The occurrence and paragenesis of the ores of titanium

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THE OCCURRENCE AND PARAGENESIS OF THE ORES OF TITANIUM

by

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CHAPTER I

INTRODUCTION

This part of the thesis is a survey with an economic emphasis, presented primarily as an annotated bibliography of references, of the world's titanium mineral resources. All deposits, whether actual or potential ores, are discussed. In certain instances occurrences of no economic value are mentioned because they have been cited elsewhere as potential ores, and it is desirable in the light of more recent information to point out the incorrectness of such statements.

The geology of a deposit is only discussed in detail when it has not been considered in part I. The two parts are intended to be used in conjunction with one another, but each is also an entity within itself. Wherever possible detailed analyses of the ore constituting a deposit are given but in cases where the literature provides a proliferation of analyses only a selection has been reproduced.

The term 'ore' has been used as far as possible within the definition 'rock or mineral which can be won with, or with hope of, profit'. However, to avoid unnecessary circumlocution it has occasionally been used in a looser context by applying it to showings of titanium minerals which at the present time could not be profitably mined.

References are given in two ways. Where the name of an author appears in brackets with a date this refers to the bibliography, arranged in alphabetical order of authors' names, at the rear of this volume, where the fullest possible details of the article or scientific paper are given. In certain instances no date may appear by the author's name because the date of publication of the article is unknown. In some cases, usually where reference is made to anonymous articles or brief news bulletins in technical magazines, a full reference is given in the text in brackets beside the relevant information.

Apart from the works cited in the text, special acknowledgement is made to bibliographies contained in the following works:-

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TITANIUM MINERAL DEPOSITS OF EUROPE, THE URAL MOUNTAINS AND ASIA MINOR

Titanium Mineral Deposits of Europe

Legend

1. Kramsta, Jarvso
2. Ulvon, Hernosand
3. Taberg, Smaland
4. Routivare
5. Otanmaki
6. Vuorokas and Itaranta
7. Susimaki
8. Attu
9. Faroe Islands
10. Dublin Bay
11. Otava River, near Plzen
12. Burgas
13. Ciftalen
14. Sile
15. Ulcini
16. Vardar River
18. Deposits Along the Tyrrhenian Seabord
19. River Orba
20. Margherita Di Savoia
21. Szarvasko, Bukk Mountains
22. Warnemunde
23. Wangeroog and Sylt
24. Odet and le Blavet
25. Castelo Branco, Belmonte
26. Praia de Sines Torpes
27. Ovidelas, Beja District
28. Ruzo
29. Olot
30. Hornafjord
31. Porthoustok
32. Carrock Fell
33. Verkne Ufalei
34. Kaslinskaya
35. Savel'ev Valley, Miask
36. Bilimbaerskoye
37. Chernorechenskoye
38. Kusinskoe
39. Matkalskoye
40. Satkin and Kopanskoe
42. Shaitan Dacha
43. Pervouralskoye
44. Gremyakha Vyrmes
45. Khibine and Lovozersky
46. Tikhvinskoe
47. Velimaki
48. Koykar
49. Pudoshgorsk
50. Azov sea Coast

51. Zitomir Region

52. Storgangen

53. Tellnesvann

54. Rødsand

55. Solnordal-Sjoholt-
Tafjord

56. Sordalen-Gjolanger

57. Selvaag

58. Kragero

59. Koldal-Liaasen

60. Valerianovsk

61. Orsk

CHAPTER II

EUROPE INCLUDING THE ASIATIC U.S.S.R.

The continent of Europe contains moderately abundant quantities of ilmenite which are being actively exploited in Norway and Finland to supply some of the needs of the European white pigment manufacturing industry. The ilmenite is mined from primary sources in the Scandinavian pre-Cambrian basement at Otanmaki in Finland and Hauge I Dalane in Norway. Small quantities are mined in Spain and Portugal. A recent trade mission to the United Kingdom from the U.S.S.R. offered for sale ilmenite concentrates and from the composition of the samples it is likely that they are derived from a primary source, in all probability from somewhere in the Ural Mountains. Large reserves of primary rock ilmenite are known to exist in Norway and smaller, though still considerable, reserves in Finland. The Ural Mountains contain unknown reserves of ilmenite and reserves of the less important titaniferous magnetite of several hundred million tons. Sweden also has vast reserves of titaniferous magnetite and the beaches of both the east and west Italian coasts contain large quantities of the same mineral. There are many deposits of small and unknown potential in many parts of the continent.

There is a lack, in Europe, of extensive areas of beach and dune sands containing commercially valuable titanium minerals. As a result the rutile requirements of European industry have to be satisfied from elsewhere. Rutile was mined, until the last decade, from a primary source at Kragero in Norway but the operation was conducted only on a small scale and was unable to compete with the cheaply-won marine and alluvial rutiles of Africa and Australia. As far as can be ascertained rutile has not been mined on anything but a very small scale from elsewhere in the continent, with reservations concerning activities within the Soviet Union.

BULGARIA

Deposits of ironsands containing titaniferous magnetite occur at Burgas on the Black Sea coast. According to Petraschek (1942) they contain 56% magnetite with a TiO_2 content of 5-8%, and they cover an area 3 km long by 100 m wide to a depth of 0.5-5 m. The U.S. Bureau of Mines (For. Min. Quarterly 1 (1930) 30) reported that they occupy an area of 8 square miles and are 1-2.3 m thick.

CZECHOSLOVAKIA

Ilmenite deposits were discovered in the Pilsen (Plzen) district in 1948 (Chimie et Ind. 60 (1948) 94) but no details of the occurrence are available.

In Egerland clay minerals, presumably in soils, are reported to contain 11-27% TiO_2 over a wide area (Petraschek 1938).

Gold, garnet, ilmenite, monazite and zircon occur in heavy mineral concentrates in the gravels of the Otava river but the deposits are too low in grade for economical exploitation (Jirkovsky 1947).

DENMARK (FAROE ISLANDS)

Magnetite, ilmenite, augite and olivine occur in heavy concentrates in sands of the Faroe Islands (Thomsen 1952). The minerals are derived from basaltic lava flows which form the islands' superstructure. If the deposits are to be compared with similar deposits elsewhere derived directly from locally outcropping basaltic rocks, they are of low grade due to the admixture of silicate minerals in considerable amounts and the ilmenite will have a low TiO_2 content due to a high content of the magnetite molecule which will be in solid solution in the ilmenite.

EIRE

Sands in Dublin Bay contain concentrations of heavy minerals of unknown, but probably small, size. 'Ilmenite' and probably titaniferous magnetite and hematite are present. A concentrate containing 23.8% TiO_2 has been obtained. An analysis of the black sand concentrate showed the following percentages of selected constituents.

TiO_2	FeO	Fe_2O_3	MnO	Cr_2O_5	P_2O_5	ZrO_2
7.3	5.6	22.96	2.9	0.46	0.15	8.5

(Private report).

FINLAND

Finland contains a number of ilmenite-titaniferous magnetite and titaniferous magnetite deposits. In the Otanmaki area, 5 km south of Lake Oulujarvi, in Central Finland, titaniferous magnetite-ilmenite ores are being mined (1958) to produce ilmenite, magnetite, and vanadium oxide concentrates. Small deposits which are unlikely to prove of economic importance are known to occur at a number of places in south Finland.

Deposits in the Otanmaki Region

Otanmaki.- The ore bodies at Otanmaki are oval shaped lenses dipping sensibly vertically, and striking approximately east-west in the main ore belt. The long axes of the lenses dip to the west at a high angle. There are three main ore zones each separated by about 100 m of amphibolite and gabbro. The southernmost ore zone outcrops at the surface as stringers and veins of ore but the more northerly zones are at progressively greater depths and there is little surface evidence of their existence. There may be other zones, sub-parallel with the three already known, at greater depths. Each zone consists of a number of lenses arranged in line, each succeeding lense to the west being at a slightly lower level than its easterly neighbour.

The ore bodies contain quantities of ore minerals varying from 10% to 100%. Generally no rock with less than 35% ore mineral content is mined. The following analyses of (i) an average ore containing 60% ore mineral (Runolinna 1952) and (ii) the ilmenite concentrate, are available

(i)

Fraction	Wt. %	Fe %	TiO_2 %	S %
Magnetite	35	68.5	2.5	-
Ilmenite	23.5	36.4	48.1	-
Pyrite	1.5	46.0	-	54.0
Rest	40.0	9.0	3.0	-
Ore rock	100.0	36.8	13.4	0.8

(ii)

TiO_2	FeO	Fe_2O_3	MnO	P_2O_5	Cr_2O_3	V_2O_5	Res.
43.7	40.0	9.1	0.8	0.1	0.025	0.3	2.8

The ore consists of magnetite containing fleck-like ilmenite bodies but few long lamellae, and ilmenite containing fleck-like bodies of hematite of varying size, and hence possibly of more than one generation. The texture of the ore is very variable but, in general, consists of ilmenite grains with a diameter of 0.2-0.3 mm cemented by smaller magnetite and ilmenite grains, but grains of ilmenite and, less commonly, magnetite up to 2 mm in diameter are not rare. The ilmenite crystallized before the magnetite and simultaneously with it. Grinding to 65 mesh is normally sufficient to obtain a reasonable magnetite-ilmenite separation. The vanadium content of the ore is in the magnetite molecule, and may rise to 0.53% V (Jarvinen 1948; Runolinna 1952).

The ore bodies are intimately connected with amphibolite, hornblende-gabbro and anorthosite. The belt of ore bodies associated with anorthosite and anorthosite-gabbro is found in the amphibolite close to the northern margin of a gabbro body. The amphibolite and all related rock types occur probably as a zenolithic raft enclosed in later granites and granite gneisses. The belt of ore bearing rocks is curved and roughly concordant with the general strike and dip of the enclosing amphibolite. A study of the main structural features of the area shews that the ores occur at, or near, the apex of an isoclinal fold in the amphibolite, and it is tentatively suggested that structural control of the ore bodies has been exercised by the folding causing them to be injected in low stress areas near the fold apex. This concept is in agreement with Paakkonen (1956). The geology and mineralogy of the orebodies are more fully described in Part I of this thesis.

Ore reserves at Otanmaki are not yet definitely known but certainly exceed 50 million tons.

The Otanmaki ore deposit was discovered in 1938 (Eskola 1941) but it was not until 1951 that it was decided to mine the ore. Production of ore commenced in 1953 in small quantity and since July 1954 ore has been raised at a rate of 50,000 metric tons per month.

Present hoisting facilities do not allow for much more than 800,000 tons of rock to be raised per annum of which about 630,000 tons would normally be ore, although 740,000 tons is reported to have been produced in 1956. (Chem. Age 77 1957 885).

Ilmenite and magnetite and, since 1956, vanadium concentrates are produced at the mine. These have been exported since 1954. (Private communication; Stigzelius 1949; 1952).

Otanneva.- At Otanneva, 1 km south-west of Otanmaki, low grade ore bodies of small size occur in amphibolite which has a high opaque mineral content. (Paakkonen (1956)). No other details concerning this deposit are available.

Vuorokas.- The full extent of the Vuorokas ore bodies which lie at a distance of four kilometres east of Otanmaki, is not yet known. The ore is essentially similar to that of Otanmaki and is thus commercially interesting, since the production of suitably high grade magnetite and ilmenite concentrates would be possible. The ore bodies occur in amphibolite associated with gabbro. There are probably several million tons of ore available. (Paakkonen 1956).

Pentipuro.- The Pentipuro deposits, 11 km north west of Otanmaki, do not outcrop at the surface of the ground because of a layer of Quaternary sediments ten metres thick which overlies them. The ore bodies are not of high grade, except for about 100,000 tons, but there may be a reserve of lower grade ore up to several million tons. The ore occurs in amphibolite close to its contact with leucogabbro. Over a thickness of 11 m between the 54 m and 65 m mark in a drill core the Ti content of the ore varied from 10.2 to 7.6%, Fe from 49.4 to 24% and V from 0.32 to 0.2%.

Itaranta.- A few small ore bodies occur in amphibolite at Itaranta, 11 km north-east of Otanmaki. Their total reserve of ore probably does not exceed a few hundred thousand tons.

Other Finnish Deposits

Susimaki. S.W. Finland.- Ilmenite-magnetite olivinites from Susimaki have been described by Palmunen (1925). The ilmenite-magnetite olivinite was the first rock to crystallize in a series of which peridotite, hornblende-ilmenite-gabbro and hornblende-biotite-gabbro were the later crystallizing components. About 40% of the olivinite is made up of ilmenite and magnetite in approximately equal quantities, with small amounts of accessory pyrite, pyrrhotite and pentlandite. The magnetite contains small exsolution discs of spinel, an unidentified mineral, and rather rare exsolution lamellae of ilmenite. The ilmenite is free from inclusions and exsolution lamellae.

The peridotite, (in reality a gabbro because of its labradorite-bytownite feldspar content) contains less ore minerals and an increased proportion of hypersthene and hornblende. Biotite, apatite and hercynite also occur.

The deposit is not an economic proposition at the present time (Vaasjoki 1955).

Riuttamaa.- Two small deposits of the Susimaki type occur at Riuttamaa, four kilometres from Susimaki. They are not of economic importance. (Vaasjoki 1955; Palmunen 1925).

Vuorijarvi.- Contact metamorphic deposits in a thin limestone at Vuorijarvi in Kuolajarvi contain intergrown magnetite and ilmenite crystals. (Palmunen 1925). The purer ores contain 22% TiO_2 (Hackman 1925).

Kitula.- A small ilmenite-magnetite deposit associated with hornblende and sulphide-bearing rocks is reported to occur at Kitula near Kirju in the Suomusjarvi district.

Attu.- Titaniferous magnetite-ilmenite deposits associated with a gabbro intrusion occur at Attu on Runholm Island. An analysis of the ore shewed 29.97% TiO_2. The deposit, which is not an economic proposition, was described by Pehrmann (1927).

FRANCE

There are no known workable deposits of titaniferous minerals in France.

Paris Basin

The sedimentary rocks of the Paris basin, particularly those of Tertiary age, contain rutile and brookite in their detrital mineral assemblages. (Duplaix 1946; Duplaix and Malterre 1946; Brajnikov 1942; Vatan 1935; Jodot 1936). There may be a slight possibility that rutile rich alluvial deposits, formed from these sediments, exist in certain areas particularly to the south of the Seine.

Brittany

Ilmenite, rutile and brookite are found in Brittany near Dinard (Berthois 1928), and in the Vannes region (Lacroix 1935). The first of these occurrences is solely of mineralogical interest. The sands of many beaches between Odet and le Blavet, particularly near Concarneau, and between Croisic point and the mouth of the Vitaine river, contain ilmenite. Ilmenite also occurs in sands near the Ile de Groix. The deposits are probably too small to be worth working (Charrin 1950; 1953).

Other Areas

<u>Marsdon</u>.- At Marsdon, south of the Loire pitting has revealed three veins of ilmenite from 0.5-1 metre in thickness (Charrin 1953).

<u>Pilat</u>.- Ilmenite occurs in black sands at Pilat and Moulleau (Duplaix 1948).

The waste products of aluminium plants using overseas bauxites contain 9-12% TiO_2 which might be recoverable.

GERMANY

No deposits containing titaniferous minerals are worked in Germany but deposits of unknown potential exist on the North Sea and Baltic coasts.

North Sea Coast

Heavy mineral accumulations occur in the beach sands of Wangeroog in the Frisian Islands. In places thin layers contain 50-60%, and rarely 90%, of heavy minerals which are mostly magnetite and ilmenite in a ratio of 1:4. Other minerals present are garnet, rutile, hornblende, augite, tourmaline, and zircon. (Trusheim 1935).

The sands on the island of Sylt were unsuccessfully smelted in the 1870's, but it may not have then been appreciated that much of the sand was ilmenite. According to Chem. Zeitung. (Jan. 10 1953) important titaniferous deposits exist on the west side of the island of Sylt.

Baltic Sea Coast

Heavy mineral concentrations occur in the sands of the north German coast between Warnemunde and Darssar Orst. The principal minerals present are garnet, ilmenite and magnetite. (von Engelhardt 1937).

GREAT BRITAIN

No deposits of titanium minerals which are at present of workable grade or size are known to exist in the British Isles. Deposits which are at present of no economic value occur in Carrock Fell, Cumberland, in certain Cornish beaches and in the Dartmoor granite.

Cornwall

Ilmenite occurs in the Lizard gabbro as an accessory mineral. On weathering the ilmenite is released and transported to the sea coast via streams and rivers where it is concentrated on the beaches. At Godrevy Cove, south of Porthoustock black sand in river gravel analysed 45.12% TiO_2. The occurrence is not of economic significance because of itssmall size. (Lamming (1952)).

Pliocene deposits resting on the gabbro contain no heavy mineral accumulations. (Milner).

Carrock Fell

Marginal facies of a gabbro complex forming part of Carrock Fell, Cumberland contain concentrations of opaque iron-titanium-oxide minerals. The gabbro complex consists of a sub-parallel series of vertical inclined sheets and lenselike bodies of quartz gabbro, gabbro and melagabbro. The complex is elongated in an east-west direction which is also the strike direction of the constituent gabbro sheets. Melagabbros form the southern and northern marginal sheets. The southern sheet contains a high proportion of zenolithic material which appreciably lowers the overall ore grade of this gabbro sheet. The northern melagabbro belt varies from an ilmenite-magnetite rich rock to a hornblende gabbro and contains many feldspathic, pegmatitic patches. On its northern margin thin sheets of a hybrid basic granophyre separate it from the adjacent Carrock Fell granophyre.

The northern melagabbro's mineral constituents are labradorite, diallagic pyroxene partly replaced by brown hornblende or chlorite, and magnetite. Secondary chlorite is abundant and quartz, magnetite and green biotite also occur. The ilmenite occurs as homogenous grains surrounded by magnetite, containing exsolution lamellae of ilmenite, which seems to have crystallized later than the ilmenite. The mineralogy of the ilmenite-gabbro is described in greater detail in Part I of this Thesis.

An analysis of the ilmenite gabbro is available (Harker 1894) which quotes 5.05% TiO_2. An appreciable percentage of the TiO_2 content of the rock is contained in silicate minerals and ilmenite exsolution lamellae in magnetite and would be commercially irretrievable.

The ilmenite gabbro outcrops over an area of at least one mile x 50 yds and extends at its eastern end over a vertical distance of 1,000' so that although of low grade, the reserve of titanium in the complex is probably very large indeed.

The Dartmoor Granite

Rutile, anatase and brookite occur in veins and geodes in the Dartmoor granite, but the occurrences are not of economic significance. No detrital deposits of any appreciable size are known to occur. (Brammall and Harwood 1927; Brammall 1928).

No mention of Skye or Rhum

HUNGARY

There are no deposits containing titaniferous minerals which are being mined in Hungary at the present time but a gabbro intrusion at Szarvasko is known to contain large, but probably in the main low grade, reserves of titaniferous magnetite and ilmenite.

Near Szarvasko on the west side of the Bukk Mountains, a gabbro intrusion, probably of Upper Cretaceous Age, has been intruded into Triassic shales. The intrusion contains ultrabasic diallage-peridotite and dunite differentiates. Ilmenite and magnetite occur in the peridotites (wehrlites) in amounts forming up to 90% of the rock. (Szentpery 1937a; 1937b; 1938; Nahoczky 1940; Vendl 1939; Papp 1939; Panto 1952). The richer bodies average 23.2% TiO_2 (Szentpery 1937a). Analyses of titaniferous magnetites (probably a combined titaniferous magnetite-ilmenite) shew 32-41% TiO_2 and 38-40% Fe. (Szentpery 1937a).

Panto (1952) gives six analyses of wehrlite which contain from 3.21-18.8% TiO_2. One of the analyses is given below:

Locality:- Polner

	%		%
SiO_2	30.82	MgO	13.68
TiO_2	18.8	CaO	7.68
Al_2O_3	2.8	Na_2O	0.56
Fe_2O_3	1.5	K_2O	0.22
FeO	22.15	P_2O_5	tr
MnO	0.77	H_2O	0.94

On the reasonable assumption that all the Fe_2O_3 and TiO_2 are in magnetite and ilmenite the amount of FeO available for the silicate minerals appears to be so extraordinarily small that either much of the TiO_2 must be in the pyroxenes, or the presence of rutile must be suspected. In the rocks with a low TiO_2 content far more FeO is available after the normative formation of magnetite and ilmenite, so that no doubt need arise in their case concerning the identity of the host minerals of the TiO_2.

ICELAND

Black sands from Hornafjord inlet in south-east Iceland contain 5% of opaque minerals. Ilmenite and titaniferous magnetite are present but the respective quantities of each is not recorded (Stuart 1927). No details of the extent of the sands is given but it is thought to be rather limited.

ITALY

West Coast

Beach sands containing titaniferous magnetite, and probably some ilmenite, occur on the Tyrrhenian (west) coast of Italy between Civitavecchio and Salerno. These deposits have been described by Cattaneo and Maddalena (1919); Abbolito (1941; 1946) and Coppa-Suchari (1942); Corradi (1940), and Paschke (1942). In 1940 these sands were estimated to contain a total of 1,650,000 short tons of iron-titanium minerals. Three types of concentrate were produced by various companies who commenced work in 1939:- a) An iron concentrate with 62% Fe and 5-8% TiO_2 b) A titanium concentrate with 35% TiO_2 and 24% Fe and c) A zircon concentrate with 40% Zr. (U.S. Bur. Mines 1946 Min. Trade Notes 23 No 3 13-14).

East Coast

Iron sands occur on the east coast of Italy at Margherita di Savoia, (Lawthers) and extensive deposits of black sand are supposed to exist at a number of other localities. They contain an average of 5% ilmenite which is easily separated magnetically. Youngman (1930) quotes five references including Bianchi, and Magistretti (1912).

Elba

Other Areas

River Tessin.- In the river Tessin sands suitable for exploitation occur at two places, containing 28% and 21% of ilmenite respectively (Abbolito 1941).

River Orba.- A factory at Puorto Nuova was reported to be treating sands from the river Orba and producing 6 tons of magnetite and 0.75 tons of ilmenite daily. (Pelloux 1941).

