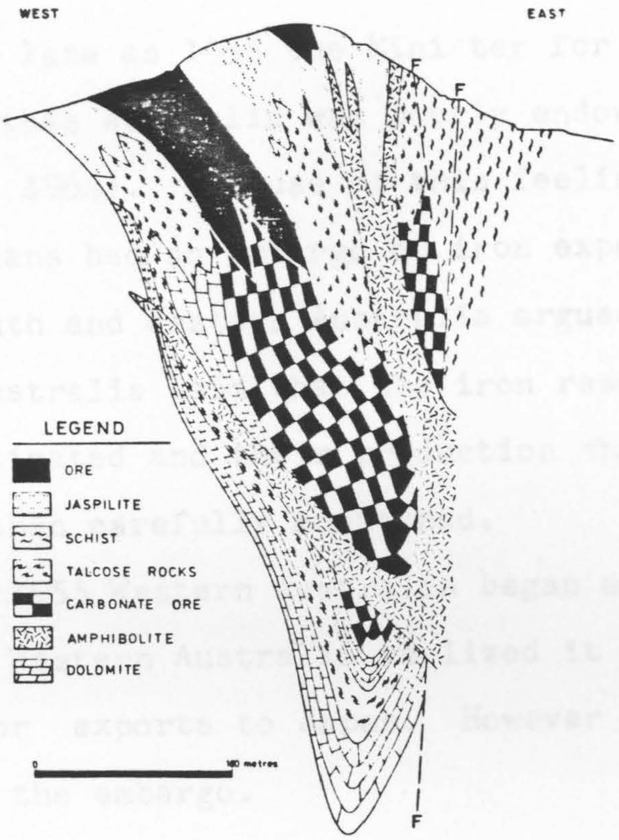
from Furber and Cook, 1975

Iron Duke Deposit -- Middleback Range

Here the ore lies in the east limb of a syncline for "2220 m and a maximum width of 180 m" (Furber and Cook, 1975). Thrust faults and dikes are present in the east with magnetite adjacent to the dikes. The ore grades into carbonates.

See Figure 24.

Figure 24 CROSS SECTION OF IRON DUKE



from Furber and Cook, 1975

In 1975 there had not been any production from Iron Duke or many of the orebodies.

IRON PRODUCTION

"As late as 1955 the Minister for External Affairs... claimed that Australia was poorly endowed with iron resources " (Hughes, 1964). Because of this feeling of scarcity the Australians had an embargo on iron exports.

South and Western Australia argued against this attitude. South Australia said that the iron resources were greatly underestimated and their production should be increased rather than carefully monitored.

In 1955 Western Australia began a survey of its iron ore. By 1957 Western Australia realized it great potential and made plans for exports to Japan. However the Commonwealth refused to lift the embargo.

By 1960, under increased pressure, the government issued a partial lifting of the embargo. The different states and branches of the Commonwealth government all were reporting increases in iron resources. However exports from high grade deposits such as the Middleback Range, Yampi Sound, and Koolyanobbing were still prohibited. There was, however, a surge in exploration due to the partial lifting. Development of scree and jaspilite ores began. In 1961, the Hammersly Range Iron Ore was discovered. The potential of this deposit was twice that of any other deposit in the world. The insecurity of limited resources was disappearing but the still persisted.

Lack of capital prevented a boom in production. Thoughts of adding to foreign earnings by shipping the ore abroad were discouraging.

The iron industry started to grow and the embargo faded out. The pioneering Broken Hill Proprietary was largely responsible for this development. BHP constructed steel smelting and rolling plants in South Australia. In turn BHP received sole rights to the Middleback Range. Further integrated steelworks followed that could provide a variety of steel products. Increased power facilities, machine shops, roads, housing, and drainage were all either direct or indirect products of BHP's own development.

This trend continued elsewhere and other industries followed BHP's lead. 1960 saw the first uniform gauge railroad stretch across Australia.

Australia developed new industries and new attitudes under BHP and the growth has not stopped. In 1966, less than two years after signing sales contracts with Japan, Hammersly Iron Pty. Ltd. made its initial shipments.

> The expenditure of more than $100 million had created a large open-pit mine, a crushing plant, storage and load out facilities for sized ore, and a supporting township at Mt. Tom Price; a 182 mile standard gauge railway; and port and loading facilities...as well as a port town.. (Anonymous, 1967).

In 1964 no iron ore was exported from Australia.

> Five years later, and after expenditures amounting to approximately one half billion dollars, BHP and seven new companies exported about 15 million long tons of iron ore and pellets (Beall, 1969).

Obviously the Australian iron industry blossomed to influence world supplies very quickly, and today they are frontrunners in iron ore exports.

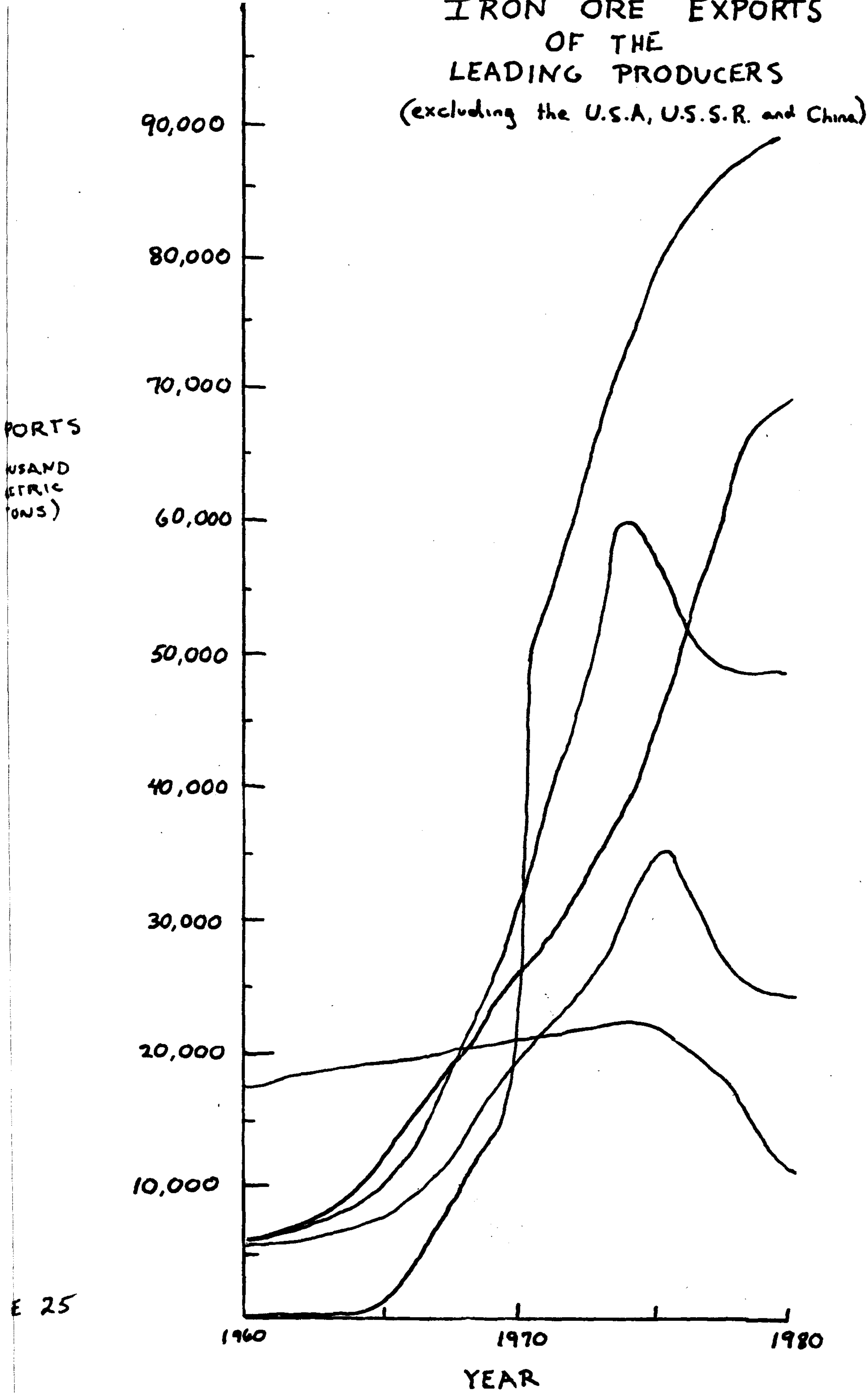
The immediate demand for Australian iron ore comes from Japan. This is market is nearby and of such great quantity that Australia has a good jump on leading the world in iron ore exports; it is the largest iron importer to Japan. In order to secure this position Australia constructed a new port, deepened another port, built over 600 miles new standard gauge railways, built many new facilities and at least six new communities.

This aggressive attitude did capture Japan's market and keeps the industry growing. In 1969 Mt. Newman was exporting ore; Mt. Goldsworthy opened in 1966 and was expanding in 1969. Robe River operations were being set-up in 1970,at a cost of 300 million dollars, and shipments started in 1972.

These developments translated into a great new income for Australia and a large impact on the world market. Figure 25 shows how Australia leaped to its new role in world iron ore trade. It is important to note that other than Australia, Brazil is the only nation with a strong enough hand in the world market to survive the recent economic slump without a large downturn in productivity and exports. Australia ranks second to only the U.S.S.R. in total iron ore production, but the Soviet Union does not play a leading role in world markets because of its own consumption and policies. (For these reasons the U.S.A., U.S.S.R.,and China have been excluded from Figure 25.) Since Australian reserves are in the thousands of of millions of tons and world demand is projected to continue its upward path, Australia can become only more significant in world trade of iron ore in the next twenty years.

IRON ORE EXPORTS OF THE LEADING PRODUCERS

(excluding the U.S.A, U.S.S.R. and China)



E 25

As costs increase worldwide, Australia's advantages include: easily accessible deposits, relatively pure and high grade ores, local ports, inexpensive ocean transport, and an integrated industry.

> Iron ore developments in Australia have grown rapidly because of the need for iron ore in Japan. However, Australian ores and their products, already reaching steelmakers in Europe and the U.S. will increase in volume to these distant consumers because of the size and quality of the deposits, the capabilities of the companies which can produce them at low cost and because of reduction in shipping cost through the increased usage of large tonnage and multi-cargo vessels (Beall, 1969).

Figure 26 PRINCIPAL IRON ORE LOCALITIES

FIG. 24-3

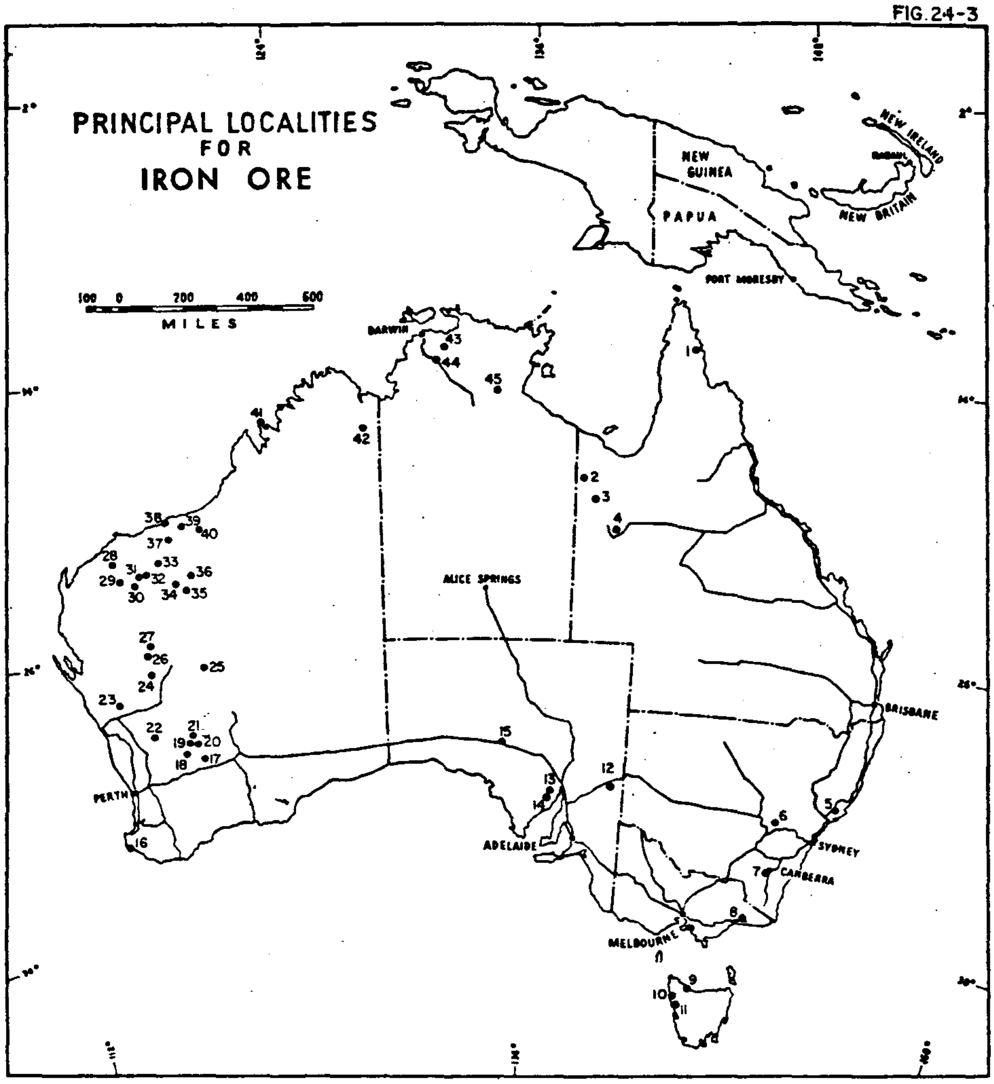


Fig. 24-3.
1. Iron Range.
2. Constance Range.
3. Mount Oxide.
4. Mount Philp.
5. Williams River, Karauah River.
6. Cadia.
7. Paddys River.
8. Nowa Nowa.
9. Natone, Highclere, Hampshire, Blythe River.
10. Savage River, Meredith River, Paradise River, Rocky River.
11. Comstock.
12. Grant's Quarry, Albert's Quarry.
13. IRON KNOB, IRON MONARCH.
14. MIDDLEBACK RANGES.
15. Wilgena Hill.
16. Scott River.
17. KOOLYANOBBING.
18. Mayfield.
19. Mount Jackson, Windarling.
20. Bungalbin.
21. Mount Manning, Pigeon Rocks.
22. Mount Gibson.
23. Tallering Peak.
24. Weld Range.
25. Joyners Find.
26. Mount Hale.
27. Mount Gould.
28. Robe River.
29. Duck Creek.
30. Turner River, Mount Turner.
31. Mount Brockman.
32. Hamersley.
33. Mulga Downs.
34. Weeli Wolli Spring.
35. Mount Newman.
36. Roy Hill.
37. Strelley Gorge.
38. Ord Range.
39. Mount Goldsworthy.
40. Yarrie.
41. YAMPI SOUND.
42. Pompeys Pillar.
43. Mount Bundey.
44. Burrundie.
45. Roper River.

from McLeod, 1965

MINERAL SANDS -- TITANIUM AND ZIRCON

Although titanium is abundant in the earth's crust, only ilmenite, altered ilmenite, and rutile are considered titanium ore minerals.

Current mining of heavy mineral sands in Australia is primarily in three areas: the southeastern coast along New South Wales and Queensland, the western coast area just south of Perth, and north of Perth several miles inland.

The requirements for titanium placers are:

> 1) a 'hinterland' of crystalline rocks in which the heavy minerals were accessory constituents, 2) a period of deep weathering, 3) uplift with rapid erosion and quick dumping into the sea of the products of stream erosion, and 4) emergence of the coastline with longshore drift and high-energy waves acting during the process of shoreline straightening (Lynd and Lefond, 1975).

Deposits containing 50% heavy minerals were common in Austrlaia but have been mined out. The average decreased to roughly 3% heavy minerals in the east and 10% in the west. The inland deposit developed at Eneabba in 1970 varies between 5-10%.

Eastern Mineral Sands

The heavy mineral beach and dune system extends 1000 km along the coast, averages 3 km in width and roughly 30 m in depth at sea level , decreasing inland.

The mineral deposits occur on the present beach and in a lofted dune system. The development of this system is complex.

Meandering Tertiary streams drained a peneplained continent cutting deep valleys. The stream transported Mesozoic and Tertiary sediments, which included volcanics, eastward. The Ice Age approached and sea level dropped. This also caused the streams to cut deeper channels and it left a 5-10 km wide margin of sediment exposed to the surface elements. The unconsolidated sands were blown inland forming the upper dune system. The Ice Age subsequently ceased and the coast and deep river cuts were drownd.

A new equilibrium was reached by rebuilding the coast. The high dune system became a source of sediment for the new stream system and was used to rebuild the coast. When the coast had advanced far enough seaward, and embayments had been filled by the sediments, a new base level was set and a third period began.