Bolzeno.- Orthomagmatic titaniferous iron ore concentrations occur in Monzonite at Viezzana near Bolzeno, and titaniferous magnetite has been detected in the sands of Bolzeno Lake but details concerning these occurrences are lacking. (Iron Ores of Italy, in Iron Ore Deposits of the World XIX Int. Geol. Cong. 1952; Abbolito and Coppa-Suchari 1942).

NEDERLAND

It is very probable that the beaches of the Dutch Frisian Islands contain heavy mineral concentrations of the same type as those found in the German Frisian Islands but there are no references to any such deposits in the literature.

Nelson and Niggli (1950) carried out mineralogical work on heavy fractions of some Dutch sands, but their results do not include any details of the amount of heavy minerals in the sands they studied, nor the extent of the sand areas from which their specimens were taken. They found that dunesands from North Brabant contained ilmenite and rutile as did fluvial sands taken from the North Limburg area. Beachsands from Goeree contained rutile, ilmenite and magnetite.

NORWAY

Norway is extremely rich in ilmenite-magnetite and titaniferous magnetite deposits and a rutile deposit from which concentrates have been actively produced is situated in south Norway. Many of the titaniferous magnetite deposits, which are usually of small size, have been unsuccessfully worked in the past for their magnetite content. The only mine at present producing marketable ilmenite concentrates is the Titania A/S (Frederikstad) deposit, called Storgangen, near Hauge I Dalane, Sogndal in south-west Norway. The Rødsand Gruber at Møre produces an 'ilmenite' concentrate as a byproduct of the magnetite concentration process, but it has too low a TiO_2 content to be marketable.

The Egersund - Sogndal Region of south-west Norway

The Pre-Cambrian massif of south-west Norway, consisting of anorthosite and congenetic rocks, contains a large number of titaniferous ore bodies of various types. The ilmenite-magnetite deposits of Storgangen and Tellnesvann are large ore bodies of economic importance, the former of which has been worked for a number of years. The smaller ilmenite deposits such as Helleland, Koldal and Blaafjell are too small for economic exploitation although the quality of the concentrate which can be produced from them is quite adequate for commercial purposes.

Storgangen.- The Storgangen orebody lies 2 km to the north-east of Hauge I Dalane, Sogndal about 80 km south-south-east of Stavanger. It is a dyke like body of ilmenite-norite, 1600 m long and averaging 60 m in width, intrusive into anorthosite. It strikes east-north-east and dips 60° to the north-north-west at the surface but shallows to 40° at a depth of about 50-150 m. About 30% of the norite dyke rock consists of disseminated ilmenite and magnetite in a ratio of 6:1.

The ore has an average grain size of 1-2 mm. After crushing it is separated into ilmenite, magnetite and waste fractions. The ilmenite concentrates are carried by overhead cableway for 7 km to the south-south-east to Jossingfjord where they are stored ready for loading direct onto ships. The magnetite concentrates are taken by small gauge railway an equal distance south-west to Rekefjord where they are also stored prior to shipment.

The crude ore as taken from the mine analyses:

TiO_2	FeO	Fe_2O_3	V_2O_3	M_2O_3	MgO	SiO_2	$CaONaOK_2O$
18.00	23.8	2.3	0.12	8.5	11.0	32.5	2.3

Typical analyses of the ilmenite concentrate are as follows:-

	TiO_2	FeO	Fe_2O_3	Cr_2O_3	V_2O_5	MnO	P_2O_5	Residue
1.	44.0	35.4	11.0	0.01	0.30			
2.	43.0	34.0	14.0	0.025	0.25	0.35	0.06	4.5

1. Gillson (1949).
2. Private source.

The ilmenite never has a higher TiO_2 content than 46% owing to small exsolution bodies of hematite present in it, oriented along the 0001 cleavage planes of the mineral. The magnetite contains 2.9% TiO_2 owing to the presence of ilmenite lamellae exsolved from the magnetite. Vanadium is also concentrated in the magnetite up to 0.64% V_2O_5.

The proved reserves in the Storgangen deposit are 150 million tons of ore but the total reserves are considerably in excess of this figure.

The Storgangen and Blaafjell mines were opened in the 1860's as iron mines and 100,000 tons were produced (Poulsen 1952). Storgangen was reopened in 1917 and during the years before the 1939-1945 war the production of ilmenite concentrates was usually about 60-70,000 tons per annum. Total production up to 1948 was 1,000,000 tons of ilmenite. Since the war production has increased and in 1955 was 158,830 tons of ilmenite and 26,130 tons of magnetite. Production in 1956 was probably about 180,000 tons of ilmenite.

The Storgangen deposit has been briefly described many times. For a geological description see Part I of this thesis and also Bugge (1953). Other references are Kolderup (1896), (1928), Foslie (1928); Vogt (1910); Schneiderhohn (1941); Louis (1934); and Lenschow (1950).

Tellnesvann.- The Tellnesvann deposit lies 6 km to the south-west of the Storgangen orebody and 3 km east-north-east of Jossingfjord. It was discovered in 1955 by aeromagnetic survey methods although the existence of a norite intrusive had been known at the locality for some years. The orebody is 1½ km long, strikes north-west to south-east, and is 200-300 metres wide. It is a pod-shaped body narrowing and finally lensing out at both ends. The south-east end of the orebody probably continues at depth under the anorthosite country rock exposed at the surface. The ore is essentially similar to the Storgangen ore, and contains 18.00% TiO_2 as ilmenite. The reserves of ore are at least 350 million tons.

A geological description of this deposit is included in the relevant section of this thesis. See also Metal Bull. 4187 (1957); Chem. Age 76 (1945) 42; Financial Times (October 12, 1955):

Blaafjell.- This deposit consists of ilmenite veins in anorthosite. It lies 2 km to the east-south-east of Storgangen. The veins of ilmenite occur in an irregular manner in the anorthosite host-rock. Locally they thicken to several metres in width. They are part of a more or less continuous ore zone extending southwards for about 3 kilometres to Odrevann, which lies 2 km east of Tellnesvann.

The Blaffjell ore was worked in the last half of the 19th Century for iron ore. The venture was a failure because the titanium content of the ore caused slagging difficulties which could not at the time be overcome. The ilmenite contains at least 44% TiO_2 and is therefore suitable for the present commercial market but the deposit is too small to be an economic proposition at the present time. The ore reserve has been estimated to be 100,000 tons in Blaafjell itself (Youngman 1930) with considerably more in the extension of the ore zone towards Odrevann.

A small deposit, probably of a similar type is known to exist at Aursland, one kilometre east of Storgangen.

Deposits near Egersund.- To the north of Sogndal an ore zone extends east from Egeroy, 3 km south of Egersund, for a distance of 14 km to Liaavann. This zone has been worked unsuccessfully at various times in the past, in particular at Haaland, Koldal, Kydland and Liaasen. The ore is variable but is predominantly ilmenite, containing exsolution hematite bodies, together with small percentages of magnetite. The ilmenite-magnetite ratio is about 9:1. The ilmenite occurs as irregular veins in anorthosite and norite, sometimes forming a zone up to several metres wide where they bunch together.

The deposits are not of sufficient size to make mining an economic proposition at the present time although an ilmenite concentrate with a sufficiently high percentage of TiO_2 could undoubtedly be produced.

Flekkefjord.- At Hidra, Flekkefjord, a small deposit containing 24% TiO_2 and 22% Fe (i.e. ilmenite in low concentrations) is known to occur. (Private communication, Raae).

Deposits in North Norway

? [illegible] Varangerfjord

Selvaag Deposit.- An ilmenite-titaniferous magnetite ore deposit occurs in gabbro at Selvaag, near Bö on Langoy, Vesteralen. According to Imp. Min. Res. Bur. (1922) and Poulsen (1952) the ore contains 4% TiO_2 and 32-35% Fe. The actual TiO_2 content may well be higher than this figure because the magnetite is known to be useless owing to its high TiO_2 content contained in including ilmenite lamellae, yet homogenous ilmenite crystals occur free from any inclusions.

The gabbro body surrounds a quartz monzonite intrusion and contains, as well as ore lenses, lenses of dunite. The minerals in the gabbro are plagioclase 80%, olivine 5-20% and diopsidic pyroxene 3-20%. The ore minerals probably crystallized later than the silicate minerals and tend to replace the feldspar.

The area has suffered metamorphism in granulite facies conditions, altering the gabbro to hypersthene gneiss which finally merges into monzonite. At the eastern side of the gabbro, metamorphism is of amphibolite grade. Carbonate from local limestone bands has reacted with plagioclase in the foliated margin of the gabbro to form scapolite. (Private communication from K. Heier; Vogt 1900). According to Poulsen (1952) the amount of ore in sight is 20 million tons, probable ore reserves being as high as 60 million tons.

At Hjelsand on Langoy a similar smaller deposit occurs (Vogt 1910).

Stjernoy, Finnmark.- Ore occurs over an area of 100,000 sq. m. It contains 3-7% TiO_2 and 13-18% Fe and is a low grade deposit (Vogt 1910) of little immediate commercial interest. The ore contains titanomagnetite, diallage and spinel (Vogt 1900).

Komagfjord, Finnmark.- A deposit containing 20-25% TiO_2 is reported to occur in this locality (Private communication from Raae).

Moskensö.- A deposit of beach sands with 13% TiO_2 and 55% Fe, consisting of ilmenite and magnetite occurs on Flakstad Is, Vesteralen (Vogt (1910)).

Ringvassoy, Troms.- An occurrence of ore containing 4-19% TiO_2 and 19-42% Fe is reported from this locality (Private comm. Raae).

Deposits in West Norway

Rødsand, Romsdal.- Ore concentrations occur in amphibolites, which are probably metamorphosed gabbros, enclosed in younger granite gneisses. The ore minerals are titaniferous magnetite and ilmenite containing abundant hematite lamellae. The ilmenite cannot be sufficiently concentrated to yield a saleable product.

The ore has been mined since 1910 and at present produces about 40,000 tons of magnetite concentrates yearly, which contain 62% Fe, 0.5% V and 2.5% TiO_2. (Bugge 1953). There are six million tons of ore in reserve (Poulsen 1952). The magnetite concentrate represents about 0.33% of the ore as mined.

Heindalen (Meisingset) Romsdal.- The Heindalen deposit contains about 3,000 tons of potential ore containing 8% TiO_2 and 30-35% Fe (Lenschow 1950).

Upper Roddal and Oyenseter, Tafjord, 62°14'N, 7°25°E.- The two deposits in Tafjord lie only a few kilometres from each other but are quite different in character.

Oyenseter.- Ilmenite and magnetite are concentrated to form small potential ore bodies in an amphibolite. Fine grinding followed by heavy liquid and magnetic separation yielded a magnetite and an ilmenite concentrate. The following analyses of the concentrates are given by Gjelsvik (1956).

		TiO_2	FeO	MgO	MnO	Fe_2O_3	Cr_2O_3	V_2O_3
Oyenseter	(Magnetite	1.1	31.3	-	-	65.1	1.9	1.0
	(Ilmenite	46.9	41.6	-	0.7	10.1	0.1	0.3
Upper Roddal	(Magnetite	14.6	41.5	-	0.3	44.0	-	0.1
	(Ilmenite	50.2	46.6	-	0.9	3.9	-	-

Upper Roddal.- The Upper Roddal magnetite contains a lattice-work exsolution intergrowth of ulvospinel. The ore minerals occur in an enriched olivine gabbro body and are interpreted as a late magmatic accumulation, mainly on account of the absence of chromium (Gjelsvik 1956).

Fiska, Vanvlven, Vanylvsfjord 62°06'N 5°35'E.- At Fiska ore is found to occur in two different ways which can be approximately correlated with the Blafjell and Storangen ore types of south-west Norway (Gjelsvik 1956). Magnetite and ilmenite occur as compact ore layers in labradorite-anorthosite and ilmenite occurs in an ilmenite-norite within the anorthosite. There is an abundance of garnet which is interpreted to be due to a later metamorphism. The following analyses of the ore minerals are quoted by Gjelsvik (1956).

	Massive ore:		Ilmenite-norite:
	Magnetite	Ilmenite	Ilmenite
TiO_2	1.0	45.1	38.6
FeO	32.0	33.1	30.1
MgO	0.4	3.1	1.6
MnO	0.2	0.5	0.1
Fe_2O_3	64.2	18.4	28.7
Cr_2O_3	0.7	-	0.1
V_2O_3	0.8	0.3	0.8

The ilmenite from both types of ore contains blebs and lamellae of hematite of small size. The magnetite contains lamellae of ilmenite which are, in the main, sufficiently coarse to be removed by fine-grinding.

Verkshaugen, Bergsoya 60°20'N 5°40'E.- The accumulation of magnetite and ilmenite in the eclogite (olivine-garnet-feldspar rock) of Verkshaugen is strip-like in form. Analyses of the ore minerals are given by Gjelsvik (1956) as follows:-

	TiO_2	FeO	MgO	MnO	Fe_2O_3	Cr_2O_3	V_2O_3
Magnetite	1.9	31.4	3.5	0.1	55.7	0.1	0.9
Ilmenite	51.3	35.5	6.6	0.5	7.1	-	0.2

The composition of the ilmenite is very unusual and it would appear that it must contain either free rutile or titanium bearing spinels.

Solnordal and Sjoholt.- There are two closely related deposits near Storfjord and Skodje, in Romsdal. They are magmatic segregations in gabbro and contain 10-15% TiO_2 and 35-48% Fe. Preliminary tests indicated that a magnetite concentrate with 3% TiO_2 and 45% Fe, and an ilmenite concentrate with 44% TiO_2 and 35% Fe could be obtained. The deposit apparently consists of about 70% magnetite and 30% ilmenite (Imp. Min. Res. Bur. 1922; Vogt 1910).

Sellevold, Loland and Rado.- These are all small deposits in Fjordane containing from 7-16% TiO_2, except for Rado which is supposed to contain 20-30% TiO_2 (Vogt 1910; Lenschow 1950). Apart from the Rado deposit very probably do not contain significant percentages of ilmenite.

Gjolanger (Sordal?, Hellevik?), North of Sognefjord.- Granular disseminated ilmenite and magnetite, enclosed in a chlorite rich rock which in its turn is enclosed within amphibolite, is reported to occur at this locality. Good quality concentrates of both minerals should be obtainable (Private comm. Heier).

The Bergen Area.- In the Bergen area of West Norway ilmenite-pyroxenites, ilmenite-norites and ilmenite-gabbros occur within anorthosites in association with the Pre-Cambrian anticlinal parts of the Bergen arcs, Deposits of ilmenite which have been worked lie in these ilmenite rich rocks at Lindaaes, Lödoy, Askeland, Lysenknappen, Soltvedt, Alvaestrommen, Espetveit and Holseno (Kolderup 1903). No other information regarding them is available.

South and South-East Norway

Spisholt.- Titanomagnetite ores with up to 50-60% of ore mineral occur as concentrations in gabbro at Spisholt near Buskerud, 6 km east of Kongsberg. The TiO_2 content is supposed to be 34% (Vogt 1900).

Gjerstad, Aust-Agder.- A deposit of unknown type is reported from this locality by Lenschow. It contains 8-25% TiO_2 and 30-50% Fe.

Gamoy, Langoy and Herrefjord.- These are deposits in the Langesund area of unknown size containing 6-10% TiO_2 (Lenschow).

Kilsfjord.- This is a deposit near Kragero of unknown size containing 15% TiO_2 (Lenschow).

Ramsöy, Kongsviger.- Ore in concentrations of up to 85% occurs in quartz-amphibolite gabbro at Ramsöy. Average ore contains 61% magnetite, 15% ilmenite and 24% silicates and an analysis indicates 49% Fe, 7.78% TiO_2, and traces of P and S. (Foslie 1913).

Flaad mine, Evje.- Hematite-ilmenite and magnetite occur together with the sulphide minerals in the Flaad Nickel mine. There is no record of the ilmenite being concentrated for sale. (Bjorrlykke 1947).

The Kragerö Rutile Mine.- In the Pre-Cambrian Kongsberg-Bamle formation of south-east Norway near Kragerö, dykes and irregularly shaped bodies of albitite contain, locally, high concentrations of rutile. There are two major albitite masses in the area; one a quartz-albite is 2.6 km long and up to 400 metres wide, the other termed 'krageroite' by Brögger on account of its rutile content, is smaller having an area of 350 x 60 metres.

Rutile is normally only an accessory mineral in the albitite together with biotite, tourmaline, apatite, pyrite sphene, actinolite, chlorite, zircon and calcite. In parts of the Krageroite mass though, the TiO_2 content may rise to as high as 25% (Watson 1912 a:b). There is, apparently, some variation in the composition of the rutiles. The analyses published by Watson (1912b) and Green (1956), quoted below, are similar but Green mentions that Brögger stated that the rutile was an iron rich variety containing 6.32% Fe_2O_3. The analysis recorded in Gillson's (1949) paper, has an intermediate value for iron.

	Watson (1912) %	Green (1956) %	Gillson (1949)
TiO_2	97.68		95.6
SiO_2	1.06	1.08	
FeO	0.81		3.67
Cr_2O_3	0.39	0.18	
V_2O_3	0.55		
Fe_2O_3		1.05	
	100.49		

The vanadium content of the rutile is exceptionally high.

In 1901 exploitation of the rutile deposits commenced and continued intermittently until the late 1940's, but they are too low in grade at the present time to constitute ore.

PORTUGAL

Portugal has been producing and exporting ilmenite concentrates on a small scale since 1926. The ilmenite has been mined, together with cassiterite and uraniferous minerals, from alluvial deposits at Castelo Branco near Belmonte 150 km north-east of Lisbon. The ilmenite is a byproduct of the tin and uranium mineral concentration processes. The alluvial deposits, varying in thickness from 12-50', cover the floor of the wide Belmonte valley. The ilmenite concentrates have a TiO_2 content close to that of theoretically pure ilmenite, but a lower content of iron. (Youngman 1930; Lawthers).

TiO_2	SiO_2	FeO	Al_2O_3	MgO	P	MnO	CuO
52.24	0.27	42.15	0.29	0.03	0.016	5.00	0.00

Production statistics are as follows (Youngman 1930; Gillson 1949).

Metric Tons Ilmenite Concentrates

1926	1030	1937	1456
1927	703	1938	568
1928	703	1939	409
1929-		1940	899
1932	?	1941	798
1933	654	1942	?
1934	434	1943	120
1935	385	1944	?
1936	530	1945	301

Praia de Sines Torpes deposit

Conflicting reports concerning this deposit exist in the published literature. It has been described (Castro Leandro 1947) as a placer deposit, derived from olivine gabbro, containing ilmenite and magnetite, with a TiO_2 content of 40% and an ironoxide content of 48%, extending over an area 3 miles long, 60 ft wide and 6" thick. Another report describes it as a titaniferous magnetite deposit from which a magnetically treated sample containing only 23.49% TiO_2, 45.0% Fe_2O_3, and 17.9% FeO could be produced (da Silva 1945). The economic potentialities of the deposit are thus not at all clear.

Odivelas and Ponte Serpa de Ferreira do Alentejo deposits

Deposits, probably of titanomagnetite in gabbro, are reported to exist at these two localities in the Beja district. The ore contains 48.7% Fe and 9.75% TiO_2. (da Silva 1948).

RUMANIA

The only recorded occurrence of titanium minerals in Rumania is at Nagyalmas, Komitat Hunyad, Siebenburgen whence a vein of titanomagnetite in andesite tuffs has been described. (Ferenczi 1939).

SPAIN

Ilmenite concentrates have been produced from sand deposits in

Coruna and Huelva Provinees. Production from 1941-1950 inclusive was 2,605 metric tons (Lawthers).

Coruna Province

On the north-west coast of Coruna Province black sands containing more ilmenite than magnetite were reported to occur at 42 places by Parga Pondal and Lorenzo (1930). The ilmenite was free from intergrowths. The most important of these deposits is probably the one of Ruzo (Carle 1946) at the Allones river mouth. The deposit averages 10% TiO_2 and a concentrate containing 50-52% TiO_2 has been produced. The ilmenite is derived from ilmenite ore streaks in amphibolite.

The accessory minerals of the kaolinite granite of Lage, Coruna contain, amongst others, zircon, rutile, brookite, cassiterite, ilmenite, columbite, tantalite and wolframite. They could be easily extracted. (Parga Pondal 1952).

Other Deposits

There does not seem to be any recorded information describing an alleged ilmenite deposit in Huelva Province.

Ilmenite sands have been recorded to occur at the following places in Spain:- River Sil, Galicia; Asurias, Carbilla; Serrama de Ronda, Andalusia (Barriero 1942); in the Alagon, Gata, Elijas, Tietar and Aerte rivers of central Spain (de Lome 1930); and in the Balearic islands (Mathews 1942). At Olot, in the foothills of the Pyrenees west of Barcelona, titaniferous magnetite has been worked by Industria Titan S.A. and Sociedad Titania S.A., Galicia. (Minerals Year Book 1943 815). Near Montego de la Sierra opaque minerals are common constituents of alluvial placers. (Mateos and Taboadela 1950).

The following articles also deal with titanium in Spain:- Barcelo (1943); Pardo (1930); Pia Garro (1944).

SWEDEN

Ilmenite and titaniferous-magnetite ore deposits occur in many parts of Sweden. They are probably all of Pre-Cambrian age. It is believed that none of the deposits has been worked for its titanium content and there is no record of any production of ilmenite in Sweden.

Kramsta (Jarvso) deposit. Helsingland

This is a low grade deposit of ilmenite and titaniferous magnetite occurring as disseminated mineral grains in a slightly metamorphosed gabbro. The pyroxene has been altered to hornblende, and plagioclase of a new generation has formed at the expense of large older grains. (Paakkonen 1956).

Concentration tests shew that about 18% of the ore can be extracted as a magnetite concentrate containing 64% Fe and 6.2% TiO_2, and 3.6% as an ilmenite concentrate containing 38-40% TiO_2. Reserves of ore are given as 27 million tons. (Magnusson quoted by Lawthers).

Taberg Smaland. South Sweden

Titaniferous magnetite forms 25-35% of a rock whose other constituent minerals are olivine 43-58%, and irregularly distributed labradorite. This rock is bordered by hyperite containing the same minerals but with the plagioclase the dominant mineral phase. Small amounts of anorthosite are present.

The ore mineral is a titaniferous magnetite with lamellar intergrowths of spinel and ilmenite occurring in grains 0.2-1.0 mm in diameter. Ulvospinel is also almost certainly present. An analysis of the ore mineral (Hjelmquist 1949) is given below.

TiO_2	FeO	Fe_2O_3	Al_2O_3	MgO
15.3%	36.7%	32.4%	6.2%	4.4%

also

SiO_2	CaO	V_2O_3	P_2O_5	S	H_2O^+
1.81	0.16	0.86	0.03	0.02	1.31

It is most unlikely that a titanium concentrate of saleable quality could be produced from this ore. The ore reserve is 150 million tons.

Routivare, Norrbotten

Titaniferous magnetite, ilmenite, spinel and corundum occur as lenses in anorthosite. The ore contains 11% TiO_2 and 46% Fe. An unsuccessful attempt was made to work the ore in 1910. The reserves are variously estimated to be between 18 and 33 million tons.

The ore bodies were produced by magmatic differentiation of a gabbroic parent intrusion. The intrusive body has suffered metamorphism during the Caledonian orogeny and the silicate minerals show evidence of this. The ore minerals apparently do not (Ramdohr 1945). Two hypotheses which have been advanced to account for this are... 1. The ore minerals are more resistant to stress than silicates and remain unaffected unless the metamorphism is very severe (Ramdohr 1945). 2. The ore minerals are the first to react to stress, becoming mobile, and they reconcentrate themselves in low stress areas. In this case the deposit owes its origin in part to regional metamorphism (Paakkonen 1956). This is a problem of genesis more fully discussed in the geological part of this report, but with regard to the Routivare deposit it is only just to point out that Paakkonen has not visited the locality.

Sodra Ulvon.

A titaniferous magnetite-ulvospinel-ilmenite ore occurs in olivine-dolerite at the Grundhamm mine, in the Angermanland Archipelago, North Sweden. The high grade ore contains 52% of ore minerals and occurs as sheets varying from 0.1 to 5.8 metres in thickness. The dolerite consists of plagioclase, olivine, monoclinic pyroxene, biotite, apatite and ore minerals. In the ore, the olivine content is enriched at the expense of the pyroxene and to a less marked extent, of the plagioclase. (Mogensen 1946).

The ore, which contains 8% TiO_2 and 25% Fe, is a magnetite-ulvospinel-ilmenite mixture with a very small amount of free-crystallizing ilmenite present. An analysis of the magnetite shows that aluminium, vanadium, chromium, magnesium, calcium and manganese ions occur in solid solution either in the magnetite or the ulvospinel. An analysis of the magnetite is as follows.

TiO_2	Fe_2O_3	Al_2O_3	V_2O_3	Cr_2O_3	FeO	MnO	CaO	MgO
18.41	27.93	2.35	0.92	0.94	45.82	0.42	0.73	2.48

Mogensen (1946).

The ore has supposedly been formed by early crystallization and settling of olivine and magnetite.

An ilmenite concentrate cannot be economically produced from this ore and reserves are only 20,000 tons. (Magnusson 1953).

Inglamala, south of Jonkoping

An ore deposit containing 4-7% TiO_2 and 30% Fe has been recorded to occur at this locality. (Landergren 1948b).

Alno Island

Titaniferous magnetite deposits are known to exist on Alno Island but are not thought to be economically important.

U.S.S.R.

Although a considerable amount has been written about deposits of titanium minerals in the U.S.S.R., and a number of articles of geological importance have appeared in various journals, little is known of the economic aspect of the subject. The Soviet Government has to a large extent suppressed production and ore reserve statistics and only a fragmentary picture of the Soviet titanium mining industry results from a survey of the literature. Only geological articles have been studied for the production of this thesis and a diligent perusal of chemical and mining trade magazines might easily improve the scope of the survey here presented. Titanium minerals from the U.S.S.R. have not been used beyond the 'Iron Curtain' but a recent trade delegation to the United Kingdom presented samples of ilmenite for study.

The Soviet Union will be dealt with on a regional basis.

Ural Mountains Area

This is undoubtedly one of the most important metallogenic areas of the world. Deposits of titaniferous iron ores are abundant and rutile and ilmenite deposits also occur.

The total reserve of titaniferous magnetite in the Urals region is certainly not less than 100 million tons containing about 10-15% TiO_2, but how much of this potential ore material would be of use for obtaining titanium dioxide concentrates it is impossible to surmise.

Rutile Deposits

Verkhne-Ufalets, Kyshtym.- A quartz, rutile, ilmenite, pyrite vein in the endocontact zone of a granite massif contains large rutile crystals. The rutile content of the vein is apparently about 2% but alluvial deposits occur in the neighbouring Sukhoi Sugomak creek.

Analysis of the rutile:-

TiO_2	SiO_2	Fe_2O_3	Cr_2O_3	Al_2O_3
95.98	0.54	2.84	0.28	0.43

(Gordienko (1929) Nikolajew (1915)) Vertushkov (1949)

A similar deposit in the same location is mentioned by Syrokomskii (1928) but the host rock of the veins is supposed to be pneumatolysed gabbro-peridotite. They are probably the same deposit.

Ilmenite Deposits

Kaslin.- At Kaslin, 7 km east of St. Mauk on the Kasel road ilmenite associated with apatite and dolomite is reported to occur. The deposit appears to have formed at the contact of granite gneiss and chromite bearing serpentine, and is lense-shaped having a length of 38 m on the surface. (Syrokomskii 1928).

To judge by the description of Bonshedt-Kupletskaya (1952) this deposit, together with one at Bektau-Ata, north-west Pribalkhashe, are of mineralogical interest only.

Ilmen Mountain.- Ilmenite occurs in miaskite pegmatites associated with the alkaline complex of the Ilmen mountains, together with pyrochlore and ilmenorutile (Panteleev 1938). Ilmenite bearing alluvial deposits derived from miaskite occur in the Savel'ev valley in the neighbourhood of Mias plant. The ilmenite contains 45% TiO_2 (Syrokomskii 1928).

The ilmenite from this region, near Miask, is homogenous (Warren 1918). Analyses show, however, considerable amounts of ferric iron and manganese, which are presumably in a solid solution in the ilmenite.

TiO_2	Fe_2O_3	FeO	MnO	MgO
45.93	14.30	36.52	2.72	0.59

(Rammelsberg 1858 quoted by Warren 1918).

It is possible that the resolving power of Warrens microscope was not sufficient to detect small exsolution intergrowths, or he may have missed signs of alteration in the ilmenite. If he did neither, the amount of Fe_2O_3 in solution is abnormally high.

Alkaline syenites, nepheline syenites and granite occur in the Ilmen mountains in the Mariupol alkaline massif. Ilmenite and titaniferous magnetite occurs in these rocks. Titanium tends to be concentrated in non-felspathoidal syenite pegmatites associated with the main rock masses, as ilmenite, sphene, titaniferous magnetite and ilmenorutile. Tantalum and niobium bearing minerals also occur in close association with them. The occurrences seem to be of geochemical interest only, although the rare earth content of the pegmatites may cause economic exploitation (Yurk and Tsarovskii 1940; Panteleev 1938).

The ilmenite concentrate presented by a recent Russian trade delegation has been analysed with the following result. The source of the mineral is not known but is thought to be in the Ural Mountains. From the analysis it is clear that the ilmenite is either primary or derived from an eluvial or alluvial deposit close to its parent rock.

TiO_2	FeO	Fe_2O_3	MnO	P_2O_5	Cr_2O_3	V_2O_5	Res.
41.3	34.7	10.7	0.65	0.03	.09	0.34	4.2

Titaniferous Magnetite Deposits

(In this section the reference (Lawthers (1)) indicates that information is obtained from Tsentral 'nogo Ispolintelnogo Komiteta i Soveta Narodynkh Komissarov Soyuza S.S.R. (1939) via Lawthers).

Bilimbaerskoye.- Locality 57°30' N 59°35' E, thirty miles south of Nizhny Tagil. A titaniferous magnetite sheet occurs as an inclusion in peridotite. There is an ore reserve of 3,100,000 tons with 3-4% TiO_2 (Lawthers (1); Malyshev and Panteleev (1934)).

Chernorechenskoe (Black River).- 55°18' N 59°45' E., five miles east of Magnitkoye. Dyke-like bodies up to 200 m long of titaniferous magnetite occur in slaty gabbro with reserves of up to 700,000 tons containing 10-16% TiO_2, 50-57% Fe, and 0.4-0.8% V_2O_5. (Syrokomskii 1928; Malyshev and Panteleev 1934).

Kusinsk deposit.- 55°20' N 59°40' E, between eight and nine miles east of Kusa. The Kusinsk (alternatively Kusa, Kusin, Kisin, Zlatoust) deposit lies in the Magnitka or Nazyamsk hills. There are six parallel dyke-like ore bodies striking north-east-south-west, dipping at 70-80° to the south east. (Malyshev 1934, 1937). The ore zone has been proved to a depth of at least 85 m (Syrokomskii 1928).

The ore bodies occur in a heavily metamorphosed diorite, gabbro and anorthosite complex of Pre-Cambrian age. (Panteleev 1938). The titaniferous-magnetite ilmenite ores are derivatives, pegmatitic in character, of the gabbro magma produced by a filter pressing action, acting during the crystallization of the gabbroic rock, which concentrated the late crystallizing constituents in tectonic fissures (low pressure areas). Where no pressure acted during crystallization the ores remained disseminated in the gabbro. The geology of the deposit is more fully described in Part I of this thesis.

The following analyses are of the four largest ore lenses taken in order of intrusion from north-west to south-east (Panteleev 1938).

	No. 1	No. 2	No. 3	No. 4
%Fe	47.37	52.57	52.59	54.50
TiO_2	14.82	14.08	14.01	13.57
Cr_2O_3	0.42	0.44	0.87	1.07
Ti:Fe	0.188	0.161	0.158	0.149
Cr:Fe	0.006	0.0057	0.0112	0.035

Malyshev (1934) quotes a vanadium content of 0.5%, Lipski (1933) quotes 0.64% V_2O_5.

Concentration tests shew that a magnetic concentrate containing 64% Fe and 7% TiO_2, and a non-magnetic concentrate containing 42% TiO_2 can be obtained with 87% recovery (Kulibin 1934). The reserves of ore (Malyshev 1934) are 33 million tons of confirmed ore and probably 60 million tons total reserve.

Matkalskoye.- Streaks of ore up to 1 m thick and 100 m in length occur in gabbro at Matkalskoye, fifty kilometres south-west from Zlatoust. The ore, consisting of ilmenite, magnetite and rare hematite, contains 10-15% TiO_2 and 40% Fe, (Malyshev 1934).

Radost (Radush).- Veinlike inclusions of titanomagnetite up to 1 m wide occur at Radost, thirty-two kilometres north-east of Kusinsk, near Maloi. The ore analyses 0.88% TiO_2 or higher (Syrokomskii 1928).

Satkin.- Sheetlike ore bodies occur associated with ore bearing gabbros and syenites at Satkin on the Kopansk river. The deposits are highly folded, consisting of four ore bodies 700-800 m in length, containing 13.58% TiO_2 and 35% Fe. The reserve of ore is 1.6 million tons.

(Syrokomskii 1928). This deposit may be synonymous with the Kopanskoe deposit.

Kopanskoe.- 55°8' N 59°20'E, twenty-five kilometres south-west of Zlatoust.

A sheetlike body of titaniferous magnetite 1 m wide, occurs in a sheet of gabbro 1,000 metres thick. An analysis of the ore shewed

TiO_2	Fe	V_2O_5
14%	49%	0.5%

Ore reserves are 10-15 million tons but the ore is too variable in composition to be of great value. (Malyshev 1934); Lawthers (1). The ore is essentially the same type as that occurring at Kusinsk.

Pervouralskoe deposit.- 56°50'N 60°00'E. Ore, which crystallized from a late fraction of a gabbro magma intruded into Siluro-Devonian sediments, lies enclosed in hornblendite. Panteleev (1938) has recorded the geochemical distribution in the seven ore bodies which constitute the deposit. These ore bodies he has arranged in the order of their intrusion and has shewn that the ratio of Ti:Fe falls from 0.1 to 0.05. The ores contain from 3-6% TiO_2. The iron content rises from 10-60% while SiO_2, Al_2O_3, MnO and MgO all drop by the following amounts:- SiO_2 40-1%, Al_2O_3 15-6.5%, MnO 12-3%, MgO 12.5-2%. The high MnO content of the first intruded ore body is most unusual for a deposit of this type.

As a result of his work on this deposit Panteleev has drawn the following general conclusions regarding titaniferous magnetite ores. 1) A high concentration of titanium in a residual magma is due to a low iron content in the parent magma. 2) Late concentration of chromium in ore bodies is due to preferential entry of Fe" into the Fe_3O_4 lattice. These conclusions are discussed in Part I of this thesis.

The ore reserves in this deposit (Malyshev 1934) are 10 million tons.

Kachkanar deposit 58°50'N 59°30'E.- The Kachkanar massif is built of pyroxenites, gabbros and dunites intruded into Siluro-Devonian sediments (Panteleev 1938, Rupasova 1948). The ore occurs as disseminations in olivine diallage pyroxenites with concentrations of ore varying from 15-45% of the rock, and as compact ore veins in medium and coarse grained diallage pyroxenites. The ore content of the dunites is less than 20% and "of no economic value." The ore minerals are principally magnetite and ilmenite with some chalcopyrite and iron pyrites. Reserves are 31,000,000 tons of ore containing 2-5% of TiO_2 (Malyshev 1934 Lawthers (1)). The ore is of a type similar to the Pervouralskoye ore. The deposit has also been described by Michailov (1941).

Kaslinskaya Dacha.- Titaniferous magnetite is reported to occur in gneissic serpentine masses at Kaslinskaya Dacha, 114 miles north of Chelyabinsk, 15-20 miles north of Kyshtym (Lawthers). This deposit may be connected with the ilmenite deposit of similar name.

Turatashkoye deposit.- Veins and blocks of magnetite occur in diorite in the same general region as the Kaslinskaya deposit at Turatashkoye. The iron content rises to 44% but the TiO_2 content is unknown. (Syrokomskii (1928)).

Ivanovsk deposit.- In the Ufalei region near the Kaslinskaya deposit, an irregular vein 1½-4 m wide occurs in chlorite schist. The iron content is 63% and TiO_2 9%. This deposit was worked in the

1880's.

Shaitan Dacha. 53°50'N 59°5'E, near Magnitogorsk.- An ore deposit, supposedly containing 100 million tons of ore occurs as a differentiate from a gabbro magma. Analyses by Zasypkin quoted by Syrokomskii (1928) are as follows,

	TiO_2	FeO	Fe_2O_3
1.	4.48	25.76	50.86
2.	7.95	20.05	49.85
3.	11.47	26.75	46.94

indicating a titaniferous magnetite ore probably with little free ilmenite.

Spornoe deposit 57°40'N.- Ilmenite-magnetite schlieren containing 60% Fe and 5-8% TiO_2 occur here. The reserves of ore are 100,000 tons. (Malyshev 1934).

Barancinski Massif.- Ores in the Barancinski Massif contain 3-5% TiO_2 (Malyshev (1934)). These are also described by Kasin (1946) and Krasnopolski (1909).

Denezkhin deposit 60°25'N 59°25'E.- Ore bodies segregated from a gabbro intrusion occur near here.

Kinresla deposit, Visera river. (Ybryshka deposit).- Ore occurs as a segregation from a gabbro intruded into schists. Several million tons of reserves are supposed to exist. (Malyshev 1934). An analysis by Duparc and Pearce (1909) gave

TiO_2	Fe_2O_3	FeO	SiO_2	Al_2O_3	CaO	MgO	K_2O	Na_2O
9.5	19.5	21.8	26.6	11.6	6.47	2.5	0.34	1.06

Syrokomskii (1928) quotes 17.2% TiO_2 and 1.25% V_2O_5.

Perovskite-Spinel-Magnetite deposit

A deposit of titaniferous minerals probably of a unique type occurs in the Praskoie-Eugenievsky mine in the Shishim Mountains, South Urals. (Shilin 1940b: Bonshedt-Kupletskaya (1952)).

The pyrometasomatic ore occurs at the contact of gabbro with limestones in chlorite-serpentine rocks. The "orebody" is only 15-20 m long and 20-50 cm thick and is presumably of no economic significance. The mineral assemblage has developed as a skarn resulting from the assimilation of limestone at the contact of a titaniferous magnetite ore body.

The titaniferous minerals occur in the following amounts. Magnetite (ilmenite and hematite) 71.6%, Spinel 15.16%, Perovskite 13.24%. The texture of the rock is as follows. Magnetite with a rim of hematite forms the groundmass of the orebody as a mass of interlocking grains surrounded by the perovskite. Spinel occurs as irregular grains in the ore, in part probably developing from perovskite and magnetite.

An analysis of the magnetite-perovskite-spinel rock is given below and is compared with the titaniferous magnetite from the same mine.

	P.S.M.	Titaniferous Magnetite		P.S.M.	Titaniferous Magnetite
SiO_2	0.04	1.11	CaO	7.35	1.70
TiO_2	10.75	15.41	CuO	0.08	-
Al_2O_3	10.73	-	MgO	7.27	2.25
Fe_2O_3	43.53	56.06	ZnO	0.43	-
Cr_2O_3	2.14	2.48	SnO_2	0,007	-
V_2O_3	0.23	0.59	H_2O^+	0.80	0.73
WO_3	0.04	-	H_2O^-	0.04	-
FeO	18.14	18.95	P_2O_5	0.00	0.02
NiO	0.07	0.07	S	0.42	-
MnO	0.67	1.35			

A recalculation of the analyses gives the following result

	P.S.M.	Titaniferous Magnetite
Ilmenite	-	31.25
Perovskite	23.15	1.78
Spinel	27.03	-
Magnetite	49.85	60.97

Where transverse fissures of calcite cut the perovskite bearing rock, picroilmenite encrusted with perovskite is formed. The picroilmenite contains 52-58% Mg TiO_3, 32-35.5% Fe TiO_3 and 3-10% Mn TiO_3. (Bonshedt-Kupletskaya 1952).

Ilmenorutile Black Rutile

Ilmenorutile intergrown with ilmenite and containing (exsolution?) lamellae of ilmenite has been described from nepheline pegmatites near the cryolite mines of Mount Kossaya, Ilmen Mountains (Sosedko (1939)). The economic importance of the deposit is not discussed but is probably insignificant.

Deposits of the Kola Peninsula

There are four intrusive massifs in the Kola Peninsula region each of which contains accumulations of titanium-bearing minerals. This region of the Soviet Union contains the largest and some of the least well described occurrences of alkaline igneous rocks in the world. Great confusion has been caused in the past because of the number of different names which have been applied to the same pluton and to its associated mineral occurrences.

The Kola region is a mineral collectors paradise; more rare minerals have been described from pegmatites and similar rocks in that region than from any other. Many of them are rare earth oxides, titanates and silicates carrying titanium and where they are mined for their rare earth element content the titanium may be concentrated as a by-product. Sphene is supposed to have been mined for its titanium content; if this is the case then it is a mining proposition of a very unusual type.

The igneous plutons of the region are 1) The Khibine (Kirovsk, Khibinogorsk) or Umptek alkaline-massif; 2) The Lovozersky or Lujavurt alkaline massif; 3) The Gremyakha-Vyrmes complex pluton on the Tuloma river and 4) The Africanda and Chabozero complex consisting of basic, ultrabasic and intermediate rocks.

The following accounts are based almost exclusively on articles which have appeared in English or with English summaries. Undoubtedly a greater store of information is available in the Russian literature.

<u>The Khibine alkaline igneous pluton.</u>- The Khibine pluton has a roughly circular shape with its constituent rock bodies outcropping as a series of rings one within the other. The outer ring is coarse nepheline syenite followed by fine grained nepheline syenite, ijolite and urtite and finally a core of foyaite. Apatite and nepheline-bearing rocks containing magnetite, ilmenite and sphene occur between the ijolite-urtites and the fine grained nepheline syenite on the hanging wall of the ijolite cone sheet intrusion. (Kupletskii 1936a; Eliseev 1937; Labuntzov 1930; Nature <u>141</u> (1938) 354; Fersman 1929). The apatite deposits apparently contain 2.4% sphene and 2-16% titanomagnetite. The reserves of TiO_2 in the deposit has been estimated not to exceed two million tons (Hausen 1942). Pegmatites associated with these rocks are mined for rincolite (Ti bearing silicate of Ca, Sr, Na) and loparite (Ti bearing niobate of Ce, Ca, Na).

Svyatlovskii and Diterikhs (1939) described two types of apatite intrusion, one with, and one without, sphene. The apatite-sphene rock is associated with the ijolite. The sphene has been mineralogically described by Kupletskii (1930) and Bonshedt (1936).

The Lovozersky alkaline igneous pluton.- The Lovozersky alkaline pluton, covering an area of 650 square kilometres, forms the mountain massif of Lujavurt which rises to a height of 1127 m. The alkaline igneous rocks have been intruded into Archaen gneisses and Devonian lavas. Four separate intrusive rock groups are recognised (Eliseev, Zelenkov et al. 1938) of which the second and third are the essential rock types of the massif forming the greater part of the intrusive complex. Arranged in chronological order they are

1) A complex of fine grained nepheline and alkaline syenites sodalite syenites, foyaites, urtites and juvites.
2) A primary stratified loparite bearing complex of foyaite, urtite, malignite and lujavite.
3) A primary stratified complex of eudialyte-lujavites.
4) A complex of vein and dyke rocks.

There are seven different loparite rich horizons, up to several metres thick in the lower foyaite complex. The loparite, (Nb_2O_3, Ta_2O_3 10-12%, TiO_2 38.5%, rare-earth oxides 34%) is mainly near the upper surface of the 500-800 m thick complex, despite its high specific gravity (4.75-4.78). It became concentrated at the top of the complex by a gas transfer pseumatolysis process. (Eliseev 1937; Vorobieva 1938). Loparite also occurs in the contact zone of the urtite phase of the complex where it has accumulated by gravity settling to form local ore concentrations.

No figures of reserve tonnages of ore have been quoted in the literature but they are thought to be in the millions of tons category.