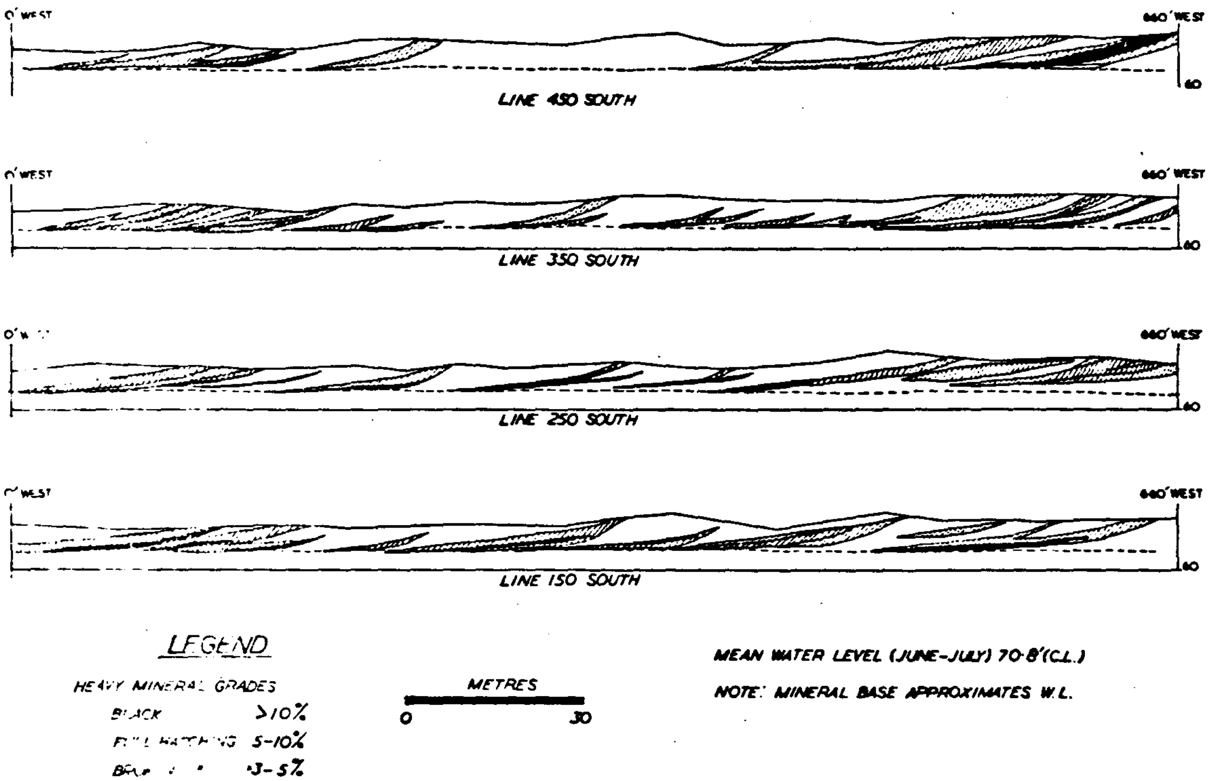
In this stage the rivers no longer carried a high load of sand to the ocean. Their load was mainly clays and silts. The ocean currents stopped redistributing sand to straighten the drowned coast, and now rework material in the surf zone.

This long cycle of erosion and deposition offers many chances for the development of a heavy mineral placer. Usually these placers are redistributed in later erosion, however they occasionally are preserved. These deposits are formed by surf, wind, and streams.

Surf concentrations form under severe weather conditions. After a cyclone-type storm, much of a beach my be eroded. However the heavier sands will not be transported away and instead form a series of lenses in the top 10 m of a beach.

These lenses are soon subject to the erosion of wind and tide. If subsequent accretion takes place, the seam will be preserved. This is the case in both present and paleobeaches.

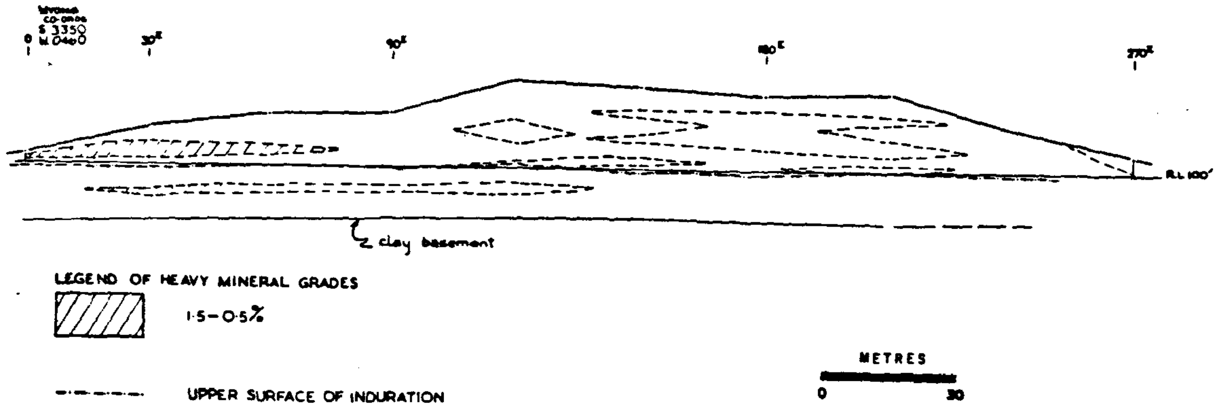
Figure 27 CROSS SECTION OF BEACH DEPOSITS



from McKellar, 1975

As wind develops transgressive dunes, heavy metals build up at certain points within the dune, where wind velocity is less, and lighter sands continue in transport. Development of a large low grade ore formed by this process in the high dunes.

Figure 28 CROSS SECTION OF HIGH DUNE DEPOSIT



from McKellar, 1975

Finally streams may deposit heavy sands in scours and meanders. These ores are of less significance but sometimes are encountered below beach deposits

Table 6 ...gives percentages of certain mineral at selected localities from north to south. It shows the increasing proportion of rutile and zircon at the expense of ilmenite (McKellar, 1975).

Table 6 LONGSHORE TRANSPORT AND HEAVY SAND DEPOSITS

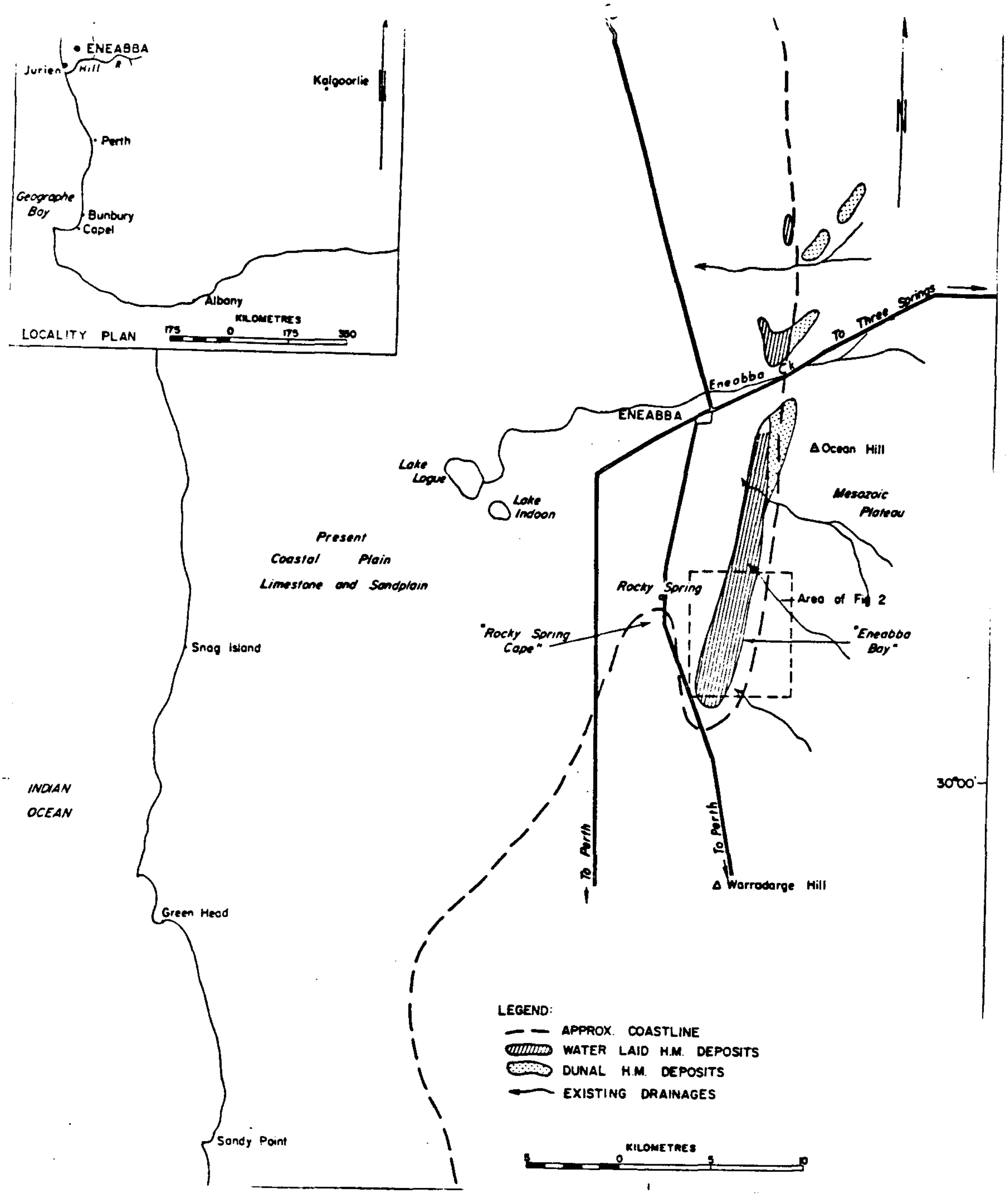
Locality (see Fig. 1)	R %	Z %	(R+Z) %	IL %	(R+Z)/(IL)	Cr_2O_3 %	Mon %
Yeppoon	4·5	9·9	14·4	62·8	·23	·35	·1
Moreton Is.	21·5	15·4	36·9	47·1	·78	2·11	·5
N.S.I.—							
High dunes	15·8	12·5	28·3	50·1	·56	1·29	·2
Below S.L.	18·8	15·6	34·4	39·7	·87	1·90	·3
Beach	31·1	22·9	54·0	27·0	2·00	3·31	·3
Evans Head	29·0	32·0	61·0	22·9	2·66	4·45	·6
Jerusalem Creek	31·3	36·5	67·8	16·6	4·08	5·99	·8
Bonny Hills	38·6	40·3	78·9	15·7	5·03	8·46	·3
Dunbogan	35·2	38·2	73·4	17·5	4·19	5·0	·3
Diamond Head	38·6	28·4	67·0	13·2	5·08	3·4	·5
Swan Bay	29·4	35·3	64·7	12·4	5·22	2·5	·2
Tuggerah—							
High dunes	46·2	22·7	68·9	14·0	4·92	1·0	·8
Low dunes	50·4	30·0	80·4	10·0	8·04	1·5	·4

from McKellar, 1975

Eneabba Mineral Sands

The great deposits at Eneabba were formed in a bay enviornment at a higher sea level. The bay received heavy minerals from streams and they were deposited by prevailing southwesterly waves and wind. See Figure 29.