In the upper 300-600 m thick lujavite complex, eudialyte occurs in bands, streaks and pegmatites. This complex is less well differentiated than the foyaite-urtites. Melanocratic eudialyte-lujavites containing up to 25% eudialyte form thick sheets in part of the complex and locally pegmatites contain 85% eudialyte. Eudialyte contains 13% $Zr\ O_2$.

Other titanium bearing minerals which occur in the Lovozersky massif include murmanite, titanoelpidite, enigmatite, steenstrupine and mangano-ilmenite. These have been described by, amongst others, Zolotar and Sakharov (1936); Gerasimovskii (1936; 1940a; 1940b); Perushin (1935); and Fersman (1926).

The Gremyakha-Vyrmes Pluton. - Three separate complexes form this pluton. (Polkanov 1944). They are:-

a) An hortonolite-barkevitite gabbro-akerite-pulaskite-laurvikite complex.

b) A nepheline syenite complex.

c) An alkaline granite and syenite complex.

Two intrusion sub-phases are distinguishable in the gabbroic complex, fifty sq. km in extent, which contains the iron-titanium oxide minerals. The sub-phases, of basically similar type both having a primary layered structure, differ slightly petrographically since one is an hortonolite gabbro-akerite association and the other an hortonolite pyroxenite-laurvikite association. The ore minerals are associated with the periodotites and pyroxenites of each sub-phase.

The ore minerals are titaniferous magnetite and ilmenite, the former always containing ilmenite exsolution lamellae. Ilmenite is not universally present but may on occasion form 15.2% of the host rock together with 11.6% of titaniferous magnetite. The opaque constituents of the oxide-rich rocks have accumulated by downward migration of heavy liquids (Polkanov 1944) but the accumulative process does not seem to have taken place in a sufficiently intense manner for the formation of orebodies; the opaque minerals remain disseminated among the silicate constituents of the host rock. The overall TiO_2 content of the rock does not rise above 17.9%. The average of three analyses given by Polkanov is 14.5%, and the specimens may not have been purely random samples. The reserves of titanium in the complex are not recorded but must presumably be considerable although of low grade.

The Africanda Complex.- The Africanda complex has a zonal structure of which the peripheral zone is composed of nepheline pyroxenite (nepheline 40% pyroxene 55%). Adjacent to it is a zone of fine grained pyroxenite, principally of diopside augite composition, while the central zone is a coarse grained pyroxenite, rich in titaniferous minerals, which has been called Africandite. (Chirvinskii, Afanasev and Ushakova 1940). This rock consists of pyroxene 53%, titanomagnetite 22%, knopite 18% and nepheline. Rarely the titanomagnetite content reaches 52% with 16% knopite and, also rarely, titanomagnetite 26% knopite 56%. The pyroxene is diopside-hedenbergite. Analyses of the titanium minerals are as follows (Kupletskii 1936b; 1938).

	Titaniferous Magnetite	Knopite		Titaniferous Magnetite	Knopite
SiO_2	0.12	0.96	MnO	0.48	0.02
TiO_2	20.15	56.35	CaO	4.98	37.52
Al_2O_3	0.18	0.24	MgO	5.22	0.14
Fe_2O_3	43.01	0.78	H_2O^-	0.12	0.16
Rare Earth	-	2.23	H_2O^+	-	0.57
FeO	26.26	0.70	V_2O_5	0.08	-

The rock has a sideronitic texture (Eliseev 1937) in common with the textures of the oxide-rich rocks of the Gremyakha-Vyrmes pluton with which it is similar. Titaniferous magnetite forming up to 65% of the rock forms, in hortonolite peridotite, bands containing 4.9-10.8% TiO_2 (Kupletskii 1938) in the central pyroxenite.

The whole massif is intruded by the following veins. In chronological sequence they are

1. Pegmatoidal pyroxenite.
2. Pyroxene-nepheline pegmatite. (Africandite).
3. Mica Veins. a) Biotite veins.
   b) Lepidomelane veins with knopite and titaniferous magnetite.
4. Titanomagnetite veins up to 20-50 cm thick.
5. Pegmatites. a) schorlomite-nepheline
   b) amphibole nepheline
   c) amphibole-apatite
   d) mica pyroxenite. Knopite and titanomagnetite occur in small amounts.
6. Calcite and other carbonate veins.
7. Subalkaline mineral veins.

Other Deposits of the U.S.S.R.

Koikar (Koykarsh, Koykory).- Titanomagnetite deposits, possibly of considerable importance, occur in gabbroic rocks near the Suna river, Lake Vygo, west of Lake Onega. (Syrokomskii 1928).

Pudashgorsk.- Titaniferous magnetite deposits occur in dioritic rocks enclosed in granite gneiss in the parish of Pudoshgorsk, east of Lake Onega. The ore contains 8.7-10.8% TiO_2 and 30-40% Fe. Over an area of 275 sq.ft. to a depth of 275' there are 406,000 tons of ore (Syrokomskii 1928; Eng. Min. J. 149 (1948) 96; Hausen 1942).

Velimaki deposit.- Uralitized pyroxenite lenses in gabbro-diorite containing titaniferous magnetite occur at Velimaki, Serdobol north-east of Lake Ladoga. The ore contains 7.5% TiO_2 in ilmenite-titanomagnetite intergrowths. (Syrokomskii (1928).

Tikhvinskoe bauxite deposit.- 59°40'N 30°35'E. 100 miles east of Leningrad. This deposit containing 6.5% TiO_2 is now apparently worked out (Syrokomskii 1928; Lawthers).

Azhinsk gabbro.- The Azhinsk gabbro complex is in the Oirotia region of western Siberia and forms part of the Aji mountain massif at the junction of the Bia and Yshna rivers. The complex of Caledonian age includes pyroxenites containing titaniferous magnetite and pyrite, and ilmenite-rich gabbros as schlieric masses in the pyroxenite. The titaniferous magnetite, in large crystals, forms irregular aggregates which were the last products of crystallization. The opaque minerals are associated with late crystallizing chlorite and serpentine.

Ilmenite is an essential mineral constituent of the gabbro. It occurs together with blue-green plagioclase and black titaniferous augite. The ilmenite occurs in large automorphic crystals and as irregular rims. It contains a very small, quantity of magnetite in solution (possibly exsolution lamellae?). A chlorite-serpentine mineral frequently accompanies the ilmenite. Apatite occurs as rare grains embedded in augite but more commonly as xenomorphic interstitial fillings, and it was the last mineral to crystallize apart from the ilmenite. The rock contains 42% augite and 7% ilmenite.

Analyses of the gabbro, pyroxenite and titaniferous augite are given by Lebedev and Lebedev (1934). The gabbro contains 4.84% TiO_2

and the pyroxenite 4.04%. Titanium is remarkably concentrated in the augite which contains 8.97% TiO_2. V_2O_5 concentrates in the ilmenite (an unusual feature) up to 0.42%

Patyn gabbro.- The Patyn gabbro is situated in the Kusnetsk-Alatau in North Altai, western Siberia. It is a complex of banded gabbro sheets, containing sill-like bodies of titaniferous magnetite-rich gabbro. (Lebedev P.I 1935).

Gabbro-Norites of the Ukraine.- Ilmenite-magnetites shewing intergrowth and exsolution textures have been described in Ukrainian gabbroic rocks (Serdyuchenko 1950). The opaque minerals probably do not constitute potential ore bodies.

Pambak and Gedzali.- A gabbro-porphyry intrusion at Gedzali (Armenia) contains 21.05% TiO_2, 46.90% SiO_2, 8.29% Fe_2O_3, 6.14% MgO and 5% Na_2O + K_2O. (Balasanyan 1955).

Tur Achyr.- Titaniferous magnetite containing 15.34% TiO_2 occurs at Tur Achyr in the Kirghiz steppe (Syrokomskii 1928).

Alibashli.- Titaniferous magnetite containing 1-14% TiO_2 occurs near Alibashli in the Caucasus. (Syrokomskii).

Secondary Deposits

Azov Sea Coast.- Black sand deposits occur on the northern shore of the sea of Azov. They contain varying quantities of ilmenite together with quartz, graphite, anatase, baddeleyite, zircon, magnetite, kyanite, garnet, hornblende, monazite and various silicate minerals. (Savich-Sablotskii 1939). The most important deposits are in the Belosairaiskii Peninsula, where there are 300,000 tons containing 35% TiO_2. At Portovaja there is a small deposit of 2,000 tons containing 37% TiO_2, at Ganzukovskaia, one of 7,000 tons containing 14% TiO_2, and at Nogoskaia one of 10,000 tons containing 32% TiO_2

(Lukasev 1937; Suloev; Panteleev 1934).

Mius delta.- The deltaic sediments contain titanium rich magnetite sands (Lukasev 1937).

Chutor Najdenovka.- Sands contain 24-31% TiO_2 and 33% Fe are reported to occur at this locality.

Ukraine.- At Gakovskoe and Radno-Gakovskoe near Toreinka in the Zitomir region there are kaolin and Quartz sands which contain ilmenite. The total reserves are about 850,000 tons of ilmenite. At Andreevskoe in the same region kaolin deposits 5 m thick contain 4.6% ilmenite. (Juskevic, Sulc et al. 1933).

A concentrate containing 42.5% TiO_2, representing about 30% of the original material was obtained from raw sand in the Dnepropetrovsk region. From the concentrate a product, presumably rutile, containing 95.6% TiO_2 was obtained. (Chornii 1937).

Ilmenite occurs in cassiterite-bearing alluvial deposits in the north-western part of the Ukraine crystalline ridge. (Luchitskii and Minakov 1939).

Turgai Region.- Bauxite deposits in the Turgai region contain 3.5% of TiO_2 and associated red clays contain 2.25% TiO_2. (Burtsev 1938). Fine grained alluvial sands also contain ilmenite and rutile (Lavrov 1956). Concentration experiments with an electro-magnetic separator shewed that a concentrate containing 38-43% TiO_2 could be produced (Pylaev and Shuster 1957).

Teterev River Basin.- Ilmenite deposits described as "the biggest in the country" containing 45-50% Fe and 30-69% TiO_2 with some V_2O_5 were recorded to occur in the Teterev river basin by Bogomolov (1936).

Kysil-Kum.- Rutile deposits are supposed to exist in the Kysil-Kum desert (Shilin 1940a).

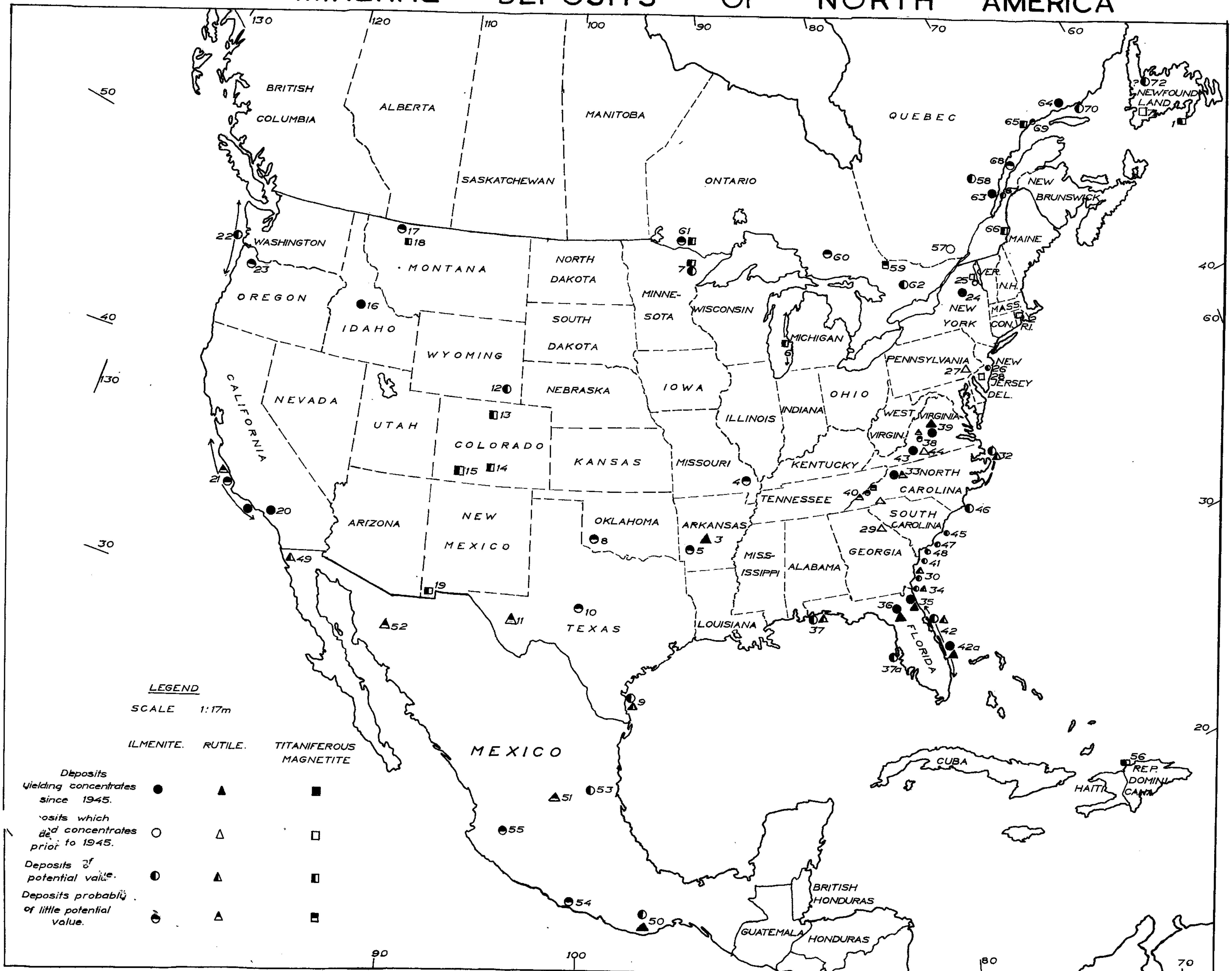
YUGOSLAVIA

Ulcini.- In beach sands at Ulcini low grade deposits of titaniferous minerals are reported to occur. (Pavlovic 1952; Protic 1951). They contain 3% chromite, 2.4% ilmenite and 1.0% magnetite.

Vardar River.- Near Strumica, the sands of the Vardar river contain monazite (47 gr/ton) sphene, zircon and rutile amongst other minerals.

Rutile also occurs at Prilepec in south Serbia.

TITANIUM MINERAL DEPOSITS OF NORTH AMERICA



<u>Titanium Mineral Deposits of North America</u>

<u>Legend</u>

1. Miquelon
2. Iron Mine Hill, Cumberland
3. Magnet Cove and Christie
4. Einstein Silver Mine
5. Beulan Green and Pink Green
6. Shores of Lake Huron
7. Duluth Gabbro
8. Wichita Mountains
9. Padre Island
10. Baringer Hill
11. Jeff Davis County
12. Laramie Mountains
13. Caribou Hill
14. Iron Mountain
15. Cebolla Creek
16. Valley County Streams
17. Blackfeet Indian Reservation
18. Choteau
19. Hidalgo County
20. West San Gabriel Mountains
21. Californian Beaches
22. North Oregon and Washington Beaches
23. Oregon Bauxite Deposits
24. Lake Sanford
25. Westport
26. Lakehurst
27. Chester County
28. New Jersey Magnetite Mines
29. Graves Mountain
30. Sapelo and St. Simons Islands
31. Gaffney and Ellenboro'
32. Albemarle Sound
33. Yadkin River
34. Amelia Island
35. Jacksonville
36. Trail Ridge
37. Pensacola
38. Buena Vista
39. Roseland
40. Small Deposits in the Appalachian Mountains of North Carolina and Tennessee
41. Tybee
42. Unexploited Deposits of the East Florida Coast

42a. Vero Beach

43. Bush-Hutchins
44. Franklin County
45. Great Pedee River Mouth
46. North of Cape Fear

47. Folly Beach
48. St. Helena and Hilton Head Islands
49. Real De Castillo
50. Pluma Hidalgo, Oaxaca
51. San Luis Potosi
52. Sonora
53. Vicotira
54. Papanao
55. Cauton de Guadalajara
56. Monte Christi
57. Ivry and Desgrosbois
58. St. Charles
59. Angus
60. Three Ducks Lake
61. Mine Centre
62. Pusey Mine
63. St. Urbain
64. Allard Lake
65. Bay of Seven Islands
66. Beauceville
67. Chaloupe River Mouth
68. Bersimis and Manikouagan
69. Moisie River
70. Natashkwan
71. St. George's Bay
72. Southern White Bay.

CHAPTER III

NORTH AND CENTRAL AMERICA

CANADA

Canada is rapidly moving to the forefront of titanium mineral producing nations of the world. Since the last century ilmenite-magnetite deposits have been worked in Quebec, which contains the important titaniferous deposits, but until the 1939-45 war production was very limited. During the war, production from the St. Urbain mines surged upwards to over 60,000 tons in 1943 but has since declined.

The discovery in 1941 of the immense ilmenite deposit near an unnamed lake - since appropriately christened TiO - in the Allard Lake area of the Lower Romaine river region, has made Canada into the country with the largest known reserves of hard-rock ilmenite in the world. The export from the Sorel smelter to the U.S.A. of 129,823 tons of titanium slag containing 70% TiO_2 places Canada on an equal footing with India and the U.S.A. as one of the world's most important titanium producing countries.

British Columbia

New deposits of titanium bearing ore have been found on Queen Charlotte Island according to Chem. Age (1948) 831. It is reported to contain 60% TiO_2 and is therefore presumably a sand concentrate.

Newfoundland

Indian Head, St. Georges Bay.- "At Indian Head and to the north-east, is a horst of Pre-Cambrian comprising anorthosite, mafic gabbro, mafic syenite, soda granite and granite. The nature of the complex suggests by analogy with the Adirondacks that they may constitute the western border of the St. Georges anorthosite massif (20 miles east of Indian Head). The ilmenite magnetite gabbro of Indian Head resembles that of the Split Rock Mine in the Adirondacks". (Buddington 1939b quoted by Heyl and Ronan 1954).

Apart from the above quotation very little is known about the ilmenite-magnetite deposits of this region. The work on them was carried out by Ronan who was killed before he could publish, and his work has been pieced together to form the report of Heyl and Ronan (1954). Magnetite deposits with little or no titanium content are quite commonly associated with the gneissic granites of the region. Ilmenite-magnetite deposits are presumably those of the Lower and Upper Drill Brook mines worked by DOSCO in 1942. Various ore analyses indicate TiO_2 contents of 2-7% with from 30-60% Fe. The ores occur in norite gneiss.

<u>Bishop Claim, St. Georges</u>.- A titaniferous magnetite deposit occurs in anorthosite 3 miles south-east of St. Georges village. It is known as Bishops claim. The titanium content occurs as ilmenite exsolution lamellae in magnetite. The anorthosite was intruded as a liquid magmatic body. (Baird 1954). The ore was intruded into still hot anorthosite as a magmatic-hydrothermal fluid which reacted with the feldspars to form garnet reaction rims. Amphibolitized pyroxenes also accompany the ore which is coarse grained, ungranulated and somewhat pegmatitic in character. No chemical details are given.

The occurrence of titaniferous magnetite at St. Georges has been referred to as follows:- Snelgrove (1938); Min. Rec. <u>60</u> (1949) 1;

C.T.J. 131 (1952) 1420. These references probably concern the deposits described above.

North Newfoundland.- Titanium deposits were reported to exist in North Newfoundland (Chem. Age 68 (1953) 33). The White Bay region of north-east Newfoundland contains titanium deposits (Betz 1948). These may be the same as those mentioned by Chem. Age 68.

Titanium deposits were also recorded to occur in the Mealy Mountains (World Min. 5 (1952) 69).

No further details are known concerning these deposits except that a smelter had been planned which would use the ores in North Newfoundland. They are presumably titaniferous magnetite deposits.

North West Territories

A band of titaniferous magnetite up to 1.5 m thick containing 11.0% TiO_2 occurs in a basic intrusive complex near the Francois river, Great Slave Lake (Joliffe 1937).

Beach sand concentrates from near Yellowknife derived from Archaen gneisses contain monazite, magnetite, ilmenite and almandine garnet. (Folinsbee 1955).

Ontario

Ilmenite and titaniferous magnetite.

Angus Township, Nipissing.- An intrusion of diabase into granite contains unusually large amounts of titaniferous magnetite. At its eastern end rich segregations of opaque minerals occur which were analysed with the following result:-

Fe	TiO_2	P_2O_5	V_2O_5	S
43.62	21.96	0.05	0.18	0.03

The diabase is thought to be younger than the enclosing granite and the ore is considered to be a contact metamorphic deposit (Hurst 1932).

Three Ducks Lake Area.- A small deposit of ilmenite occurs near Three Ducks lake, 100 miles north-west of Sudbury as an irregular mass in granite on one side of a lamprophyre dyke. The ore outcrop covers an area of 10' x 30'. The dyke is thought to have acted as a barrier to mineralizing solutions from the granite. (Laird).

Seine Bay, Rainy River District.- A narrow belt of ilmenite-magnetite ore extends for 14 miles along the north shore of Seine Bay, and Bad Vermilion lake near Mine Centre. It is included in hornblende gabbro which has intruded the Keewatin series. The flattened lenticular ore lenses have a maximum length of 100' and width of 62', and are aligned conformably within the foliation. Preliminary beneficiation tests shewed that only concentrates containing between 6% and 26% TiO_2 and 33-45% Fe could be obtained. (Robinson 1922). This indicates that the bulk of the ore mineral must be magnetite with ilmenite exsolution lamellae.

Hastings County.- Titanium bearing ores were recorded to occur at the Chaffey and Mathews mines, Newboro and at Millbridge, Hastings County (Pope 1899).

Pusey Mine, Glamorgan Township.- Titaniferous ores occur at the Pusey Mine in Glamorgan Township, Haliburton County. (Foye 1916). The ore occurs in bands parallel to the primary banding in a gabbro intrusive. The ore and silicates may be thin or thick-banded. The silicate minerals are titaniferous augite and strongly zoned plagioclase and the iron ore is interstitial to, and shews reaction relationships with, them. When it is in contact with augite a rim of dark brown hornblende is formed; at its contact with plagioclase there is a rim of light green hornblende.

The ore consists of ilmenite and magnetite with the former usually in dominant amounts. Foye considered the ore to be contact metamorphic in origin due to the intrusion of nepheline syenite into the gabbro but Osborne (1928) could find no deposits at the contacts between gabbro and syenite and concluded that the ores were magmatic concentrations.

Eagle Lake.- In the Eagle lake region, a banded igneous rock complex some ten square miles in extent comprised of norite, gabbro, pyroxenite, anorthosite and troctolite is locally enriched in titaniferous magnetite and ilmenite. The rock may contain up to 50% of oxide minerals. The titaniferous magnetite, which contains exsolved ilmenite lamellae, is of deuteric origin and frequently is rimmed by a reaction rim of hornblende especially where it is in contact with plagioclase. The opaque minerals probably do not occupy sufficiently large areas to be considered as a potential source of ore.

Toronto.- Natural black sand concentrates on the shore of Lake Ontario east of Toronto harbour were reported to contain up to 66% ilmenite, (Trainer 1930). No record was made of the opaque mineral content of the average beach sand, nor of the extent and quantity available.

Rutile

Rutile was recorded to occur in the Parry Sound district, Bethune in garnet amphibolite. (Ann. Rept. Ont. Dept. Mines 51 1942).

Sphene

Sphene containing 40% TiO_2 was mined in 1934 at Leeds City.

Total production, 40 tons.

Quebec

There are a large number of small and large deposits of titaniferous magnetite and ilmenite-magnetite in Quebec. They are all situated in anorthosite massifs, which stretch from Labrador to the Ontario boundary. A number of attempts to mine some of these deposits have been made in the past but in most cases their titanium content prevented them from being smelted in the usual manner adopted for iron ores, and the mines closed. Those deposits which have been worked are at Ivry; Lake St. John in the Saquenay river area; and at several points adjacent to the north shore of the St. Lawrence river, notably at St. Urbain de Charlevoix, Bay of Seven Islands and in the Romaine river area. The St. Urbain deposit has been in regular production for many years and the Ivry deposit has also shipped ore for a number of years. The total production of the two deposits with an insignificant contribution from other areas was only 55,000 tons up to 1940, of which about 2,000 tons was from Ivry. Since then production has increased in the following manner (Dresser and Denis 1949; Gillson 1949)

	metric tons		tons		tons
1940	4,114	1945	12,834	1950	?
1941	11,477	1946	1,227	1951	?
1942	9,100	1947	?	*1952	51
1943	62,092	1948	?	*1953	4, 6 58
1944	30,820	1949	?		

*(Tumin 1953).

In 1941 a large deposit of hematite-ilmenite ore was discovered in the Allard Lake region north of Havre St. Pierre on the Lower Romaine river near the point where it discharges into the St. Lawrence river north of Anticosti island. Small amounts of ore were removed in 1946 and 1947 for test purposes and by 1951, in the first full season of mining, 340,000 tons of ore had been mined of which 7,200 tons were shipped to the smelting plant at Sorel. (Brown 1951).

The Allard lake deposits have made Canada one of the most important producers of ilmenite concentrates in the world. The methods by which the ores, low in TiO_2 content, are smelted has opened up possibilities for smelting titaniferous magnetite ores hitherto considered unusuable.

Deposits in the Morin anorthosite massif.- The Morin anorthosite massif, covering an area of 900 square miles, lies to the north-west of Montreal, at its nearest point 25 miles from the city. The mass is surrounded by granite gneisses, most of which are older than the anorthosite, except on its southern margin where Grenville sediments and younger granites genetically related to the feldspathic rocks are found. The anorthosite consists of andesine-labradorite plagioclase with, rarely, up to 10% of the accessory minerals hypersthene, augite, biotite, ilmenite, apatite, orthoclase and quartz. It is usually coarse-grained but fine-grained foliated facies do occur. Large ilmenite bodies are found at two localities. (Adams 1895; Dresser and Denis 1949).

1) Ivry Deposit, (lot 38, range V, Beresford township). Prior to 1918, 1,600 tons of ore were produced from the Ivry deposit, which lies five miles west of St. Agathe, and shipped to the Titanium Alloy Co. of New York State. (Robinson 1922). Between 1927 and 1935 a further 500 tons was mined for experimental purposes (Osborne 1935).

The ore was intruded into anorthosite as dyke-like bodies with a low content of 'mineralizers'. The ore contacts are usually sharp but occasionally gradational contacts are found. Intrusion apparently occurred before complete consolidation of the anorthosite because dykes of it cut the ore. The ore is a medium to coarse grained aggregate of ilmenite grains containing exsolved hematite blebs. Later veinlets and scattered grains of pyrrhotite, chalcopyrite, pyrite and marcasite penetrate the ilmenite particularly on the margins of the orebody.

The ore field, according to a geophysical survey (Keys, quoted by Osborne 1935) consists of two main orebodies and a number of minor masses. The largest of the orebodies is a lense-like mass 800' long and 75' wide extending downwards to a depth of 93'. The other body 75' west of the larger mass is only slightly smaller.

Analyses of the ore quoted by Robinson (1922) are:-

	I	II	III	IV
Ti	18.18	19.00	19.92	19.84
Fe	48.05	47.86	42.75	42.98
SiO_2			7.54	
P			0.036	0.076
S			0.010	0.144
V_2O_5			-	0.04
Cr_2O_3			-	0.08

The Titanium Development Corporation has investigated the Ivry deposit (Tumin 1953). The geological relationships of the ore are more fully described in the appropriate section of this thesis.

2) Desgrobois Deposit (Lots 39, 40 and 41, range VI, Beresford township).

This is a low grade, more disseminated ore body than the Ivry deposit and the ore minerals are ilmenite and magnetite with ilmenite exsolution lamellae. The ore minerals are intimately intergrown with the silicate minerals of the country rock, which is a gabbroic facies of anorthosite (Robinson 1922).

The ore body is at least 70' x 27' in area (Dulieux 1913), and probably 1,300' x 400' (Keys in Osborne 1935). Analyses (Dulieux 1913) quoted by Dresser and Denis (1949) are as follows:-

	I	II	III	IV
Iron	46.59	40.76	42.85	44.04
Titanium	18.09	4.49	6.73	5.09

These seem to indicate a rather variable orebody which would probably be difficult to mine as an economic proposition.

Drilling has recently been carried out by Pershing Amalgamated Mines Ltd., to investigate the Desgrosbois deposit (Tumin 1953).

St. Charles or Bourget Deposit.- The St. Charles deposit lies in lot 44 and 45 range I, Bourget township, near the Saguenay river in the Lake St. John region of Chicoutimi country. The deposit occurs in anorthosite as dyke-like bodies the contacts of which against massive anorthosite are clean and sharp and dip at a steep angle. Two types of ore can be distinguished a) coarse grained compact ore with a little gangue material and b) fine-grained ore with a considerable amount of gangue silicates, of which analyses are given below

	Fe	Ti	P	S	V_2O_5
a)	48.18%	13.5%	0.40%	0.007%	0.36%
b)	33.77%	7.44%	3.85%	0.038%	0.36%

Robinson (1926a, 1926b).

The fine grained ore contains up to 24% by weight of apatite (Osborne 1944). Other analyses are given by Robinson (1922) (II and

III below), and Dulieux (1913) (I) quoted by Dresser and Denis (1949) and Stansfield (1916)

	I	II	III	Original ore recalculated IV
Fe	52.97	50.50	52.10	50.53
Ti	9.32	10.08	12.60	10.55
S	0.02	0.492	0.034	0.02
P	0.21	0.046	0.079	0.03
V_2O_5			0.10	
TiO_2				17.6
SiO_2				5.2
Al_2O_3				4.4
MgO				2.4 + gangue 12%
CaO				

Osborne (1944) records the following analyses of specimens taken from nine different exposures of the St. Charles deposit.

	Fe	TiO_2	SiO_2	Al_2O_3	CaO	MgO	P	S	V
1.	40.08	13.35	13.05	6.36	0.20	11.35	.03	.05	0.11
2.	38.40	17.14	1.91	10.25	7.65	2.35	3.12	3.12	0.10
3.	33.32	13.38	15.11	7.56	6.71	6.84	2.06	2.06	0.09
4.	37.60	16.29	5.15	6.14	7.55	4.48	3.19	3.19	0.09
5.	45.43	20.72	2.11	4.60	3.39	4.73	1.31	1.31	0.14
6.	37.15	15.19	6.80	2.52	9.51	7.15	3.35	3.35	0.09
7.	35.38	14.40	4.27	4.40	13.31	5.24	4.45	4.45	0.08
8.	33.27	12.30	7.19	4.67	13.76	6.88	4.43	4.43	0.06
9.	35.30	12.29	6.31	5.32	12.44	5.59	4.54	4.54	0.07

The ore consists of magnetite, ilmenite, spinel and apatite. There is a wide diversity of textures among the various outcrops of ore. Magnetite may contain intergrowths of ilmenite as coarse or fine rods and lamellae, or may be free from all intergrowths. Ilmenite when present as discrete grains is free from inclusions. Spinel, either pleonaste or hercynite, occurs both as individual grains and as exsolution rods in magnetite. (Osborne 1944).

The ore contains inclusions of anorthosite which are separated from the ore by reaction zones of amphibole, pyroxene, and olivine.

The olivine is an iron-rich variety. Chlorite may also occur as a gangue mineral. (Osborne 1944).

From the study of the mineral relationships it appears that both an ilmenite and a titaniferous magnetite concentrate could be obtained from this ore, but the latter would probably be largely useless unless the type of process in use for smelting the Allard Lake ores could be applied in this case.

There are twelve separate orebodies containing reserves of about five million tons. (Dulieux 1913). The ore outcrops over an area of 2,200' x 1,500' (Denis 1924).

The deposit has been thoroughly described by Jooste (1949) but the work has not been available for study.

The possibility of using the St Charles ore as a metallurgical feed was investigated by Stansfield (1916) who considered that it was possible to produce iron with 0.4% TiO_2 and a slag with 35% TiO_2. The Javelin Foundries and Machine Works Ltd have the mining rights of the St. Charles deposit (Tumin 1953).

St. Urbain.- The St. Urbain ilmenite deposits, in Charlevoix County, about eight miles north of Baie St. Paul, were discovered in or about 1666 but it was not until 1872 that any investigation with a view to extracting ore took place. Testing proved unsatisfactory and the area was abandoned until 1908 when the American titanic ore company commenced and has continued production until the present day. (Dresser and Denis 1949).

The deposits occur within a body of anorthosite, rudely elliptical in form, with dimensions of 20 miles from north to south by nine miles east to west. The anorthosite is surrounded by granite and dioritic rocks except to the south where Grenville sediments and granite gneisses older than the granite-diorites are found. (Mawdsley, 1927, 1949).

The anorthosite occurs as two facies, granulated basic andesine-acid labradorite, which forms the central areas of the massif, and a more sodic gneissic border facies which cuts the central anorthosite. Accessory minerals include hypersthene, hornblende, biotite, ilmenite, apatite and, in the more sodic anorthosite, orthoclase.

All the deposits which have been studied lie within a square mile of country two miles south of St. Urbain village and less than one mile from the edge of the anorthosite massif, although other deposits have been recorded to occur some ten miles to the north near the centre of the massif in labradorite anorthosite but these are probably of small size (Mawdsley 1927). Six separate ore bodies are known to occur lying in two structural directions sensibly at right angles to one another. The Coulomb and Glen Proppect mines lie along a structural line trending west north-west to east south-east. The other deposits all lie along separate structural planes aligned north-east to south-west.

The ore-mineral in each of the deposits is ilmenite containing exsolved hematite lamellae. The General Electric orebody also contains some rutile. Pyrite, pyrrotite and chalcopyrite are also present in small amount; they crystallized later than the ilmenite. The ore is usually coarsely granular varying in grain size from $\frac{1}{8}$-$\frac{1}{4}$" diameter.

The individual ore deposits of the area are described below. Furnace deposit, $1\frac{3}{4}$ miles south-east of St. Urbain village.- Dresser and Denis (1949) describe this deposit as "four dyke-like bodies of ilmenite striking north-east, the width of the combined zone being 250'." Karpoff (1953) describes the deposit as "a lenticular body" but figures it in a cross section as an irregular narrow dyke-like body dipping south at about 80° with a large sub-horizontal, lenticular offshoot on its north side, and a number of similar small sub-horizontal bodies given off on each side of it. The ore zone is apparently bounded on each side by longitudinal faults in the anorthosite. Pyroxene, plagioclase, a little biotite, pyrite and spinel accompany the ore of which the pyroxene and plagioclase are dominant in the disseminated ore zones bordering the massive orebodies. Analyses of the ore are tabulated on the following page. (Robinson 1922).

The ilmenite contains hematite lamellae 0.005 mm thick and 0.05 mm apart.

West and East Coulomb deposits.- The Coulomb deposits lie about one mile south south-east of the Furnace deposit in an east south-east striking ore zone. The area of ore exposed (Dresser and Denis 1949) is 18,000 square feet but the actual outcrop of the orebody is probably nearer 60,000 sq. ft. It is dyke-like in form, elongated in the strike direction of the orezone, and is about 80' wide dipping south at an angle of about 65° and extending in depth to a minimum of about 300' (Karpoff 1953). Low grade ore extends southwards in the hanging wall of the orebody (Gillson 1932).

The hematite-ilmenite ore occurs as interstitial grains between plagioclase and hypersthene crystals and it corrodes the latter to a marked degree but the plagioclase is less affected (Karpoff 1953; Osborne 1928). The granularity of the ore is 5 mm and the hematite lamellae measure 0.007 mm x 0.3 mm on the prism zone and are 0.03 mm apart.

	Robinson (1922)	Composite samples of 3,000 ton lots of ore from Furnace and Coulomb pits. Karpoff 1953			Warren 1912 calc. from rock	Warren (? date) in Karpoff 1953
TiO_2	40.46	41.95	38.70		43.4	40.00
Fe_2O_3 } Total Fe	45.49	18.64	18.64		19.3	20.35
FeO }		29.30	28.66		34.7	29.57
SiO_2		2.56	4.27)	9.96		1.91
Al_2O_3		2.70	4.00)	to		4.00
MgO		4.30	4.80)	13.57	2.2	3.17
CaO		0.40	0.50			1.00
MnO_2		0.10	0.12		0.4	
Na_2O		0.01	0.05			
P_2O_5 (P)	0.058	-	-			
V_2O_5	0.09	0.18	0.16			
Cr_2O_3	0.25	0.20	0.08			
NiO_3	Nil	0.10	0.01			
CuO		0.01	0.04			
BaO		0.001	0.01			
Sb_2O_5		0.002	0.002			
		100.453				

	West Coulomb (Dulieux)	East Coulomb (Dulieux)		Coulomb (Gillson)
TiO_2	41.00	35.46		38.8
SiO_2	2.64	3.12	FeO	28.7
P	0.040	0.044	Fe_2O_3	19.0
S	0.041	0.040	Cr_2O_3	0.11
Total Fe	40.09	42.82		35.7
Total Ti	24.62	21.30	V_2O_5	0.38

Ore dressing investigations have been carried out on this deposit (Karpoff 1953) with the following results. Jigging of 8-10 mesh size yielded a concentrate containing 43.29% TiO_2 with a titanium recovery of 92% by weight. Tabling of 10-35 mesh and under yielded a concentrate containing 42.90% TiO_2 with a titanium recovery of 70%. Losses in fines under 100 mesh were reduced by re-treating the tailings from 10-35 and under 35 mesh sizes on special tables by which means recovery was raised to 94%. By treatment of 10-35 and under 35 mesh sizes on a Ding's separator, thus completely eliminating associated silicate minerals, the average tenor of the concentrate was raised to about 43.10% TiO_2.

It was not possible to obtain from the non-rutilated St. Urbain ore a concentrate of greater TiO_2 tenor on account of the hematite lamellae and a little included silicate material.

Analyses of the Coulomb ores published by Dulieux (1912) quoted by Bruce (1933) and a concentrate analysis by Gillson (1949) are reproduced on the adjacent page. For analyses of composite Coulomb-Furnace ore see under Furnace deposit.

The mining rights to the Coulomb and Furnace deposits are held by the St. Lawrence Iron and Titanium Mines Ltd.

Bignell Deposit.- The Bignell deposit situated about a half mile west of the Furnace deposit was the deposit worked in 1872-1874 unsuccessfully by the Canadian Titanic Iron Company. It is a small deposit striking north-east which passes rapidly along the strike into disseminated ore in anorthosite. Low grade deposits are developed in the hanging wall. The ore body is not now visible on the surface owing to caving of the old workings. (Gillson 1932).

Glen Prospect.- This deposit is situated about a half mile east of the Coulomb mine and is essentially an extension of the same ore zone in an east south-east direction (Gillson 1932). It is a narrow high grade dyke-like body, from 10-20' wide, which dips to the south-west at an angle of about 50°. It has sharply defined walls in anorthosite and is paralleled by similar narrower bodies. It has been worked at some time in the past. (Dresser and Denis (1949) call this orebody the Joseph Bouchard or Glen deposit but Gillson's (1932) map taken from Robinson (1922) shews these to be separate deposits).

Joseph Bouchard Prospect.- This is a south-west directed extension of a cross zone in the Coulomb deposit. (Gillson 1932).

General Electric Deposit.- The General Electric deposit situated about a half mile south south-west of the Furnace Deposit has provided the bulk of the ore shipped from St. Urbain. Ore is exposed over an area of 300 x 150' sq.feet but is known (Gillson 1932) to extend to the south-west over a much greater area.

This orebody has received much more attention than the others on account of the rutile content of the ore and anorthosite immediately adjacent to the ore. The opaque ore mineral forming the bulk of the ore body is hematite-ilmenite, essentially similar to that in the other deposits. The hematite lamellae are 0.004 mm thick by 0.15 mm long and are 0.03 mm apart on the prism zone. (Osborne 1944). Associated with the ore and replacing anorthosite on its margins are phlogopite, apatite, tourmaline, rutile, [illegible] Staurolite sapphirine, quartz, spinel, zoisite, chlorite, sericite, serpentine, carbonate and zeolites, all developed to a very much larger degree than in the other deposits. The West Coulomb is the only other deposit to shew such a well-developed pneumatolytic-hydrothermal mineral assemblage but according to Gillson such minerals are not absent in the other deposits.

The following analyses of General Electric ore have appeared in the literature. I is a rutile-rich specimen (Warren 1912) and II a specimen of ilmenite ore (Dulieux 1912). Both analyses were quoted by Dresser and Denis (1949).

	TiO_2	SiO_2	Fe_2O_3	FeO	MnO	MgO	CaO	Total Fe	Total Ti
I	53.35	2.24	13.61	24.49	0.30	4.04	0.30	28.54	32.01
II	41.61	1.10						44.52	24.98

Electromagnetic separation will produce a high grade rutile concentrate. (Karpoff 1953).

There is considerable difference of opinion as to the origin of the St. Urbain deposits. Mawdsley (1927) and Osborne (1928) are of the opinion that the ore was injected as a relatively water free residual magma forcing aside and engulfing the anorthosite and, in places, penetrating it to form the disseminated deposits. Mawdsley thought that the ore bodies were randomly distributed in the anorthosite but Gillson has definitely shewn that they fall into a distinct structural pattern.

Gillson (1932) concluded that the ores were formed by replacement of anorthosite and were deposited from gaseous or liquid solutions which soaked through the rock. Their occurrence within the anorthosite was controlled by structural lines developed after the solidification of the host rock. The geological relationships and genesis of the orebody are more fully discussed in the relevant section of this thesis.

According to recent information (Northern Miner 42 No. 52 (1957) 17 and 24) the Continental Iron and Titanium Mining Co. have carried out test drillings on an ilmenite body near Bay St. Paul, and have proved 3 million tons of ore containing 21-36% TiO_2 and 23-35% Fe. This probably refers to one of the St. Urbain deposits but it is not known which one.

Lower Romaine River Area.- Lake Allard, Lake Tio, Lake Petit-Pas Deposits. The ore deposits in the vicinity of Allard Lake were discovered by Retty who carried out preliminary investigations (Retty 1942; 1944; Longley 1943; 1944). In 1944 the Kennecott Copper Corporation became interested in the possibilities of the deposit and in 1946 Kennco Explorations Ltd. began a full scale investigation. In 1948 the Quebec Iron and Titanium Corporation was formed jointly by Kennecott Copper Corporation and New Jersey Zinc Co. Preliminary mining commenced in 1948 and the mine commenced serious production in 1951 when 339,224 tons of ore were extracted. In 1952 and 1953 237,249 tons and 141,266 tons respectively were mined. (Tumin 1953; Brown 1951).

The deposits are situated 25 miles north of Havre St. Pierre on the north shore of the St. Lawrence some 400 miles north-east of Quebec. They occur in the Allard Lake anorthositic massif, which is about 90 miles long by 20-30 miles wide with its long axis parallelling the Gulf of St. Lawrence. The bulk of the massif is made up of andesine-labradorite (An 40-56) feldspar of medium grain sometimes containing large porphyritic crystals. Dark minerals rarely comprise more than 5% of the rock and where present are hypersthene, augite and ilmenite. The feldspars are very commonly granulated on their margins. (Hammond, 1949 a:b; 1952).

Within the anorthosite a facies containing disseminated ilmenite (5-20%), pyroxene, biotite, pyrite and minor magnetite occurs particularly on the east sides of the ore deposits near Allard Lake, Lake Puyjalon and Lake Manitou. It is a medium to coarse grained rock containing a slightly more basic feldspar than is usual (An 50-60). On the north east margins of the mass foliated norite occurs.

The ore deposits all lie within the north-east corner of the anorthosite mass, from two to fifteen miles west of its contact with the surrounding granites. There are six orebodies each containing more than one million tons of ore. Three types of ore body are present:- a) flat lying tabular bodies of large areal extent (Lake Tio and satellite bodies); b) steeply dipping dyke-like bodies (Puyjalon deposit) and c) irregular lenticular masses (Mills deposit).

The Lake Tio Deposit.- This deposit is by far the largest in the region and is the one now being mined. It lies between Allard and puyjalon lakes 22.5 miles north-east of Havre St. Pierre. It is 3,600' long, 3,400' wide with a surface area of 134 acres, and in its eastern part at least 300' thick. It contains more than 125,000,000 short tons of ore averaging 32% TiO_2 and 36% Fe. (Hammond 1952).