Figure 29 PHYSIOGRAPHIC ELEMENTS AT THE TIME OF DEPOSITION OF ENEABBA HEAVY MINERAL SANDS

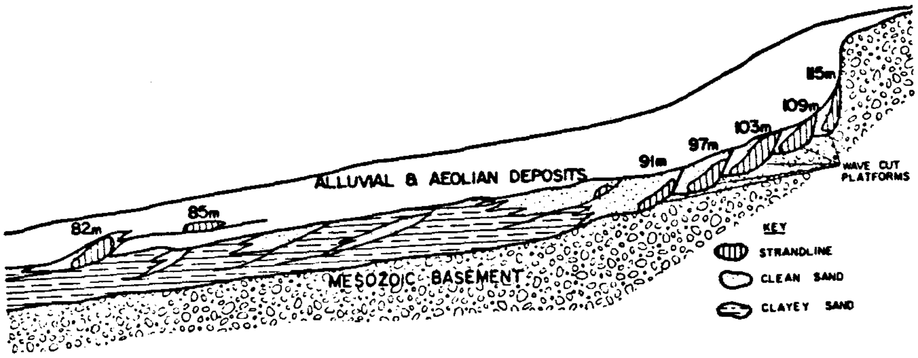


from Lissiman and Oxenford, 1975

The same circumstances are currently depositing heavy minerals in the Geographe Bay (Inset Figure 29). The minerals are deposited as the longshore current rounds the southern cape losing velocity and/or forming an eddy in the bay.

The deposit occurs in parallel strands resulting from various sea levels and wave carved terraces. See Figures 30 and 31.

Figure 30 CROSS SECTION OF ENEABBA DEPOSIT



after J. McDonald in Lissiman and Oxenford, 1975

The upper part of the deposit was formed by dunes after a drop in sea level. Content within the deposit varies randomly.

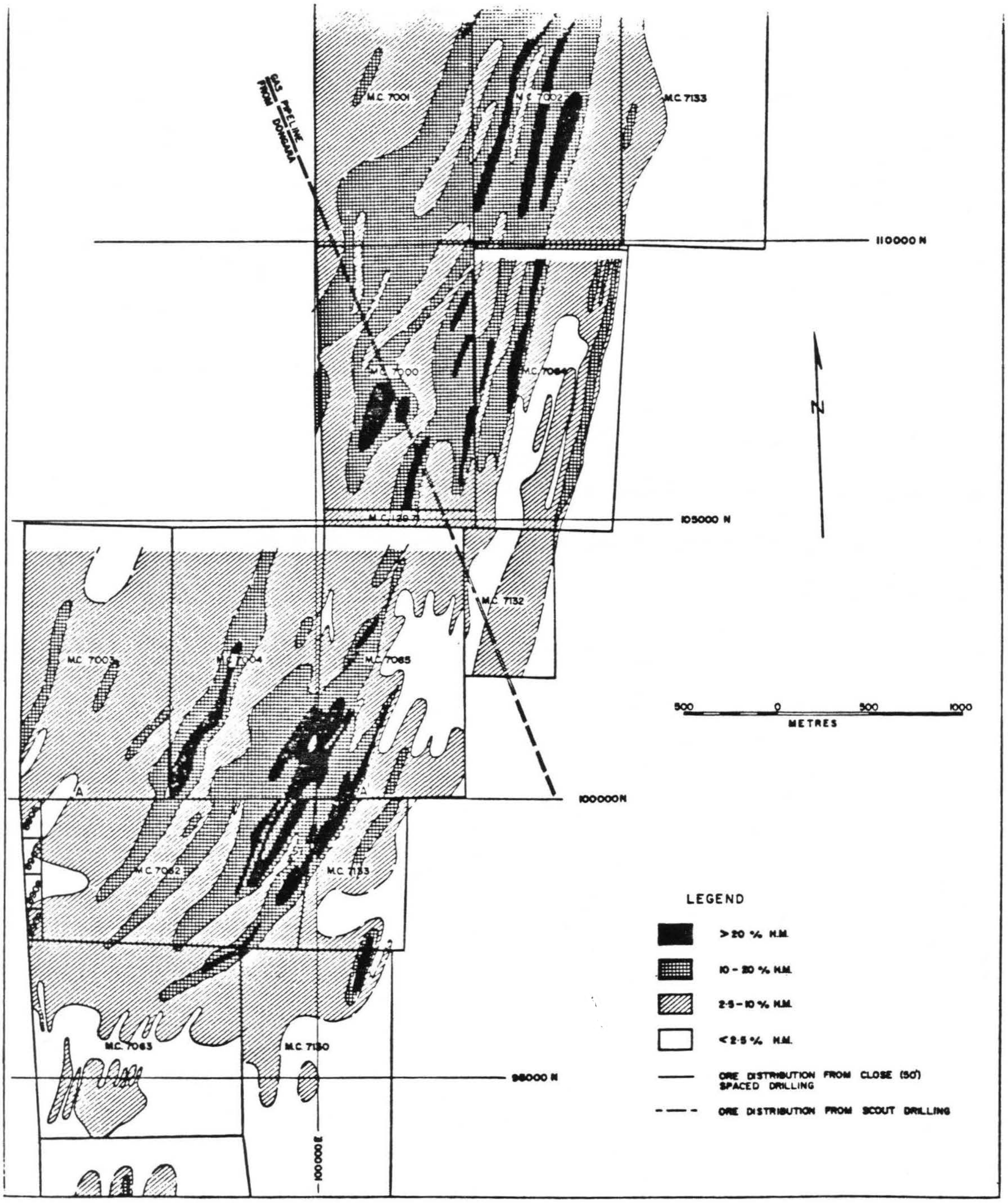
Table 7 HEAVY MINERAL CONTENT AT ENEABBA

Source of sample	Ilmenite	Zircon	Rutile	Leucoxene	Kyanite	Monazite	Others [1]
128 m strand	46·0	35·7	7·6	— [2]	3·7	— [2]	7·0
115 m strand	27·9	61·1	4·9	0·5	2·4	1·0	2·2
109 m + 103 m strand	53·3	23·3	10·0	1·3	4·9	0·7	6·5
97 m strand	61·9	15·1	10·2	1·8	4·2	0·8	6·0
91 m strand	62·1	18·1	8·0	1·4	4·0	2·4	4·0
85 m strand—north	48·5	6·8	8·8	1·6	— [2]	0·4	34·0
—south	50·9	9·4	8·2	2·9	— [2]	0·6	27·9
82 m strand—north	45·6	17·6	8·4	1·4	— [2]	0·8	26·1
—south	52·3	8·7	10·3	2·7	— [2]	0·4	25·5
Bulk sample R, (dunal sand—S extremity)	38·4	29·2	9·5	1·5	11·8	1·8	7·8
Bulk sample L, (dunal sand—S area)	45·8	22·2	9·6	3·2	9·7	0·3	9·2
Zone A (dunal sand—N extremity)	62·8	11·8	14·1	0·8	2·8	Tr	7·7
Surface (dunal sand—W area)	45·2	18·5	13·7	4·8	— [2]	0·1	17·7

1 "Others" includes staurolite; silimanite; garnet; spinel; hornblende; pyroxene; brookite; limonite; tourmaline; laterite pebbles.
2 Included in "others".

from Lissiman and Oxenford, 1975

Figure 3| HEAVY MINERAL DISTRIBUTION AT ENEABBA



from Lissiman and Oxenford, 1975

The high zircon content of the 128 m and **115 m strands is a** result of their direct erosion of cliff faces. They **were therefore** under higher energy and have better sorting.