The ore occurs in anorthosite and leucogabbro. A steeply dipping north-south fault has thrown down the east side of the ore body 300'. West of the fault the ore forms a thin flat-lying body of 25-200' thick with a flat westerly dip. East of the fault the orebody has a basin-like or synclinal attitude. Blocks of barren anorthosite are found within the orebody but they shew no evidence of replacement by ilmenite and presumably represent country rock engulfed during the emplacement of the ore. Disseminated ore is arranged in bands parallelling the upper surface of the orebody emphasing its tabular form. The ore is particularly coarse grained at its contacts with anorthosite which are very sharp.

The Cliff orebody is a broad flat lying mass of ilmenite on the west side of Lake Tio separated from the main-mass by barren anorthosite. Its surface dimensions are 1240' x 740' and it has an average thickness of 200'. It contains 12,000,000 tons of proved ore.

Puyjalon deposit.- This dyke-like deposit lies 2 miles south-east of Lake Tio near Puyjalon Lake. It strikes north-east and dips south-east at 60-70°. Exposures of ore have been traced over an area of 2,400' x 20'-250'.

Mills Deposit.- Four irregularly-shaped massive lenses of ore extending in a well defined mineralized zone for a distance of about 3,000', occur eight miles south-west of Lake Tio. They are known as the Mills deposit.

The Ore Minerals.- The ore is formed by thick tabular crystals of ilmenite containing up to 20% of hematite as exsolution blebs, with accessory pyroxene, feldspar, pyrite, pyrrotite and chalcopyrite making up only about 5% by volume of high grade ore. The included hematite occurs as discontinuous blades or blebs, the larger of which contain discs of ilmenite which in turn contain yet smaller blades of ilmenite. (Osborne 1944).

A number of analyses of Allard Lake ore have been published. A selection from Retty (1944) (Nos. 1-6) and Hammond (1952) (Nos. 7-9). follow.

Description of sample	1	2	3	4	5	6	7	8	9
	10 lb	5 lb	8½ lb	6½ lb	2 lb	1 lb	25' drill core	25' drill core	25' drill core
TiO_2	36.0	35.98	35.9	38.14	32.2	37.6	34.8	36.0	34.4
FeO	52.98	58.0	55.7	55.8	57.9	56.14	38.8	42.8	39.1
S	0.47	0.47	0.16	0.16	0.14	0.11	0.36	0.40	0.39
P_2O_5	-	-	-	-	-	-	0.004	0.010	0.012
Cu	-	-	-	-	-	-	0.037	0.12	0.14
V	0.08	0.03	0.03	0.03	0.02	0.19	0.22	0.21	0.21
Mn	-	-	-	-	-	-	0.08	0.08	0.10
Ni	-	-	-	-	-	-	0.03	0.01	0.02
Co	-	-	-	-	-	-	0.014	0.013	0.019
SiO_2	2.57	1.78	0.96	0.87	1.36	1.42	-	-	-

The ore as mined and shipped contains 88% of titanium and iron oxides without any concentration. It is shipped to Sorel, 500 miles up the St. Lawrence river, by water and is there smelted to produce pig iron and titanium rich slag.

The process used, briefly, is as follows. The ore is blended to make a charge containing 40.5% Fe_2O_3 and 34.5% TiO_2 and dried. It is then crushed to minus $\frac{5}{8}$" particle size, mixed with 15% of coal, and fed via hoppers to the top of a 54' long, 25' wide electric arc furnace. The charge, gravity-fed down around each electrode, melts; the iron collects on the hearth with the slag on top. The hot slag containing 70% TiO_2 is corrosive to any known refractory so that the basic linings of the furnace have to be protected by unmelted feed material distributed along the walls. The furnace operates at a roof temperature of 2460-2910°F under slight pressure. Maximum power consumption is 18,000 kw at 220-440 v. 24" graphite electrodes are to be used in the new furnaces replacing the 29½" ones now being used. Analyses of the iron as tapped and the titanium rich slag are given below (Brown 1951).

Slag

TiO_2	Fe_2O_3	Fe	MgO	Al_2O_3	Cr_2O_3	V_2O_5	MnO
70.0	4.0	4.0	5.0	6.0	0.3	0.6	0.2

Iron

C	S	Ti	Fe	Mn	Si	P
1.0	0.5	0.06	98.44	nil	nil	nil

Production figures for the Lake Tio deposit (Tumin 1953) are as follows.

	Ore Mined	Slag Shipped
1951	339,224	7,179
1952	237,249	34,739
1953	141,266	129,823

Genesis of the Ore deposits.- The ore deposits are considered by Hammond to be late magmatic injections into hot anorthosite. The genesis of the Allard Lake region rocks is more fully considered in Part I of this thesis.

Deposits of the Sept-Iles Area.- The Bay of Seven Islands is situated on the north shore of the St. Lawrence river approximately 300 miles north-east of Quebec and 120 miles S.W. of Lake Allard. The rocks of the region are anorthosites, gabbros and granites of the Morin or Buckingham series, which extend the whole length of the north shore of the St. Lawrence river from the Ontario border to Labrador. The Sept-Iles anorthosite body covers an area of about 60 square miles. In the areas where the ore minerals are developed, anorthosites and gabbros alternate in broad bands with later granites which have brecciated the more basic rocks at their contacts. (Faessler and Schwartz 1941).

The ore deposits occur in two groups. 1) along the Marguerite and 2) along the Des Rapides river. The two are separated by a 10 mile long stretch of Pleistocene sands.

Marguerite river deposits.- There are two deposits on the Marguerite river near Clarke City. The country rock is anorthosite - leuconorite grading into iron rich gabbro which in turn grades to rich ore occurring in small disconnected lenses up to 80' x 15' in area. There is up to 10,000 tons of ore containing 70% FeO and 20% TiO_2. (Dulieux 1915).

Des Rapides river deposits.- There are two separate ore bodies, the Molson Mine and Outarde Falls deposits. (Robinson 1922).

The Molson mine deposit occurs in dark fine-grained gabbro, which contains inclusions of white anorthosite against which contacts are sharp. The gabbro grades into ore averaging 50-52% Fe and 12-15% Ti. Dulieux (1915) estimated that there was 300,000 tons of proved ore.

The Outarde Falls deposit is 1½ miles up river from the Molson mine. It consists of iron-rich gabbro with 25% Fe and 10% Ti, which grades marginally into normal gabbro.

The ore minerals in the ore lenses are magnetite-ilmenites and ilmenite-magnetites in about 50-50% proportions rising to 3:1 in favour of magnetite (Faessler and Schwartz 1941). In the ilmenite, magnetite forms exsolution lamellae parallel to the 0001 cleavage direction. In the magnetite a unique irregular exsolution pattern occurs. The oxides minerals in the gabbro ore disseminations have normal intergrowth textures. The unusual intergrowths are more fully discussed in the relevant portion of this thesis.

It is very unlikely that the deposits will be of much economic importance because, by reason of the intergrowths it will not be possible to produce a high grade iron or titanium concentrate. The success obtained with the Allard Lake ores, however, renders every deposit worthy of consideration despite unpromising indications.

Beauceville Map Area.- Titaniferous magnetite occurs at the contact of acid tuffs and intrusive peridotite. There is great variation in its chemical composition. Two analyses are given below. There is a 1000' long outcrop of ore.

TiO_2	FeO	Cr_2O_3
0.16	53.36	9.86
16.28	61.36	

(Mackay 1921)

La Chute Map Area.- Indications of titaniferous magnetite associated with anorthosites in this area have been recorded by Osborne and McGerrigle (1936).

The North Shore of the St. Lawrence river from the Chaloupe river to Mingan.- Longley (1944) collected a number of specimens of ilmenite from various exposures in this area, which have been described by Osborne (1944). They are all ilmenites containing hematite exsolution bodies except for one specimen from Dock which contains magnetite exsolution lamellae.

Chibougaman Lake Area.- "Appreciable concentrations of magnetite, probably all of a titaniferous variety are present in the rocks in certain parts of the area; the most important so far known being those in the serpentine on the north side of Magnetite bay". (Mawdsley and Norman (1935)). "None so far discovered contains sufficient iron for commercial ore." An analysis of the magnetite shews only 0.86% TiO_2. Black sands are also supposed to occur in this area (Tumin 1953).

Other minor hard rock deposits.- According to Lawthers (1954) quoting from Robinson (1922 a:b:c) there are small titaniferous magnetite occurrences at the following localities:- Hull and Pontiac Counties in the townships of Bristol, Clarendon, Mull, Litchfield and Templeton; and St. Maurice City, St. Boniface.

Sand Deposits along the North shore of the St. Lawrence river.- At the mouths of the rivers discharging into the St. Lawrence black sands containing ilmenite, magnetite, garnet and feldspar are known to occur. (Mackenzie 1912). The principal deposits are at the mouths of the Port Neuf, Bersimis, Moisie, Manitou, St. John, Mingan, Natashkwan, Muskwaro and Olomanshibo rivers. Half a million tons of sand are supposed to exist in the Natashkwan deposit. The Moisie sands were smelted between 1867 and 1875 for their iron content. (Faessler and Schwartz 1941).

The Thunder river mouth area also contains black sand deposits (Robinson 1922a). At the mouth of the Chaloupe river, at Bay St. Paul, sands, presumably derived from the St. Urbain deposits, occur along the shore (Robinson 1922a).

Faessler (1932) records the occurrence of a sand deposit with 16% ilmenite between Betsiamites and Manicouagan.

DOMINICAN REPUBLIC

Iron sands containing up to 12.5% TiO_2 have been reported to occur between Samana and Manzanillo bays. The largest deposits are at the mouth of the Rio Yague del Norte, near Monte Christi, (Bartels 1941).

GREENLAND

Many igneous, metamorphic and sedimentary rocks of Greenland contain titaniferous minerals but the occurrences cannot be called even potential ore deposits. Recent sands also contain titanium minerals but, in general, insufficient time has elapsed since the Pleistocene glaciation for weathering, and natural concentration processes, to be able to produce ore deposits. (See Chapter on Beach Sands). A very local occurrence of a sand containing 8.0% ilmenite and 0.2% rutile has been reported to exist in the Holsteinborg district of south-west Greenland. The minerals were derived from metamorphic rocks which form nearby headlands. (Stewart 1930).

GUATEMALA

Titanium deposits are known to exist and are probably abundant, but no details of any kind have been published. (Summ. Min. Res. Guatemala in U.S. Bur. Min. Foreign File 3979 (1918) and 4941 (1922)).

MEXICO

Rutile.- In 1954 the Republic Steel Corporation discovered the importance and extent of rutile deposits at Pluma Hidalgo and Apango, in Oaxaca state which had been recorded to exist by De Mille in 1947 (Strategic Minerals. New York-London 1947). The deposits are supposed to contain 25 million tons of rutile with an average grade of 15-20% TiO_2, rising to 95% in certain seams. It is believed to be the richest deposit in the world. (Chemische. Ind. 3 (1955) 116; Eng. Min. J. Metals and Miner. Market 26 (1955) 6). The deposit is situated 32 miles from the Pacific coast at Puerto Angel. (Min. J. 244 (1955) 15).

Rutile deposits are also recorded to occur at

1. Real de Castillo, Norte district of Baja California,
2. Part de Cerribos, Cerro del Tepozau, Sierra de Cambra in San Luis Potosi,

3. Sonora State in rutilated quartz veins. (Inst. Geol. Mex. Bull. 40 219 223 264.

Ilmenite.- Ilmenite occurs in the Cauton de Guadalajara. (Inst. Geol. Mex. op. cit.).

A deposit of ilmenite west of Victoria in Tamaulipas state is supposed to contain 50 million tons of ore, averaging 40-45% TiO_2. It is a "contact vein about 30' thick, 2,500' deep and 2 miles long". The tonnage and grade of the deposit are almost certainly overestimated. (U.S. Bur. Min. Min. Trade Notes 1947).

Ilmenite occurs in gneiss at Pluma Hidalgo, Oaxaca and in gneiss at Huitzo, Oaxaca. Ilmenite occurs together with magnetite in placers at Papanao, Guerrero. (Mejorada 1952).

ST. PIERRE AND MIQUELON

Parallel bands of magnetite-ilmenite containing 9.75% TiO_2 occur in quartzite in the Calvary Mountains. They are of varying thickness and are probably a metamorphosed deposit of sedimentary origin (de la Rue 1933).

Magnetite and ilmenite sands are found on the coast of the Langlade isthmus (Blondel 1934; de la Rue 1933).

U.S.A.

NORTH-EASTERN STATES

New Jersey

Hard-rock deposits.- The Pre-Cambrian rocks of New Jersey contain many deposits of magnetite and titaniferous magnetite. According to Singewald (1913) the titaniferous variety is restricted to gneisses, some of which may be metamorphosed gabbros. Bayley (1910) lists the following partial analyses of titaniferous magnetite ore from twelve different mines in the State.

Name of Mine	% Fe	% TiO_2
Bayard	49.5	6.0
Beers	54.6	7.83
Bloom	37.5	4.77
Cramer I	62.2	9.95
Cramer II	40.25	4.27
Day	50.88	5.08
DeKay	45.75	4.68
Hager	56.13	1.40
Jackson	52.96	4.4
Cannon	63.5	2.77
Naughright	64.77	7.62
Van Syckle	50.20	11.60

According to Bayley's interpretation of their genesis the ores were formed by the percolation through the gneisses, immediately after they solidified, of iron-enriched late magmatic fluids or vapours. The fluids or vapours crystallized to form the orebodies.

Alluvial Deposits.- Since 1956 brief news bulletins have been appearing in various trade journals describing the discovery of alluvial ilmenite deposits in New Jersey. The deposits supposedly cover an area of several square miles but their exact location is obscure and it is not clear whether there is more than one area containing potential ore deposits. One area, where the American Smelting and Refining Co. are prospecting lies in east central New Jersey between Lakehurst and the Atlantic ocean. (Chem. Week 81 (1957), 17; Chem. Eng. News 35 (1957) 30). However, Chem. Eng. News 35 (1957) 21, refer to a mineral belt 10 miles wide and running from Lakewood (10 miles north-east of Lakehurst) to Camden which lies 40 miles to the west of Lakehurst. Also, according to the state geologist, ilmenite deposits exist in the bed of the Millstone River, which is some thirty miles to the north-west of Lakehurst. (Chem. Week 79 (1956) 17).

An analysis of ilmenite from an unspecified locality in New Jersey is given below.

TiO_2	FeO	Fe_2O_3	MnO	Cr_2O_3	V_2O_5	Insol.
59.7	5.0	33.3	0.9	0.07	0.1	0.85

Pennsylvania

Rutile has been produced in very small quantity in Pennsylvania. At about the turn of the century rutile was hand picked from fields and quarries in metamorphosed Cambrian and Ordovician limestones. The small amounts obtained were sold to mineral dealers and dentists. (Youngman 1930; Watson 1914).

New York

The Adirondack Mountains of New York state are formed by an anorthosite massif of 1,200 square miles areal extent. Within, and on the borders of, this massif deposits of titaniferous magnetite-ilmenite are known to occur at a number of localities. There are two districts in which the bulk of the known ore deposits occur, the Lake Sanford area in Essex County and the Elizabethtown-Westport area on the shores of Lake Champlain. The ore deposits in both areas have been mined at several different periods during the last century but at the present time it is the Lake Sanford region only which is being actively exploited.

The Lake Sanford area.- Within the Lake Sanford area on the Hudson river near Tahawus, four bodies of titaniferous magnetite-ilmenite ore are known to exist. They are the Sanford Hill, Ore Mountain, Calamity-Hill Pond and Cheney pond deposits. All of these orebodies occur in close conjunction with leucogabbroic or gabbroic facies of the surrounding anorthosite massif. The ore bodies fall into two types:- 1. Gabbroic ore in which, by increase in the opaque mineral content of the gabbro it grades into rich ore and 2. Anorthositic ore which is found in dyke-like bodies discordantly cutting anorthosite and which is richer in opaque minerals than the bulk of the gabbroic ore.

The ore minerals are magnetite which contains exsolution lamellae of ilmenite, and ilmenite which is usually free from inclusions of any kind. (Stephenson 1945).

Sanford Hill deposit.- This is a deposit of magnetite-ilmenite bearing gabbro at least 1,800' long and 600' wide. At the eastern end of the gabbro mass are two large bodies of rich ore, and a third extends southwestward from the main mass. There are numerous bodies of lean ore. The following analyses of ores and magnetic concentrates, reproduced from Balsley (1943), were carried out on specimens from the Sanford Hill orebody. The analysis of the ilmenite concentrate is of a composite sample. (Gillson 1949).

	% Fe	TiO_2	V_2O_5	Recoverable ilmenite	Magnetic Concentrate Wt.%	TiO_2	V_2O_5
Rich Ore	53.4	20.7	0.46	18.9	78.6	12.09	0.58
" "	52.1	22.0	0.52	17.2	80.2	14.43	0.64
" "	48.4	24.0	0.45	25.6	69.2	14.46	0.65
" "	46.6	24.7	0.41	30.2	60.2	12.46	0.68
" "	40.5	24.0	0.28	35.4	42.7	9.93	0.65

	Fe	FeO	TiO_2	Fe_2O_3	Cr_2O_3	V_2O_5
Ilmenite Concentrate	32.9	37.3	44.4	5.43	0.006	0.13

The ore reserve in the Sanford Hill deposit was estimated to be 12,700,000 tons of ore containing 55% of magnetic concentrates, by the U.S. Geological Survey in 1942. (Balsley 1943). The content of ilmenite concentrate has been estimated to be 18.5% (Stephenson 1945).

The Sanford Hill orebody has a long history of mining activity. It was discovered in 1826 by a party of silver prospectors, led to it by an Indian guide, and was immediately recognised to be an iron ore of considerable potential value. From 1831 until 1858 the orebody yielded iron ore which was either smelted on the spot in the village of Adirondac which sprang up in response to the mining activity, or in Jersey City. The first cast steel plant erected in America in 1848 utilized Lake Sanford ore. During the same year the presence of titanium in the ore was recognised, and its presence caused many technological headaches to the foundrymen. In 1858 work on the site ceased until 1906 when exploratory work commenced which continued until 1909. In 1912 and 1913 the MacIntyre Iron Company shipped out between 15,000 and 20,000 tons of ore. Transportation difficulties caused mining activity to languish for a further period of years until 1941 when the National Lead Co. acquired the property from MacIntyre Iron Co., and commenced investigating the suitability of the ore as a raw material for titanium pigment manufacture. Shipment of ilmenite concentrates to the railhead started in 1948, along a new road specially constructed for the purpose. (Stephenson 1945). Since that date ilmenite concentrates have been flowing in ever increasing volume from the Sanford Hill orebody, and in 1955 production reached 300,000 tons.

Calamity-Mill Pond deposit.- The Calamity-Mill Pond deposit has similar geological relationships to the Sanford Hill orebody, albeit that they are somewhat more complex. The deposit has been exploratorily drilled and is estimated to contain eight million tons of ore containing 15% of magnetic concentrate and 30% ilmenite. (Balsley 1943).

Ore or Iron Mountain deposit.- This is a thin sheet-like body of rich ilmenite-magnetite ore which occurs in close proximity to a gabbroic orebody. There are probably 7 million tons of ore that would yield 60-70% of magnetic concentrates (Balsley 1943).

Cheney Pond deposit.- Near Cheney Pond is a small orebody which probably contains under a million tons of low grade ore. (Balsley 1943).

The Ore Minerals.- The ilmenites and magnetites which occur as the various grades of ore do not have a uniform character. In the rich ore bodies in anorthosite,magnetite is the dominant opaque mineral forming over 80% of the opaque constituents. It contains 12-14% TiO_2, after grinding to either 20 or 60 mesh followed by magnetic separation, and 0.58-0.68% V_2O_5. In the lean gabbroic orebodies ilmenite (58-64%) is the dominant opaque mineral. The magnetite which accompanies it contains about 12%-13% TiO_2, which by grinding as fine as 60 mesh can be reduced to 9%, and .65-.95% V_2O_5. This implies that a greater proportion of the TiO_2 enclosed in the lean gabbroic ore is recoverable than of the TiO_2 in the rich ores. At the same time the magnetic concentrate is also a more desirable product on account of its higher V_2O_5 and lower TiO_2 content. The releasability of the lean ore TiO_2 is due to the coarser nature of the ilmenite lamellae within the magnetite of the lean ore, which causes them to separate from their host mineral on being electrostatically or electromagnetically treated after reasonably fine grinding.

The following analyses (Balsley 1943), when compared with the analyses of the Sanford Hill rich ores illustrates the chemical difference between lean and rich ore.

	Fe %	TiO_2 %	V_2O_5 %	Recoverable ilmenite	Magnetic concentrate Wt. %	TiO_2 %	V_2O_5 %
1	36.3	18.1	0.34	18.5	49.6	12.55	0.69
2	28.8	17.2	0.13	30.8	16.6	7.02	0.81
3	23.6	13.0	0.12	17.8	13.1	9.27	0.95

1. Lean ore, Iron Mountain.
2. Lean ore, Calamity-Mill Pond.
3. Lean ore, Iron Mountain.

The conclusions to be drawn from the above statements is that 1) while rich ore has the highest total vanadium content and greatest percentage of opaque minerals, the concentrates produced from such ore has lower percentage V_2O_5 content and a higher percentage TiO_2 content than lean ore 2) Intermediate grade ore has the highest percentage of recoverable ilmenite. The most favourable type of mill feed for recovery of vanadium and titanium is therefore a mixture of rich ore to supply quantity, and lean ore to improve the quality of the concentrate.

The detailed geology and genesis of the orebodies are discussed in Part I of this thesis.

Deposits in the Eastern Adirondacks.- In unsaturated olivine-bearing metagabbros of the Eastern Adirondack mountains, there are ore segregations of titaniferous magnetite and ilmenite. The ores were mined at several localities in the latter half of the 19th century but only on a small scale. (Kemp and Ruedemann 1910).

Concentrations of opaque minerals in sufficient quantity to have been considered ore occur at Split Rock Mine, 5¼ miles north-east of Westport; Kent Mine, Lincoln Pond; and Tunnel Mountain, Elizabethtown. Only the gabbro and ore at Split Rock Mine have been described in any detail (Osborne 1928) but analyses quoted below, of the other orebodies have been published (Kemp and Ruedemann 1910).