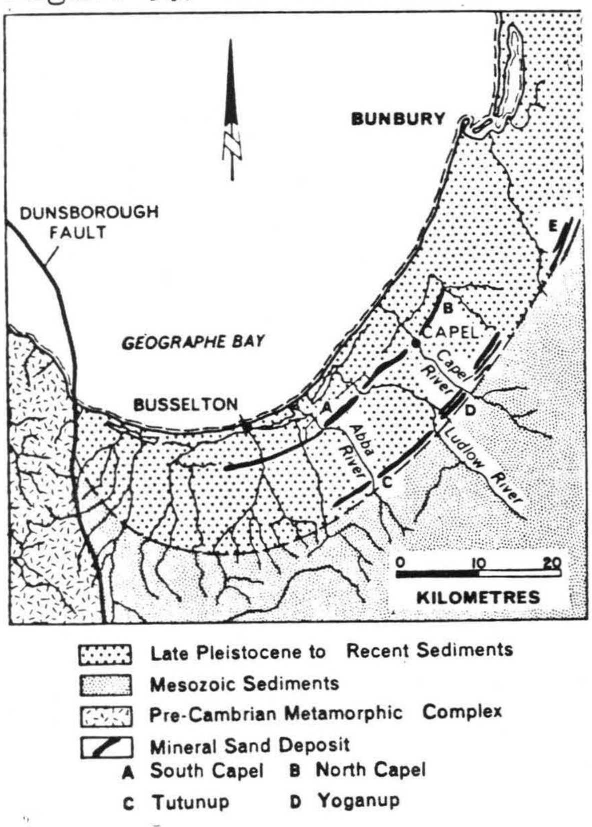
Ilmenite at Eneabba has a high TiO_2 content.

The percentage of TiO_2 content in the deposit is 63%. The deposit is one of the largest in the world and appears to have between 25 and 30 million tonnes of recoverable heavy minenerals (Lissiman and Oxenford, 1975).

Western Mineral Sands

The western deposits are located in the coastal region of Geographe Bay . (See Figure 32). Here again there is evidence of wave cut terraces and dune deposits, The heavy mineral sands are oriented parallel to the coast, representing stabilization of a fluctuatinf coastline. These fluctuations also redistributed strands, formed new deposits, and intermixed different levels of minerals.

Figure 32 HEAVY MINERAL SANDS AT GEOGRAPHE BAY

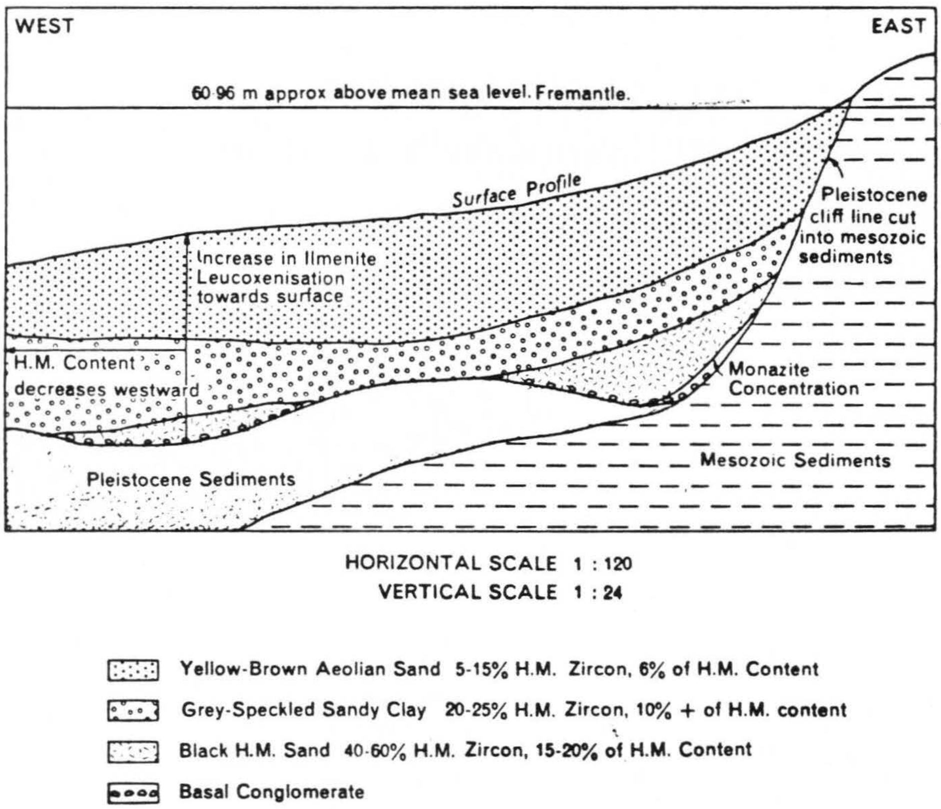


from Welch, Sofoulis, and Fitzgerald, 1975

The heavy minerals are derived from the Mesozoic sediments west of the Darling Fault. Originally these minerals were transported from pre-Cambrian metamorphic and igneous rock east of the Darling Fault.

Ilmenite is the chief constituient of the ore with zircon and little rutile present. Zircon content increases with age. Figure 33 is a typical cross section for this area.

Figure 33 CROSS SECTION OF GEOGRAPHE BAY TYPE DEPOSIT



from Welch, Sofoulis, Fitzgerald, 1975

These sands range from 3-6% heavy minerals.

> With the recent increase in price obtained for some of the products , a new cut-off of 5 cubic yards of overburden removed per ton of heavy mineral recovered for ore over 10 perent is currently being revised.... (Welch, Sofoulis, Fitzgerald, 1975).

Ilmenite is the principal heavy metal with magnatite and leucoxene also present in large amounts. Amounts of zircon mined are less, and the quantity of rutile is small.

Drill cores often detect scarps that marked the limits of past transgressions and probably represent cliffs. En echelon structure is common in the western ores. This is characteristic of foreshore deposits, reflecting sea migration and sea level fluctuation. The older strands are farther inland. TiO_2 content increases inland.

Exploration to the north revealed other heavy mineral strands there also. The resources of titanium in Australia are listed below.

Table 8 TITANIUM RESOURCES OF AUSTRALIA IN SHORT TONS

	Primary Deposits		Beach Deposits			All Deposits	
State	Titanif-erous Material	TiO_2	Rutile	Ilmenite	TiO_2	Titanif-erous Material	TiO_2
New South Wales	2,264,000	207,000	568,000	360,000	726,000	4,037,000	933,000
Queensland	–	–	2,107,000	3,325,000	3,731,000	7,784,000	3,731,000
Tasmania	–	–	–	50,000	26,000	50,000	26,000
Western Australia	1,680,000	213,000	14,000	554,000	301,000	2,576,000	514,000
Total	3,944,000	420,000	2,689,000	4,289,000	4,784,000	14,447,000	5,204,000

Source: Miller 1957

from Lynd and Lefond, 1975

HEAVY MINERAL SAND PRODUCTION -- TITANIUM AND ZIRCON

After running a very tight second to the U.S., Australian ilmenite production was the highest in 1970. Norway is also a large producer of titanium. These three countries produce roughly 80% of the world's ilmenite. Australia has less competition in the rutile industry. Australia, producing roughly 400,000 short ton per year, does not share the top with any other nation. India is the next largest producer mining less than 10% of what Australia mines.

Only a handful of nations have titanium reserves as large or larger than Australia's. Of these, the U.S. imports heavy minerals because of its high consumption, India's production is of a far less amount, Canada's titanium is not the quality used for pigments because of its high iron content, and Norway has no significant rutile reserves although it is strong in the ilmenite market.

Sierra Leone is the only nation that has reserves of rutile that are comparable to Australia's. Rutile production was suspended in Sierra Leone in 1971, when maximum production was only 12% of that in Australia.

Australia nearly has a monopoly on the rutile market and its ilmenite production consistently ranks in the top positions. In addition to having the worlds largest rutile reserves Australia's ilmenite reserves place fifth in the Free World.

In order to determine if a country has a sizable imapact on the world market, the final analysis is comparing exports. Table 11 shows that of the large titanium producers only a handful have large exports and, of these, only Australia has significant rutile exports. Notice the Australian rutile output in 1966 and the world total. Excluding the U.S.S.R., Australia produced 98% of the world's rutile.

The importance of zircon in the heavy mineral sands can be seen in Tables 9 and 10.

Table 9 ZIRCONIUM PRODUCTION IN LONG TONS

Producing Country and Description	1961	1962	1963	1964	1965	1966
COMMONWEALTH COUNTRIES						
Nigeria	743	—	791	153	—	—
Ceylon (*b*)	*n.a.*	*n.a.*	*n.a.*	*n.a.*	(*a*) 2	151
Malaysia (West) (*a*) ..	56	60	258	145	582	774
Australia—						
Zircon concentrates ..	136,462	133,844	184,830	184,082	226,863	237,846
OTHER COUNTRIES						
Egypt	94	168	39	40	—	383
Malagasy Republic ..	315	348	382	504	634	693
Senegal	5,303	2,299	3,022	546	—	—
South Africa	6,792	6,769	2,364	—	—	—
Brazil (*b*)	6,612	2,359	350	508	485	487

Zirconium minerals are also known to have been produced in India, the U.S.S.R., the United States and Cambodia.

Production of zirconium sponge metal in the United States was as follows (long tons): 1961—1,515; 1962—1,136; 1963—912; 1964—*n.a.*; 1965—*n.a.*; 1966—*n.a.*

(*a*) Exports.