At the Split Rock Mine the orebodies take the form of four subparallel zones of variable dip within an enclosing, metamorphosed, gabbro. The ore, which consists of magnetite containing exsolution bodies of ilmenite, together with free ilmenite, is probably part of what was once a continuous orezone which is now folded. The ore is banded, the banding being caused by variations in the silicate mineral content. The silicates are the same as those which occur in the enclosing gabbro but they are present in smaller proportions. They are: labradorite, olivine, hornblende, augite, biotite and garnet. The texture in the ore is sideronitic.

Partial analyses of the ores are recorded here; for fully analyses see the geological section of this thesis.

	Ore, Split Rock Mine	Ore, Tunnel Mt. Mine	Ore, Kent Mine
SiO_2	17.90	13.35	11.73
Al_2O	10.23	8.75	6.46
FeO	27.94	28.82	27.92
Fe_2O_3	15.85	20.35	30.68
TiO_2	15.66	16.45	12.31
V_2O_5	0.55	0.61	0.04
Cr_2O_3	0.51	0.55	-
CaO	2.86	2.15	3.95
MgO	6.04	6.63	3.35

The ores do not constitute attractive commercial propositions at the moment, presumably because of the small size of the deposits in conjunction with the high content of TiO_2 enclosed in the magnetite.

Rhode Island

Iron Mine Hill, Cumberland.- The cumberlandite or ilmenite-magnetite olivinite of Cumberland, Rhode Island is an igneous rock body 1,200' long and 500-600' wide, genetically associated with gabbro which occurs in it as inclusions. The rock consists of about

10% labradorite phenocrysts set in a matrix of olivine and ilmenite-spinel-magnetite which is never coarser than 2 mm grain size. (Johnson and Warren 1908; Warren 1908).

"The ilmenite-magnetite forms a mesh-like matrix" (Warren 1918) around the olivine and labradorite crystals. Ilmenite occurs sparsely as separate grains but is common as exsolution lamellae in the magnetite along the octahedral cleavage planes. Spinel also occurs rarely as separate green grains and is found in the magnetite along octahedral and not cubic cleavages, together with the ilmenite. (Warren 1918; Singewald 1913).

An analysis of the cumberlandite, quoted by Johnson and Warren (1908) brings out the remarkable similarity in composition between this rock and the magnetite olivinite of Taberg, Sweden.

	Wt. %		Wt. %
SiO_2	22.35	K_2O	0.10
TiO_2	10.11	V_2O_5	0.18
Al_2O_3	5.26	P_2O_5	0.02
Fe_2O_3	14.05	S	0.38
FeO	28.84	Cr	0.08
MnO	0.43	Zn	0.71
MgO	16.10	NiO	0.08
CaO	1.17	CuO_2	0.02
Na_2O	0.44		

The genesis of the basic intrusion is discussed in Part I of this thesis.

EAST AND SOUTH EAST STATES

Maryland

Rutile is a prominent accessory mineral in many schists throughout Maryland. It has been mined on a small scale at the Dinning mine (Ostrander 1942). Near Clermont Mills a chlorite-serpentine rock contains rutile and apatite as accessory constituents and in places the rutile content may be as high as 16%. The rock is probably a metamorphosed pyroxenite which originally contained ilmenite

Virginia

The existence of titanium minerals, especially rutile and ilmenite, in the rocks of Virginia has been known for many years. As early as 1878 the economic potentialities of the ilmenite deposits in Nelson and Amherst Counties were recognised, but efforts by the Philadelphia Reading Coal and Iron Company to utilize the ore for its iron content was unsuccessful. It was not until 1900, when the American Rutile Company commenced to exploit an ilmenite-rutile ore at Roseland, that successful mining began. Before that date, however, it is probable that a number of small occurrences scattered throughout the schists and gneisses of the state had yielded small quantities of ore for museum specimens and dental purposes.

Deposits in Nelson and Amherst Counties.- The titanium mineral deposits lie within or close to an anorthosite massif which outcrops between Lynchburg and Charlottesville. The minerals of economic interest, ilmenite, rutile and apatite occur in, or near, bodies of igneous rocks of most unusual composition known as nelsonites. The nelsonites may be veinlike, dykelike or podlike in habit, and the relative proportions of their constituent minerals may vary within wide limits. Rutile-, ilmenite-, and magnetite-nelsonites have been defined. Apart from the nelsonites there are disseminated deposits, particularly of rutile, which form important ores and which are genetically and spatially associated with the nelsonites.

The two most important centres of production of rutile and ilmenite are at Piney River and Roseland. At the latter village, the American Rutile Co. commenced mining rutile and some ilmenite during the early years of the present century. For many years production from this single quarry provided sufficient rutile for the requirements of industry within the U.S.A. At Piney River the Vanadium Corporation started mining a deeply weathered nelsonite for ilmenite, rutile and apatite in the 1930's. The deposit has since been acquired and is now worked by the American Cyanamid Company. (Gillson 1949; Ryan 1933; Pegau 1950).

The nelsonite bodies contain very variable amounts of TiO_2: of those which are mined the weathered types usually contain about 18%, mostly as rutile, and the unweathered types about 14% (Eng. Min. J. <u>150</u> (1949) 122-3; Gillson 1949). An analysis of the magnetic ilmenite concentrate is given below. (Gillson 1949).

TiO_2	Fe	FeO	Fe_2O_3	Cr_2O_3	V_2O_5
43.5	38.1	35.0	15.6	0.06	0.19

The present writer has been unable to discover any analyses of the rutile concentrates.

The reserves of ore in the area do not seem to have been accurately estimated and are usually quoted vaguely as "several millions of tons". Mathews et al. (1948) estimated Virginian reserves to be 5 million tons of rutile and 24 million tons of ilmenite, the bulk of which were probably regarded to be in the Nelson-Amherst area.

The genesis of these deposits has been the subject of intense discussion, and no small amount of acrimonious correspondence, for many years. The opposing factions, Watson (1907), Watson and Taber (1910, 1913), and Davidson Grout and Schwartz (1946) on the one hand and Ross (1941; 1947 etc) and Gillson (1949) on the other, have respectively supported late magmatic liquid injection and replacement by fluid or gas. The problem of ore genesis is discussed more fully in the geological section of this thesis.

Buena Vista.- Near Buena Vista, Rockbridge County, the basal bed of the Lower Cambrian is a sandstone containing up to 50% of ilmenite and rutile. The sandstone occupies a shallow depression in the underlying granodiorite migmatite. The heavy mineral-rich sandstone is lenticular in shape and is about 450 yards long, 15 feet thick and of unknown width. The titaniferous minerals were presumed to be derived from the regional granodiorite migmatite in which they are common accessories, and in which, at a distance of 30 miles to the north-east, the Roseland and Piney River ore bodies occur. (Bloomer and de Witt 1941).

Bush-Hutchins, Vinton, Roanoke County.- Ilmenite occurs in an irregular-shaped body of nelsonite near Vinton, Roanoke County. The deposit is designated the Bush-Hutchins property after the leaseholders in 1946, Messrs. Bush and Hutchins. The principal minerals in the nelsonite are ilmenite, apatite and magnetite with accessory quantities of feldspar, quartz, epidote and biotite. Four analyses of the ore are available.

	TiO_2	Fe	P	SiO_2	CaO	Al_2O_3
1	14.16	26.01	6.63	7.15	13.61	2.24
2	13.0	23.4	4.20	3.55		
3	16.0	29.3	3.88	8.14		
4	9.1	18.3	3.83	23.3		

The nelsonite is intruded into syenites and greenstones and its geological relationship with them has not been described.

The Bush-Hutchins nelsonite ore body has been mined intermittently since 1890 and it is estimated that a total 200,000 tons of ore has been removed. The ore was being used in the 1940's to make high phosphorus pig-iron castings. (Hickman 1947).

Teels Mill, Franklin County.- Near Teels Mill, 15 miles south-east of Roanoke, a quartz-rutile-ilmenite vein lies conformably within biotite schist. Rutile occurs as euhedral prismatic crystals up to 2½ inches in length, and as intergrowths with ilmenite. Ilmenite occurs as primarily crystallised intergrowths in rutile and as an alteration product of the rutile, and is slightly leucoxenised. Analyses of the two types of rutile occurrence are given by (Watson 1922a:b).

	TiO_2	SiO_2	Cr_2O_3	V_2O_3	FeO	MnO	H_2O	Total
a) Rutile	97.3	0.12	0.05	0.26	2.21	0.09	0.10	100.13
b) Rutile-ilmenite	80.85	0.06	0.03	0.17	18.81	0.14	0.04	100.1

These transcribed into mineral phases, are for a) 94.8% rutile 4.71% ilmenite 0.62% remainder b) 59.9% rutile 39.67% ilmenite 0.44% remainder. The deposit is presumably of little economic interest.

Other Occurrences.- Quartz-rutile veins are commonly found throughout the Piedmont region of Virginia. Watson and Taber (1913) mention, in particular, Goochland and Hanover Counties. In Amelia County granite pegmatites contain large rutile crystals which weigh up to one pound each. Watson and Watkins (1911) have described a rutile-kyanite rock from Charlotte County. Catlett (1907) and Steidtmann (1931) have also described rutile occurrences in the state.

North Carolina

In North Carolina there are both ilmenite and rutile deposits. Up to the time of writing only one, a hard rock deposit, has been mined.

Other hard rock deposits of little value and beach sands of unknown potential have been described in varying detail.

Yadkin Valley, Caldwell County.- In the Yadkin valley, 13 miles north of the town of Lenoir, the Yadkin Mica and Ilmenite Co., a subsidiary of the Glidden Paint Co. of Ohio have been working a deposit of ilmenite since 1940. The ilmenite occurs in a dyke-like rock body and is set in a matrix of chlorite, talc and micaceous minerals. The micas contain finely disseminated rutile which is not recoverable by the concentration process employed. The ore body is enclosed in gneissic rocks and its long axis parallels the grain of the surrounding rocks. The maximum dimensions of the orezone are a length of 2,000 ft, a thickness of 30 ft and at least 500 ft measured down the dip.

The ore as mined contains about 30-35% TiO_2. The ilmenite is exceptionally pure; a published analysis is as follows:- (Gillson 1949)

TiO_2	Fe	FeO	Fe_2O_3	Cr_2O_3	V_2O_5
51.6	31.3	34.9	5.91	0.08	0.57

Between the years 1944 and 1950, 164,000 tons of ilmenite concentrate were produced by a two-stage flotation process employing oleic acid and a cationic reagent. (Gillson 1949; Lawthers). Recovery of TiO_2 is low partly due to loss of the rutile.

Rutile deposits.- Rutile is a widely distributed mineral in the granites, schists and gneisses of the state. Small quantities have been produced from deposits at Ellenboro, Rutherford County and at Shooting Creek, Clay County. The Shooting Creek rutile contains 89.6% TiO_2 1.5% FeO and 2.1% Fe_2O_3. (Watson 1914; Gillson 1949).

Titaniferous magnetite deposits.- Titaniferous magnetite, sometimes associated with ilmenite and/or rutile, occurs as vein-like bodies in peridotites, olivine gabbros and talcose and serpentinous schists. Occurrences listed by Bayley (1923a), about which no details of dimensions are given, are Smith property, Ashe County; Tuscarora ore belt, Guilford County; Pennington Mine, Ashe County; Dobson Mountain and the Dannemora mine.

In the Tuscarora ore belt magnetite and rutile, with some accessory ilmenite form the ore. The rutile forms small euhedral stringers through it. Spinel (aluminous variety) and a little corundum are also closely associated with the rutile. (Singewald 1913; Bayley 1923). Bayley gives the following analyses of ore from the McCuiston property.

	SiO_2	Fe	TiO_2	Cr_2O_3
Ore	12.75	41.95	15.35	1.25
Magnetic Portion	1.30	67.60	1.27	1.45
Non-magnetic Portion	26.80	21.63	16.20	0.43

The ore can be recalculated to form magnetite and ilmenite yet the presence of rutile has been confirmed by a study of thin sections of the ore (Bayley 1923). It is undoubtedly a most unusual ore type.

The Smith property contains a magnetite-ilmenite-rutile ore of which an analysis is appended below (Bayley 1923) together with an analysis of ore from the Dannemora mine.

	Smith ore		Dannemora ore
SiO_2	5.73		4.70
Al_2O_3	1.70		8.66
Fe_2O_3	45.51		43.05
Cr_2O_3	0.39		0.34
FeO	26.20		23.51
MnO	0.34		0.15
MgO	3.99		2.96
CaO	Tr		1.42
Na_2O	Tr		0.05
K_2O	Tr		0.03
TiO_2	12.96		13.71
P_2O_5	Tr		0.052
S	Tr	Pyrite	0.33
CO_2	0.00		0.07
V_2O_3	0.00		-
H_2O^+	2.81		0.21
H_2O^-	0.06		0.96
	99.69		100.05

The insoluble portion of the Dannemora ore contained 11.82% TiO_2 of the original so that only 1.89% would be available to form ilmenite. Thus it was assumed that the ore was a rutile-magnetite ore rather than an ilmenite ore.

The ores at the Pennington mine and Dobson Mountain are of similar type, although the latter has an abnormal corundum content.

Beach Sand Deposits.- No detailed descriptions of beach sand heavy mineral accumulations in North Carolina have appeared in the literature but that sands do occur is quite certain. Lynd, Sigurdson, North and Anderson (1954) have described ilmenite concentrates from an unspecified source in North Carolina and it is apparent that the ilmenite is a variety which has suffered little leaching of its iron content (see the geological section of this thesis). McKelvey and Balsley (1948) noted from the air the existence of black sands immediately to the north and south of the Cape Fear river estuary.

Lawthers mentioned that deposits of ilmenite occur in Albemarle Sound.

South Carolina

The beaches of South Carolina contain deposits of heavy minerals including ilmenite and rutile, but few details concerning their size and composition are available. McKelvey and Balsley (1948) noted from the air black sand accumulations at the following localities:- the coast east of Georgetown; the estuary of the Santee river; Bulls Island; Folly Beach and Kiawah Island south of Charleston; St. Helena Island and Hilton Head Island.

Martens (1935) examined sand from Folly Beach. The ordinary sand of the beach contained 0.55% of heavy minerals of which 12% was ilmenite, 5% leucoxene, 1% rutile and 2% zircon. A naturally occurring heavy concentrate from the same locality, forming a thin layer at the back of the beach, contained 67% of heavy minerals of which 55% was ilmenite, 2% leucoxene, 4% rutile and 14% zircon. The extent of the deposits was not described.

Georgia

Beach Sands.- Heavy minerals occur in the sands of the Georgia coast in varying amounts at a number of localities. McKelvey and Balsley (1948) noted them at the following places:- Ossabow Island; St. Catherines Island; Sapelo Island; St. Simon Island and north of the Satilla river. Greaves-Walker (1929) and Teas (1921) also mentioned the latter two of these localities.

Martens (1935) has made a study of the beach sands of Tybee at the mouth of the Savannah river, and of St. Simons Island.

Tybee:- An ordinary beach sand and two natural heavy concentrates were studied; the mineralogical results are tabulated below.

	I	II	III
% heavy minerals	4.6	55	92
% ilmenite	27	53	62
% rutile	1	4	3
% leucoxene	2	2	0.5
% zircon	1	14	25
% monazite	0.5	1	3

I Ordinary beach sand.
II Heavy concentrate from near high tide line.
III Thin heavy concentrate near back of beach.

St. Simons Island: Two heavy concentrates from localities five miles apart, and one ordinary sand from one of these localities were studied; the mineralogical results are summarised below.

	I	II	III
% heavy minerals	0.94	88	90
% ilmenite	24	55	53
% rutile	2	4	6
% leucoxene	2	1	0.5
% zircon	3	29	31
% monazite	0.5	2	4

I Ordinary beach sand.
II Heavy concentrate from back of beach. Same locality as I.
III Thin heavy concentrate on surface.

<u>Hard Rock Deposits</u>.- In the Elberton district of Georgia ilmenite and rutile have been mined on a small scale. The rutile is found in quartzite and quartz veins at Graves Mountain, 40 miles north-west of Augusta, where it was mined in the 19th century for museum specimens (Zodac 1939). The only information available concerning the Elberton ilmenite deposit is the following ilmenite analysis recorded by Gillson (1949).

	TiO_2	Fe	FeO	Fe_2O_3	Cr_2O_3	V_2O_5
%	50.5	35.92	39.6	7.31	ND	ND

Florida

Ilmenite and rutile, together with monazite and zircon, have been mined in Florida since 1916 when Buckman and Pritchard Ltd., later to become a subsidiary of the National Lead Co., commenced operations at Pablo beach south of Jacksonville Beach in north-east Florida. Since then, except for a period during the depression years of 1929-1932, titanium minerals have been continuously mined and concentrated from sand deposits in the state.

The sand deposits fall into two categories, ocean beach deposits and fossil beach and bar deposits. The most important of these are the raised beach and bar deposits because, although they are usually of much lower grade than parts of the beaches, they occur in very large quantities and their heavy mineral content is constant over large areas. The ocean beaches usually contain thin layers and lenses of very rich 'ore' but these are variable in thickness and lateral extent and are frequently at the mercy of vagaries of tide and weather.

Fossil Beach and Bar deposits.- Jacksonville. An elevated bar 8 to 10 miles east of Jacksonville, south of the St. John's river and a few miles inland from the coast, contains an estimated twelve million tons of ilmenite, two million tons of rutile and three million tons of zircon (Cannon 1950). The deposit extends about six miles in a north-south direction, and is approximately half a mile wide and twenty feet thick. It contains about 2.5%-4% of heavy minerals evenly distributed throughout the whole of the sand mass. Ilmenite makes up 40%, leucoxene 4%, rutile 7%, zircon 11%, and monazite 0.5% of the heavy minerals, the balance being silicates such as sillimanite, kyanite, staurolite, tourmaline and garnet.

Mining first commenced in 1942 with the activities of the Rutile Mining Co. but in 1943 the leases passed to the National Lead Co. and the deposit is now mined on their behalf by Humphreys Gold Corporation. Ore is removed by suction dredge at the rate of 7,500 tons per day and is passed direct to a series of Humphreys spiral concentrators which raise the heavy mineral content to 90%. This concentrate then passes through further wet spiral concentrators before being finally divided into separate mineral fractions by high-tension electrostatic separators. (Detweiler 1952).

Trail Ridge. The fossil sand deposit of Trail Ridge near Starke, about 40 miles south-east of Jacksonville, is an old sea-spit formed by marine erosion of a delta during Tertiary times. The deposit is similar to the ore east of Jacksonville in that it is of low grade and only enormous reserves and the unconsolidated nature of the deposit, allowing inexpensive mining, makes it an economic proposition. The average heavy mineral content is between 2 and 4% locally rising to 10%, of which 45% is ilmenite and leucoxene, 14% zircon and 20% staurolite and sillimanite. (Meyer 1949; Spencer 1948). The bulk of the deposit lies between 30 ft and 70 ft below the surface level whence it is mined by suction dredges.

The importance of the Trail Ridge deposits was first recognised by the U.S. Bureau of Mines (Theonen and Warne 1949). In 1947 E.I. Dupont de Nemours and Co. leased several sections of Trail Ridge and by 1949 had commenced production. In 1951, 120,000 tons of titanium mineral concentrates were produced.

The titanium content of both the Jacksonville and Trail Ridge ilmenites and leucoxenes is exceptionally high as can be seen from a study of the analyses quoted below (Gillson 1949).

	TiO_2	Fe	FeO	Fe_2O_3	Cr_2O_3	V_2O_5
Jacksonville 'Ilmenite'	60.3	22.7	5.59	26.3	N.D.	N.D.
Trail Ridge 'Ilmenite'	64.0		4.8	26.0		
Leucoxene	82.1		1.6	9.0	N.D.	N.D.

The 'ilmenite' in the Trail Ridge deposits, in the Jacksonville deposit and, in fact, generally throughout the fossil sands of Florida has been shewn to be ilmenite in an advanced state of alteration to rutile in the form of leucoxene. (Creitz and McVay (1949); Lynd et alia (1954); Bailey et alia (1956)). This alteration is the sole cause of the abnormal TiO_2 content of the opaque minerals. The factors which have caused the change of state are fully discussed in the geological section of this thesis.

Theonen and Warne (1949) have described the fossil sands of eleven different areas in central and north-east Florida. Extensive drilling programmes were carried out in most of the areas to determine the heavy mineral content of the sands, and as a result of their investigations the Trail Ridge area was delineated as a potential economic mining proposition. None of the other areas investigated which are listed below, proved to contain sufficiently high concentrations of heavy minerals over large areas to be worth mining at the time. The areas investigated by Thoenen and Warne were:-

West and north-west of Gainesville, Alachua County.

Palatka-Interlachen area, Clay and Putnam Counties.

Baywood Promontory, Interlachen area, Putnam County.

Cambon area, Duval County.

Plummer - Callahan area, Duval and Nassau Counties.

Camp Blanding (Trail Ridge) area, Clay County.

Ocala National Forest area, Marion and Lake Counties.

Orlando area, Lake and Orange Counties.

Lake Wales area, Polk County.

Sebring - Childs' area, Highlands County.

Ocean Beach Sands.- Throughout the length of the east coast of Florida, and in particular along the section north of Cape Canaveral, titaniferous minerals occur in some degree of concentration in most ocean beaches, and also in recently formed dunes behind the beaches. The heavy minerals have been derived from the schists and gneisses of the Appalachian-Piedmont region by three routes. These are a) directly via the eastward flowing rivers of Maryland, Virginia, the Carolinas and Georgia to the sea and thence south to Florida. b) via the sediment of the Atlantic coastal plain, from which they are released either by river erosion or direct marine erosion of the sediments. c) via the Tertiary deltaic deposits of north Florida. The minerals are transported southwards by the inshore current which flows southwards from Cape Hatteras to Cape Florida, aided by beach drifting induced by the oblique impact of the north-easterly waves.

Storm-line heavy mineral deposits, and recently elevated dune and bar sands have been mined in Florida since 1922 (Martens 1928). Pablo Beach south of Jacksonville Beach was the scene of the first operations which, however, lapsed with the opening up of the inland deposits nearer Jacksonville. The Riz Mineral Co. have worked storm-line and bar deposits in the Indian river and Vero beach districts south of Cape Canaveral for a number of years but it is not clear whether they are still operating. Recently Union Carbide and Carbon Corporation have become interested in deposits on Amelia Island.