(*b*) Zircon and baddeleyite.

from Anonymous, 1968

Table 10 ZIRCONIUM EXPORTS IN LONG TONS

Exporting Country and Description	1961	1962	1963	1964	1965	1966
COMMONWEALTH COUNTRIES						
Nigeria—						
Ores and concentrates	(a) —	(a) 495	876	—	20	—
Ceylon—						
Baddeleyite	n.a.	n.a.	n.a.	n.a.	2	n.a.
Malaysia (West)—						
Zircon	56	60	258	145	582	774
Australia—						
Zircon concentrates ..	140,333	131,843	179,697	198,664	216,661	210,428
OTHER COUNTRIES						
Germany (Federal)—						
Ore	591	575	567	1,669	1,252	777
Malagasy Republic ..	n.a.	3	n.a.	—	3	123
Senegal—						
Zircon	5,280	2,054	3,247	—	—	—
South Africa—						
Zircon concentrates ..	5,240	5,950	2,504	71	2	—
United States—						
Ores and concentrates	1,140	1,487	1,266	2,232	1,573	2,063
Zirconium metal, etc. ..	80	97	131	238	95	57
Brazil (b)	53	—	—	—	—	—

(a) Years ended March 31 of year following that stated.
(b) Zircon and baddeleyite.

from Anonymous, 1968

Australia is far and away the world's largest producer of zirconium and approximately 95% of this is exported. The nations, such as Norway and Canada, that produced ilmenite on a large scale do not have this additional income of zircon. This luxury increases the feasibility of mining Australian and helps make Australia the overall dominant supplier of heavy minerals.

> Today...Australia is the world's most important heavy mineral sand mining country, producing over 95% of the rutile mined in the Free World, over 82% of the zircon and over 45% of the sand ilmenite (Lynd and Lefond, 1975).

Table 11 TITANIUM EXPORTS IN LONG TONS

Exporting Country and Description	1961	1962	1963	1964	1965	1966
COMMONWEALTH COUNTRIES						
United Kingdom—						
Ferro-titanium	533	552	1,024	1,076	1,251	1,085
Sierra Leone—						
Rutile concentrates ..	—	—	100	—	—	7
Canada—						
Titanium dioxide slag (70% TiO_2)	(a)	(a)	(a)	(a)	(a)	(a)
Ceylon—						
Ilmenite..	—	2,750	19,857	36,982	59,588	40,549
India—						
Ilmenite..	123,235	99,649	75,248	26,102	14,857	31,569
Malaysia (West)—						
Ilmenite	106,871	101,368	146,718	129,222	121,566	116,386
Singapore—						
Titanium oxide.. ..	*n.a.*	124	150	112	111	136
Australia—						
Rutile	99,652	117,291	154,508	193,893	239,454	231,289
Ilmenite..	144,009	155,075	152,040	246,056	360,719	356,462
OTHER COUNTRIES						
Belgium-Luxemburg E.U.—						
Titanium oxide ..	5,715	9,897	6,228	1,563	3,223	3,897
do, extended ..	134	34	3,975	10,648	10,322	9,764
Finland—						
Ilmenite..	34,397	37,176	62,305	49,785	82,608	49,864
Titanium oxide ..	*n.a.*	*n.a.*	*n.a.*	1,496	19,535	21,109
France—						
Titanium minerals ..	725	175	70	5	1,303	555
Ferro-titanium	1,619	1,064	1,387	1,754	2,414	2,228
Titanium oxide ..	6,917	6,664	7,744	10,508	10,557	5,780
do, extended ..	10,230	14,293	17,714	23,507	22,507	26,309
Germany (Federal)—						
Titanium minerals ..	*n.a.*	87	221	427	253	619
Titanium oxide ..	48,285	49,813	53,288	54,808	32,232	28,864
do, extended ..	*n.a.*	85	1,267	14,100	37,554	49,006
Italy—						
Titanium oxide.. ..	7,287	11,519	15,066	13,069	17,339	18,919
Netherlands—						
Titanium oxide.. ..	598	106	2,575	6,090	8,492	10,557
do, extended ..	51	14	51	86	32	564
Norway—						
Ilmenite.. .. .. } Rutile .. .. .. }	298,549	230,094	236,711	275,039	319,118	344,517
Titanium oxide, extended	2,504	1,982	1,650	3,122	5,261	7,865
Spain—						
Ilmenite.. ..	18,966	24,413	20,432	26,299	18,806	9,744
Titanium oxide.. ..	878	1,428	1,203	1,648	1,766	1,587
Sweden—						
Titanium minerals ..	48	26	25	25	43	28
Titanium oxide.. ..	21	26	18	24	82	66
do, extended ..	2	49	66	—	—	—
Cameroun—						
Rutile	—	10	—	—	*n.a.*	*n.a.*
Senegal—						
Ilmenite..	21,317	22,599	13,658	2,114	—	—
South Africa—						
Ilmenite..	80,494	59,356	14,459	16,194	*n.a.*	*n.a.*
Rutile	1,874	289	—	—	—	—

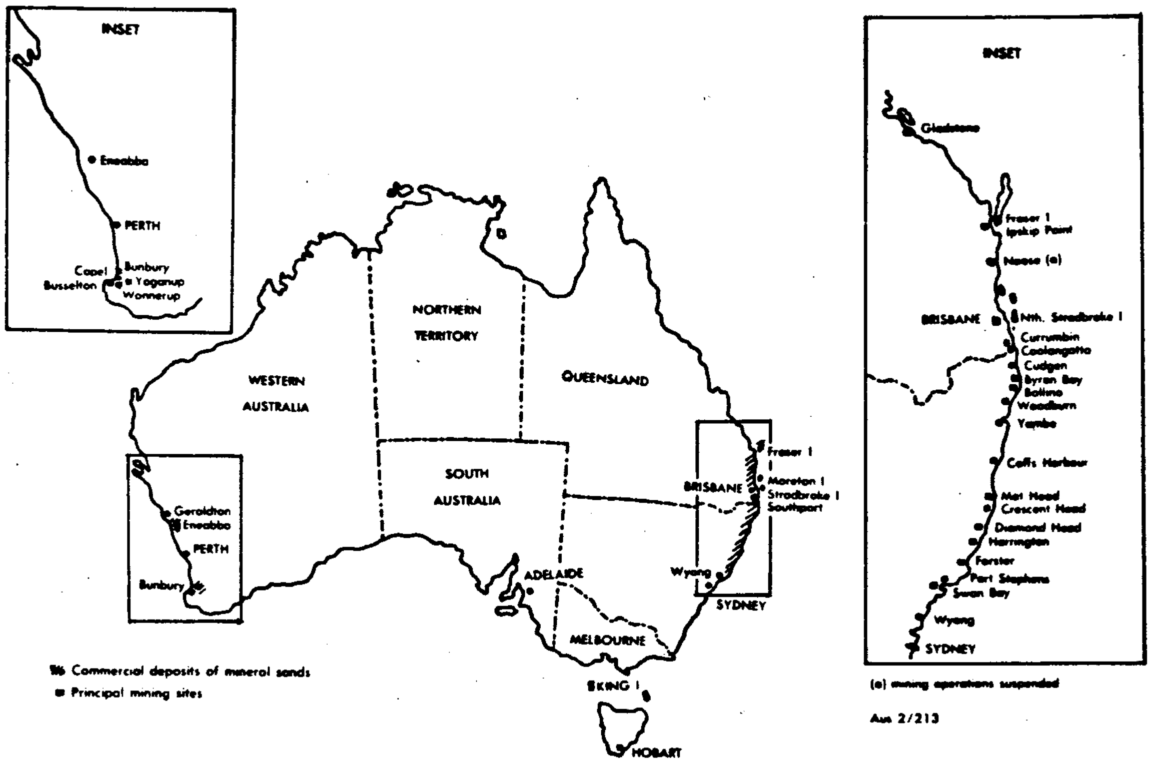
(a) Information not available. Most of the titanium dioxide slag produced in Canada (figures on page 367) is believed to be exported.

OTHER COUNTRIES *(cont.)*						
United States—						
Ores and concentrates..	1,282	1,093	1,082	1,929	1,073	1,161
Titanium metal (a) ..	1,134	1,231	1,567	2,395	2,444	1,547
Ferro-titanium	189	116	188	483	*n.a.*	*n.a.*
Titanium oxide and pigments	27,771	25,977	23,841	26,213	24,014	24,328
Brazil—						
Titanium minerals ..	20	—	—	—	—	9
Japan—						
Titanium sponge metal	1,620	989	1,189	1,549	3,264	4,474
Titanium oxide.. ..	16,199	21,692	23,576	35,411	37,511	37,148

(a) Including alloys and scrap.

from Anonymous, 1968

Figure 34 LOCATIONS OF TITANIUM AND ZIRCONIUM



after Ward, 1972 in Lynd and Lefond, 1975

COAL

Coal measures in Australia are common and widespread. Only the Northern Territory lacks deposits of economic importance. Emphasis is placed on the Permian coal measures because the are the large majority

Bowen Basin

The Bowen Basin is located in eastern Queensland. There are several black coal horizons in the Permian sediments. The western part of the basin formed over a platform and remained stable while the eastern half formed over a marginal foredeep and subsequently underwent deep subsidence.

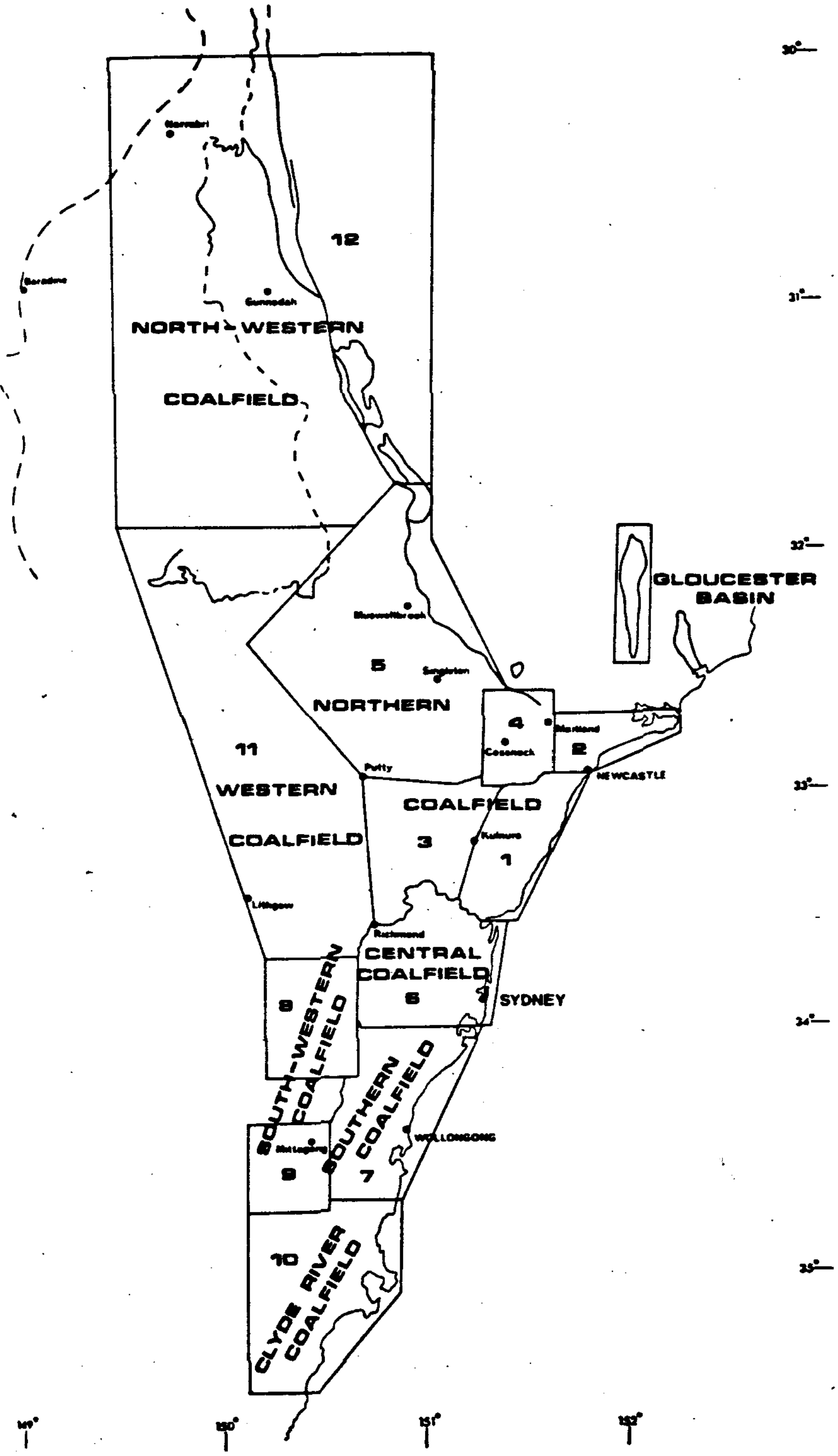
The western elements of Collinsville Shelf and Comet Ridge rested on cratonized basement rock while Denison Trough may overlie a basement fault zone. (See Figure 35).

The foredeep sediments have undergone considerable deformation since being deposited. The Folded Zone and Nebo Synclinorium are the most heavily folded areas, The Folded Zone has such extensive and tight folds that it is not economical to mine there. The Nebo Synclinorium has both open and underground mines despite its domes, anticlines, and synclines. These folds estend westward but only as broad structures.

Faulting occurs throughout the basin. Faults generally strike north-northwest and have upthrows over 600 m.

Deposition began in the Lower Permian in a series of four troughs. Volcanics occur along with terrestrial sediments and coal deposits.

Figure 35 COAL DISTRICTS OF THE BOWEN BASIN



Northern Coalfield

1. Newcastle District: Crapp & Nolan
2. East Maitland-Tomago District: Crapp
3. Wattagan District: Stuntz
4. Maitland-Cessnock-Greta District: Britten
5. Singleton-Muswellbrook District: Britten

Central Coalfield

6. Central Coalfield: Stuntz

Southern Coalfield

7. Southern Coalfield: Wilson

South-Western Coalfield

8. Burragorang region: McLean & Wright
9. Berrima District: Read

Clyde River Coalfield

10. Clyde River Coalfield: Shiels

Western Coalfield

11. Western Coalfield: Morris

North-Western Coalfield

12. North-Western Coalfield: Britten & Hanlon

from Traves and King, 1975

Marine sediments were laid down following a basin-wide transgression. When some regression took place proper enviornments for coal formation arose. There were minor fluctuations in the sea level until another basin-wide transgression at the end of the Lower Permian ended this coal deposition.

A much more extensive regression followed which lead to the deposition of thick coal measures in the Upper Permian. The entire basin was exposed and the volcanics stopped; this resulted in clean thorough coal deposits.

Changing climatic conditions ceased coal deposition at the end of the Permian and relatively little was deposited in the Bowen Basin during the Triassic.

The coal ranges from sub-bituminous to anthracite in a west to east pattern. The western coals underwent slow subsidence and overlying rocks are thin. In the east the overload is much thicker and the rank is anthracite. Overload is believed to be responsible for the rank rather than post depositional deformation, but this pattern is not true. everywhere.

Main Coal Province

The Main Coal Province is located in New South Wales. It consists of several basins including the large Sydney Basin, which is thought to have been connected to Bowen Basin at one time, to form a larger basin.

Coal was deposited in this province in both the Carboniferous and the Permian. The basin was seperated from the open sea by an island arc offshore landmass. This is reflected in the gradation of terrestrial sediments and volcanics into marine sediments to the north.

The basin itself changed as the offshore mass moved southwest,and the final depositional basin was the Sydney-Bowen Basin.

The Sydney Basin, and others in the Main Coal Province, extend offshore where rifting may have taken place. These basins represent a downthrown block or a "half-graben type structure" (Stuntz, 1975). Anticlines are also present in the basin.

The basin has coking coals grading from soft in the north to hard in the south. The harder coke was deposited in the shelf area and was altered by the depth of burial and some intrusions. The softer coke appears to be controlled by the original plant material. The coal may lose its coking quality over a short distance. It is thought that the above controls can operate at scales that would explain both the large gradation and sudden changes.

The thick Upper Permian deposits extend into the adjacent Galilee and Cooper Basins. These were also probably connected to the Bowen-Sydney Basin. However the Galilee and Cooper are not producing at this time.

> Australia's largest and best deposits of black coal are concentrated in two main areas. These are known as Bowen Basin in Queensland and the Main Coal Province of New South Wales; all but the northern portion of the latter is commonly referred to as the Sydney Basin (Raggatt, 1969).

COAL PRODUCTION

The large Permian coal deposits are very marketable because of their versatility. These deposits

> ...are bituminous, i.e. on a dry, ash-free basis the carbon content of the coal varies generally from about 80 to 90 per cent and its hydrogen content from 4.5 to 6%. Within these limits considerable variation in utilization potential exists, some bituminous coals being more suitable for industrial heating and steam raising, some for town gas manufacture and others for coking purposes (Raggart, 1969).

Most of the exports are sold for steaming or coking. However Raggart was correct in his statement because such coal mines can sell to a variety of customers and therefore are more stable.

The location of the coal also makes it more desirable economically. The coal is located near the population centers and this enhances the mines value. The coal is a fairly short distance from the ocean so expensive overland transport is reduced. The nearby ports are capable of handling such bulk exports.

The fact that Australia has economically good coal can not be argued. Australia has a large supply of coal also.

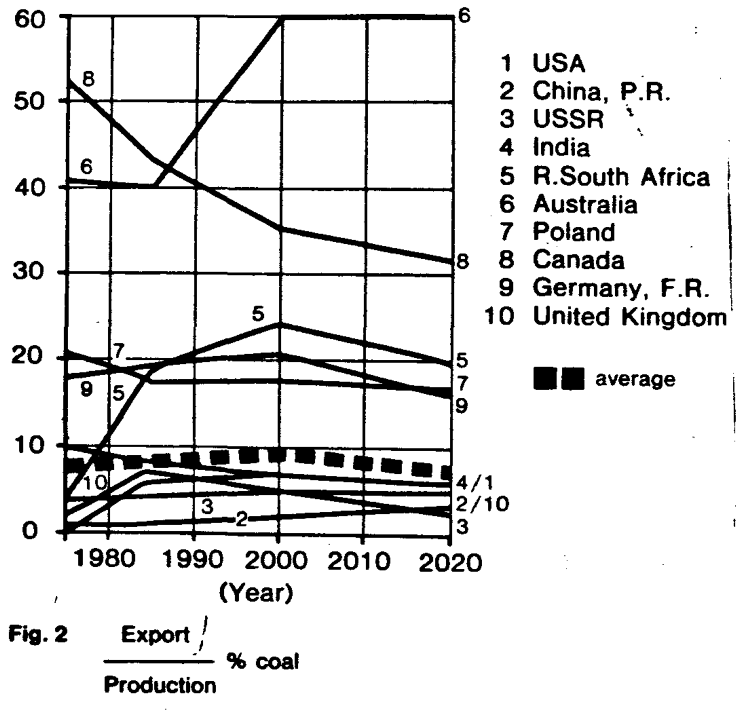
There are 28 sedimentary basins in Australia, 22 contain black coal and brown coal is known in 6. Exploration has not yet been carried out systematically except in a few deposits. So reserves can be expected to increase in the years to come. In 1978 reserves were estimated at

> ...364,000 million tonnes. Assuming that inferred reserves will, in time be established as proven reserves and 50% will be recovered, black coal reserves are adequate for 1000 years (Anonymous, 1978).

Austrlaia is suited equally well in brown coal. Victoria has the world's larges deposit of brown coal with one seam over 225 m thick. Supply is not a problem for Australia. Continued exploration will increase the abundant supply Australia already has located. As the amount of open mines and longwalling grows, so will recovery ratios.

Demand for Australian coal is most certainly on the rise. Figure 37 shows the exports of several leading nations and none come close to Australia's growth record. Australia ranks ninth in total production worldwide. Even more indicative of Australia's role in the international coal market, is the fact that Australia is the second largest coal exporter in the Free World. The significance today is obviously large. Australia's continued dominant role is demonstrated in Figure 36.

Figure 36 EXPORT PRODUCTION RATIO



from Ellyett, 1980

FIGURE 37

GENERALIZED EXPORT CURVES FOR LEADING FREE WORLD COAL PRODUCING NATIONS

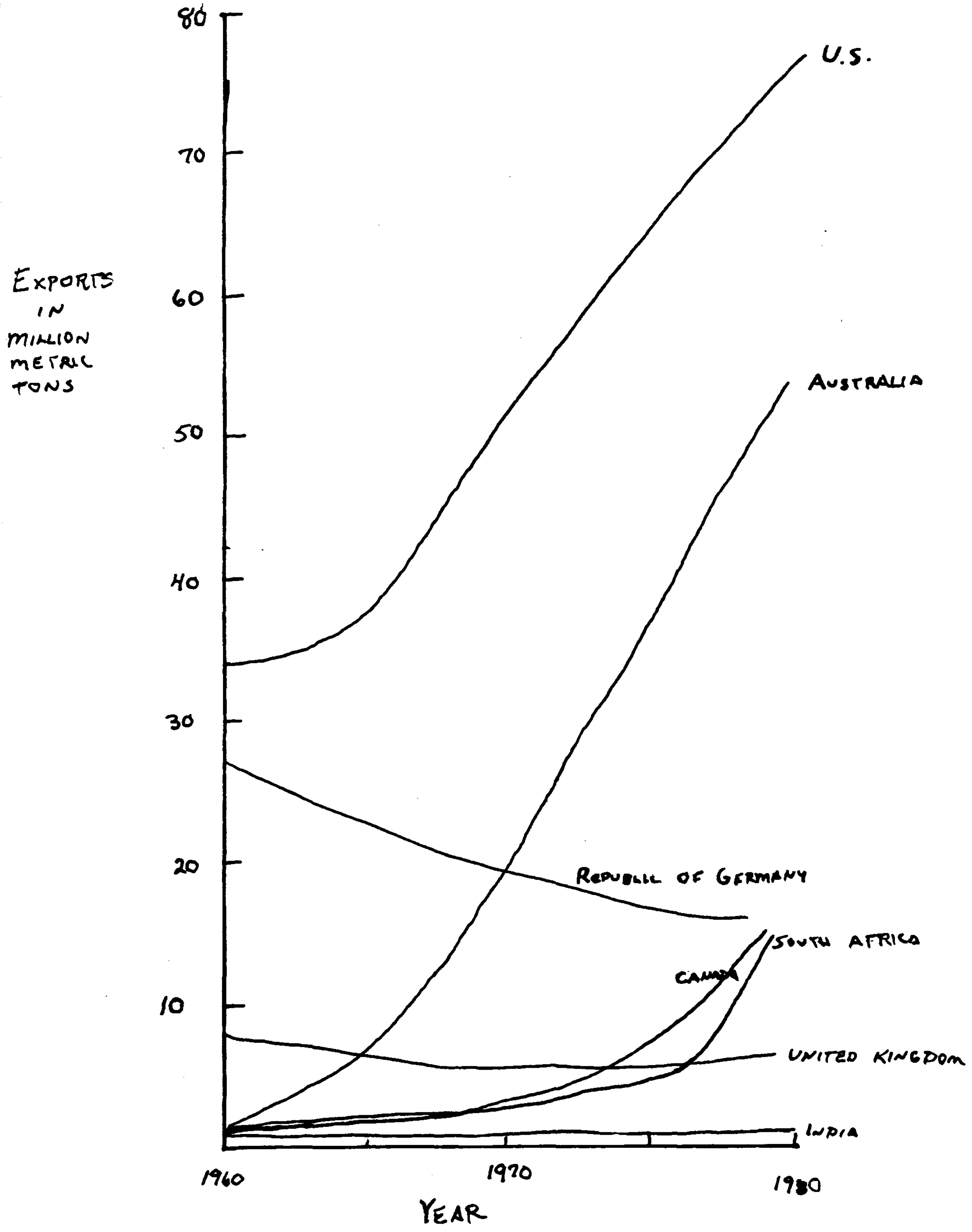
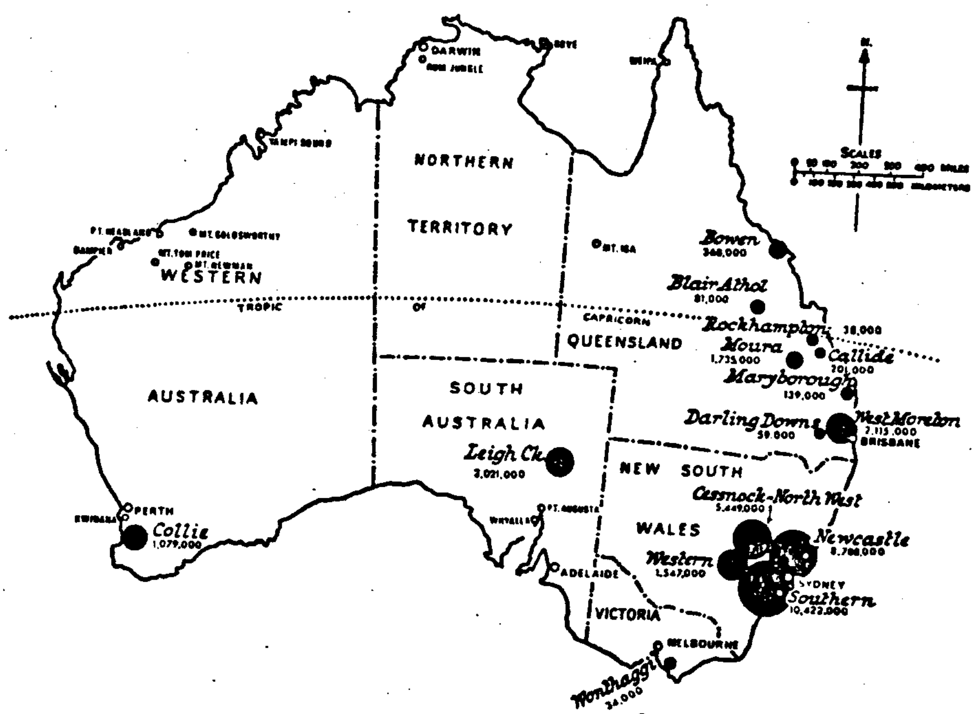


Figure 38 LOCATION OF BLACK COAL DEPOSITS



from Raggatt, 1969

CONCLUSION AND PROJECTION

There is no debate of what has happened in the last 20-30 years. Australia rose from a non-exporting country to one of great quantities and assumed a leading role as a supplier in the world mineral market.

Australia surged froward in mineral trading because: Australia has: a relatively educated work force, a government that has recently supported mineral trading, the greatest share of the Japanese market, high quality ores, and large enough reserves to meet both domestic and foreign demand for years to come.

Australia has deposits that other nations combined cannot match. Coupled with the low consumption of the country, and huge demand elsewhere, it is easy to see that Australia 's new rôle is going to loom larger in years to come.

The mineral deposits allow for profitable mining because they occur with little overburden or impurities quite often. Commonly mining is being done near the coast which keeps transportation costs down and provides the benefit of a local port. From there ocean transport is inexpensive.

As Australia increases production the limiting factor will not be supply or demand of raw material but transportation facilities for the materials. The past twenty-five years have seen the construction of a nationwide single gauge railroad and mechanized ports. Still growth has been so rapid that facilities only ten years old are outgrown.

Australia must meet its challenges in material handling with the vigor of the past two decades and Australia will maintain its position at the top of mineral trading past the turn of the century onto the year 2020. Continued exploration and production of minerals, at incresing rates, can be expected for years to come.

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