Martens (1935) and Miller (1945) have studied samples of ordinary beach sands and beach sand heavy mineral concentrates from several localities along the east coast of Florida, and their findings are summarised in tabular form on the following page. South of Miami the beaches are adulterated by so much shell sand that the heavy mineral content of the sand becomes negligible. The same is true of some beaches north of Miami studied by Martens, and where the total heavy mineral content was less than 0.1% of the sand, mineralogical details have been omitted. In all cases only the content of titaniferous minerals, monazite and zircon has been recorded. (see accompanying table).

The beach sands of the west coast of Florida also contain heavy minerals at certain points. Miller (1945) has studied a number of samples from the following localities:- Tampa beach; Clearwater beach; Santa Rosa Island near Pensacola, and beaches in Pensacola bay. Unfortunately Miller does not give the total heavy mineral content of the sands from which the heavy fractions were taken. The available information concerning each of the samples studied is summarised below.

OCEAN BEACH AND DUNE SANDS OF FLORIDA'S EAST COAST

Locality	I[1]	II[1]	III[1]	IV[2]	V[1]	VI[1]	VII[1]	VIII[2]	IX[1]	X[2]	XI[2]	XII[2]	XIII[2]	XIV[1]	XV[1]	XVI[1]	XVII[1]	XVIII[1]	XIX[1]	XX[1]	XXI[2]	XXII[1]	XXIII[2]	XXIV[1]	XXV[1]	XXVI[1]	XVII[1]	XXIII[1]	XIX[1]
Total heavy mineral content %	1.9	24	0.75	?	0.62	70	6	?	24	?	?	?	?	0.05	0.71	14	0.20	0.37	0.2	86	7	0.3	?	0.21	2.4	0.5	0.32	0.07	28
Percentage composition of heavy mineral fraction.																													
Ilmenite	42	56	26	29	27	56	43	38	46	38	34	19	51	39	43	53	28	16	33	44	36	30	26	20	32	35	39	28	41
Rutile	5	5	3	9	4	8	4	14	4	19	14	6	15	4	6	5	3	1	5	10	27	5	24	5	6	5	4	4	8
Leucoxene	1	1	3	-	2	1	2	-	4	-	-	-	-	-	5	2	3	4	2	Tr	-	1	-	4	1	Tr	1	1	1
Zircon	11	23	3	8	7	19	8	7	6	27	12	Tr	10	19	17	11	4	2	12	39	6	7	12	5	5	6	16	6	10
Monazite	1	4	-	-	1	2	1	-	2	Tr	-	-	Tr	1	-	1	Tr	-	Tr	2	Tr	Tr	-	Tr	Tr	Tr	1	Tr	Tr

I Amelia Island. Ordinary beach sand
II Amelia Island. Natural concentrate
III St. John's river mouth. Ordinary beach sand
IV 4 miles south of Atlantic beach. Dune sand
V Manhattan Beach. Ordinary dune sand
VI 2 miles south of Jacksonville beach. Natural concentrate
VII 3 miles south of Mineral City. Ordinary beach sand
VIII 10 miles south of Jacksonville Beach. Ordinary sune sand
IX South Beach, St. Augustine. Natural concentrate
X 4½ miles south of St. Augustine. Natural concentrate
XI 7 miles south of St. Augustine. Natural concentrate
XII 10 miles south of St. Augustine. Natural concentrate
XIII Matanzas Inlet. Natural concentrate
XIV Flagler Beach. Ordinary beach sand
XV Volusia County. Ordinary beach sand

XVI Daytona Beach. Poor natural concentrate
XVII Daytona Beach. Ordinary beach sand
XVIII Cocoa Beach. Ordinary dune sand
XIX Melbourne Beach. Ordinary beach sand
XX Melbourne Beach. Natural concentrate
XXI Vero beach. First concentrate from concentration plant
XXII Fort Pierce. Ordinary beach sand
XXI Fort Pierce. Natural concentrate
XXIV Olympia Beach. Ordinary beach sand
XXV 5 miles south of Jupiter. Ordinary beach sand
XXVI Riviera. Probably ordinary beach sand
XXVII Boca Raton. Ordinary beach sand
XXVIII Hollywood Beach. Backshore terrace
XXIX Hollywood Beach. Natural concentrate.

1. Martens (1935)
2. Miller (1945)

Sample	Ilmenite	Rutile	Tourmaline	Kyanite	Zircon
I	26	22	2	8	15
II	23	1	10	-	1
III	15	7	2	12	43
IV	19	9	5	45	tr
V	14	16	1	35	4
VI	9	8	2	40	1
VII	8	5	2	35	9
VIII	23	7	3	30	2

I	Tampa beach. Natural concentrate.
II	Clearwater beach. Low grade natural concentrate.
III, IV	Santa Rosa Island. Natural concentrate.
V, VI	Pensacola Bay. 10 miles west of Camp Navarre. Natural concentrate.
VII	Pensacola Bay. 14.2 miles west of Camp Navarre. Ordinary sand.
VIII	East Bay, Pensacola. Natural concentrate.

It is most likely that these concentrates are of very local occurrence and contain only limited quantities of potential ore minerals. The high content of silicate minerals in the heavy minerals fraction is a notable feature of these deposits, one which is indicative of a modified genesis in comparison with those on the east Florida coast.

Other deposits.- In the pebble phosphate deposits at Peace Valley, Florida, heavy minerals are present in amounts of up to 1%. Ilmenite and rutile form approximately 20% and 7.5% respectively of the heavy minerals. They are not worth working for their own sake but could be concentrated as a byproduct of the phosphate mining which is carried out on a very large scale. (Hunter 1949).

MIDDLE WESTERN STATES

Arkansas

Titanium minerals have been mined in Arkansas from a deposit at Magnet Cove, Hot Spring County. The mineral of economic value is rutile which occurs both here and at a number of other less important localities in the same area. Other deposits containing ilmenite occur in South Howard County.

Rutile ores in Hot Spring County.- The Magnet Cove deposit. Magnet Cove is a south-east trending elliptical basin about 3 miles long and $1\frac{1}{2}$ to 2 miles wide, hemmed in by steep hills. The igneous complex which contains the ore deposits has been studied by Washington (1900) and Landes (1931) and also by Engel and Guggenheim (1938), Fryklund (1949), Vogel (1944), Spenser (1946), Fryklund and Holbrook (1950) and Reed (1950) whose interests were biased towards the ore deposits.

Tightly folded Palaeozoic sediments were intruded by an elliptical mass of alkalic igneous magma which enveloped and metamorphosed the sediments. The rutile deposit is found at the north side of the cove bordered to the north by a narrow band of nepheline syenite forming the rim of the cove. Surface material consisting of clay and the softer altered portions of the deposit has been mined in an open pit 3,000' long, 500' wide and 30' deep. The full extent of the mineralized zone has not yet been determined (Reed 1950).

The ore deposit was first investigated in 1911-1913 by the Titanium Alloy Manufacturing Company, but after that date no further mining activity is recorded until 1930 when the Titanium Corporation of America started mining operations which continued until 1942 when the property was repurchased by the Titanium Alloy Manufacturing Co. who operated it until 1944, since which date no further exploitation has taken place. It is estimated (Reed 1950) that from 450,000-500,000 tons of ore have been removed.

The orebody consists of a complex mixture of igneous, sedimentary and metamorphic rocks containing variable amounts of titaniferous minerals. The titanium content varies from 1% to 4.5% with local accumulations containing 12.6%. Most of the titanium occurs as rutile, but brookite, octahedrite, ilmenite, perovskite, sphene, 'leucoxene', ferriferous sphene and pseudobrookite have also been identified. All the igenous rocks in the cove contain titanium but it is only in feldspar-carbonate veins and their alteration products that commercially interesting titaniferous minerals occur. The titanium contents of the ore quoted above may be misleading because so much of the titanium is held in silicate mineral lattices whence it cannot be recovered.

The genesis of the deposits is in dispute. They have been considered to be highly altered volcanic agglomerates (Ross 1941; Kinney 1949) or rutile bearing veins cutting an igneous rock complex (Fryklund 1949; Fryklund, Harner and Kaiser 1954) depending on the interpretations of the field evidence submitted by the various investigators. The geology and genesis of the deposit is more fully considered in the relevant part of this thesis.

Beneficiation tests carried out on ore containing 3.4% TiO_2 obtained a rutile concentrate containing 92.2% TiO_2, 1.4% Fe, 0.63% SiO_2, 0.52% CaO, 0.09% S and 0.60% V_2O_5. The recovery of TiO_2 was 46.35%. (Fine, Kenworthy, Fisher and Knickerbocker 1948).

Christy Brookite Deposit.- A deposit of brookite occurs about 2 miles east of the Magnet Cove rutile deposit. The geological relationships of the deposit are essentially similar to those of the Magnet Cove occurrence. Brookite occurs in porous, metamorphosed novaculite, in quartz veins and in clays. Rutile and leucoxene accompany the brookite (Holbrook 1947).

A composite sample of ore taken from a number of test pits was analysed with the following result. (Reed 1949).

	%		%
SiO_2	66.26	CaO	0.014
P	0.119	BaO	Nil
S	0.011	MgO	Tr
Fe_2O_3	14.9	H_2O	Nil
Al_2O_3	6.54	K_2O	0.13
ZrO	0.04	Na_2O	0.06
TiO_2	7.56	Ign.loss	4.4

A large number of partial analyses of material from other test pits shew TiO_2 concentrations varying from 4.9-17.2%. (Reed 1949). The ore may contain up to 1.5% V_2O_5. Full drill - core records and analyses are given by Reed (1949). Beneficiation of ore containing 10.2% TiO_2 yielded a product containing 92% TiO_2 with a TiO_2 recovery of 71% (Holbrook 1947).

<u>Titanium occurrences in South Howard County</u>.- Layers of ilmenite-rich sand occur in the Upper Cretaceous Tokio formation north-west of Mineral Springs. The Tokio formation consists of intertonguing clay, sand and lignite. The Pink Green deposit contains ilmenite concentrations, averaging 4% TiO_2 but rising to 12.8% TiO_2 at a depth of 4-8' below the surface, in a soft friable sandstone.

The Beulah Green deposit contains, at a depth of 3-4' below the surface, ilmenite concentrations with an average TiO_2 content of 0.6-28.6%. Beneficiation tests have shewn that a concentrate containing 54.9% TiO_2 with a recovery of 92% TiO_2 could be obtained. (Holbrook 1948).

Illinois

The Bethel sandstone of south central Illinois state contains ilmenite, leucoxene, sphene and rutile as accessory minerals (Pye 1944). It is not known whether there are any alluvial concentrations of these minerals near to, or within, the area of the sandstone outcrop.

Mississippi

The Eocene sediments of Mississippi state contain ilmenite, rutile and zircon but there is no record of any alluvial or eluvial deposits associated with the rocks.

Missouri

A deposit of ilmenite is supposed to occur near the Einstein silver mine which is eight miles west of Fredericktown on the St. Francois river. (Youngman 1930).

Michigan

There are no titanium deposits of immediate commercial interest in Michigan. Titaniferous magnetite and ilmenite occur in the Marquette, Menominee, Penokee and Crystal Falls iron-bearing districts in gabbros and related rocks, but the occurrences are of mineralogical interest only. (Van Hise and Bayley 1897; Irving and Van Hise 1892; Bayley 1899; 1904).

Iron sands occur along the shores of Lake Huron (Trainer 1930).

Minnesota

The Duluth gabbro in Lake and Cook Counties, Minnesota, has been known to contain iron ore for many years. "The occurrence of titaniferous magnetite..... has been known for nearly 40 years" (Winchell 1886). These occurrences have been described a number of times (Clements 1903; Singlewald 1913; Broderick 1917; Grout 1918; 1926; Van Hise and Leith 1911; Winchell and Winchell 1891).

Broderick (1917) classes the titaniferous ores into four groups:

1) Inclusions of banded Gunflint formation.
2) Irregular bodies probably the same as 1).
3) Banded segregations in the gabbro.
4) Dikes rich in titaniferous magnetite.

"The largest and most promising bodies of magnetite are the segregations. In some of these the chief gangue mineral is feldspar but in some there is olivine. The deposits are not long, continuous belts but occur in zones in the gabbro in which there are overlapping lenses of ore. Most of these lenses are lean, but some are as much as 15 feet thick, and the zone can be followed by outcrops and magnetic mapping for some miles. There is a wide range in the quality of samples... but few lenses have more than 50% Fe. Several carry more than 20% TiO_2. The dykes and irregular bodies have about the same composition." (Emmons and Grout 1943). Geographical details covering the exact locations of the various deposits are given by Singlewald (1913) and Grout (1949-50). The ore minerals in the gabbro are ilmenite apparently free from inclusions and magnetite with ilmenite and, interpreting Singlewald's (1913) description, probably also ulvospinel.

The deposits have never been seriously mined and it is doubtful whether the deposits are of sufficient size or grade to make useful titaniferous ores.

The occurrence of iron sand on the south shore of Birch Lake was recorded by Winchell and Winchell (1891). An analysis of it is given below.

SiO_2	Al_2O_3	CaO	MgO	TiO_2	Fe
5.19	2.95	tr	0.35	36.77	41.12

No estimate of quantities of available sand were made.

Oklahoma

In the Wichita Mountains of Oklahoma a granophyre intrusion cuts and overlies a stratiform complex of anorthosite and gabbro. Between the gabbros and granophyre intermediate rock types have been developed by injection of granophyric veinlets, digestion of gabbro in granophyre and diffusion of granite material into the gabbros. (Huang 1955). Titaniferous magnetite and 'ilmenite' are supposed to occur in lean mineral accumulations of small size associated with the gabbros and anorthosites. The magnetite contains 4.4% TiO_2 and the 'ilmenite' only 16.05% TiO_2 (Merritt 1938, 1939, 1940).

Alluvial sands containing ilmenite-magnetite intergrowths and rare free ilmenite are found in the streams of the Wichita Mountains but the deposits are not of commercial interest (Chase 1952).

Alluvial deposits near Lake Lawtonka contain 3.4-6.8% ilmenite from which concentrates containing 44% TiO_2 can be produced. The reserves of ilmenite are approximately 370,000 tons (Chase 1952).

Texas

Secondary Deposits.- The principal rivers of Texas, the Rio Grande, Nueces, San Antonio, Brazos, Trinity and Neches all carry heavy minerals into the Gulf of Mexico where they are deposited along the beaches. The bulk of the heavy minerals are opaque oxides of which the greater part is probably ilmenite, while rutile forms a fraction of the non-opaque heavy minerals. (Bullard 1942). Nothing is known regarding the economic possibilities of this coast but the fact that they exist is demonstrated by the fact that Columbia-Southern Chemicals Corporation have been prospecting for titaniferous minerals on Padre Island near Corpus Christie. (Wall Street Journ. 148 No. 112 (1956) 15).

Hard Rock Deposits.- Ilmenite, probably in non-commercial amounts, occurs in radiating bunches of bladelike crystals in pegmatite dykes associated with granite at Baringer hill, Llano County, 100 miles north-west of Austin and 12 miles north of Kingsland. (Hess 1907).

Rutile and kaolin from the Medley district of Texas have been described (Vogel 1942) but they are not, apparently, of commercial interest.

Silicifed tufa containing finely disseminated rutile occurs in Jeff Davis County. A concentrate containing 87% TiO_2 is obtainable (Mathews 1943).

WESTERN MOUNTAIN STATES

Colorado

Caribou Hill. (Boulder County near Cardinal).- Caribou hill is an igneous stock composed chiefly of monzonite which has been intruded into a region of pre-Cambrian granites and gneisses. Masses of titaniferous magnetite and bodies of ultramafic and gabbroic rocks occur with the monzonite. The composite mass was formed from separate successive intrusions of magma in the following order:- 1) magnetite-rich pyroxenite, 2) augite gabbro, 3) augite monzonite, and 4) aplites, pegmatites and lamprophyres. (Smith 1938). An iron titanium oxide-rich late magma fraction was concentrated from the ultramatics by filter pressing to form masses of titaniferous magnetite with up to 8.5% ilmenite. The largest occurrence of titaniferous magnetite forms a dyke-like body 1,500' long. (Singlewald 1913; Jennings 1913; Bastin and Hill 1917).

Iron Mountain. (Fremont County, 12 miles south-west of Canon City).- "Analyses of the ore shew an average of 12.95% TiO_2 in the Iron Mountain deposit. The width of the orebodies ranges from about 10 to 50 feet but does not average more than 25 feet" (Singlewald 1913). The ore is not economically important (Bastin and Hill 1917).

Iron Hill, Cebolla Creek. (Gunnison County, south of Powderhorn).- Small segregations of ore occur in gabbro, and there are local patches of ore in contact metamorphic limestone. The ore contains 9-36% TiO_2 but is too dispersed to be of economic importance according to both Singlewald (1913) and Bastin and Hill (1917).

Larsen noted that the deposit of Cebolla Creek contained "dykelike or lenselike bodies of 'iron ore', many 20' across, made of nearly pure magnetite and perovskite. The purest portions consist of coarse-grained magnetite with minor amounts of ilmenite, apatite and biotite." Analyses of rich material shewed 35.05% TiO_2, 24.03% Fe_2O_3 and 14.6% FeO.

Idaho

Alluvial sands containing heavy mineral concentrations occur in Valley County in the beds of streams draining the Idaho batholith. Jig tests have shewn that ilmenite, monazite and zircon concentrates can be obtained from the sands. (Staley and Browning 1949). Recent electrical smelting experiments (Banning et alia 1955) resulted in the production of a titanium rich slag containing, on average, 80-84% TiO_2, 4.5% Mn and 0.5% P_2O_5. One ton of ilmenite yielded 0.5 tons of slag and 0.3 tons of pig iron. Monazite has been dredged from these sands for a number of years (Kauffman and Baber 1956) but production has recently ceased.

Montana

In the Blackfeet Indian Reservation on the western border of the Great Plains at the foot of the Front Range, black lenses in Upper Cretaceous sandstones contain magnetite, ilmenite, zircon, sphene and titaniferous magnetite. The lenses are 4-5' thick and contain 6-12% TiO_2. The more important occurrences are near the South Fork of the Milk River. (Stebinger 1912).

The Choteau deposit.- A titaniferous magnetite deposit at Choteau has been investigated and concentration tests have been applied to the material (Wimmler 1946), but good concentrates were not obtainable.

Dillon Nickel Prospect.- Titaniferous magnetite occurs in the Dillon nickel prospect in south-west Montana (Sinkler 1942). The occurrence is in gabbro associated with nickeliferous ultrabasic rocks. Its potentiality as an ore is not known.

Nevada

Corundum, apatite and rutile occur in the Blue Metal corundum property. Concentration tests yielded a product containing 16% TiO_2 (Binyon 1946).

Anatase has been reported to form up to 5% of some feldspar dykes in Nevada.

New Mexico

A deposit of titanium ore of commercial grade has been reported to occur in Hidalgo County (Coulter 1939). It is a replacement body of contact metamorphic origin 70' wide and 1000' long. The content of TiO_2 increases with depth.

Wyoming

Ilmenite-magnetite ores occur in an anorthosite body in the Laramie Range, approximately 40 miles north-east of Laramie. The existence of the ore has been known since the middle of the 19th Century and in 1897-8 the Colorado Fuel and Iron Company mined several tons of the ore.

Anorthosite forms the centre of a crystalline core of Pre-Cambrian rocks exposed in the centre of an anticline. Gabbros which cut the anorthosite are found mainly on the flanks of the massif where it is in contact with surrounding granite and metamorphic rocks. Ilmenite-magnetite ore-bodies are known to occur at a number of localities in the anorthosite but they are mostly small and dyke-like in form. One small ore-body and two of moderate size have been described.

Iron Mountain Ore body.- Early descriptions of the Iron Mountain ore and orebody were given by Lindgren (1902); Kemp (1905), and Warren (1918). Fowler (1930) has described the anorthosite area in general.

The Iron Mountain orebody occurs as a dyke which "varies in width from 50 to 250 feet and extends for nearly a mile along the crest of the ridge. The dyke is a black holocrystalline rock.... Pitted surfaces are produced where olivine crystals weather out with production of limonite." "Polished surfaces... shew a granular aggregate of medium to coarse grains of magnetite, ilmenite and intergrown magnetite-ilmenite. Small amounts of spinel, olivine and limonite are present. The magnetite-ilmenite intergrowth is in the form of a fine interpenetrating network of ilmenite lamellae along octahedral parting in the magnetite. Many of the ilmenite grains are twinned and shew strain effects". (Diemer 1941).

In the richest ore where there is less than 5% of silicate gangue the ilmenite and magnetite are almost free from inclusions, but as the gangue minerals increase in amount so the intergrowths of ilmenite and spinel in magnetite become more abundant. In one of Warren's (1918) text figures an intergrowth which he calls ilmenite can be seen in the magnetite. It is arranged parallel to the cube faces of the magnetite and is very probably ulvospinel.

The dykes of ilmenite-magnetite have sharp, apparently intrusive boundaries; the ore has been interpreted as a late magmatic injection (Diemer 1941) and as a replacement body (Newhouse and Hagner quoted by Lawthers 1954).

Diemer (1941) estimated the total available tonnage of ore to be 44 million tons but re-examination by Newhouse and Hagner (U.S.G.S. Open File Report) has caused a revised estimate of 9,150,000 short tons of ore.

The following analyses are a selection of those given by Diemer (1941).

	%	%		%	%		%	%	%
TiO_2	23.49	23.18	TiO	22.85	.23.00		27.0	27.0	28.0
FeO	17.96	24.55		28.18	23.21				
						Fe	52	52	50
Fe_2O_3	45.03	48.97		36.24	45.26				
SiO_2	0.76	2.15		4.00	0.54				
Al_2O_3	3.98		AlO	7.25	6.79				
Cr_2O_3	2.45		CrO	0.031	0.026				
MnO_2	1.53			0.077	0.042				
CaO	1.11								
MgO	1.56								
ZnO	0.47								
P	Tr								
S	1.44	0.03	SO_3	0.056	0.035				
			VO	0.402	0.367	V_2O_3	0.46	0.35	0.37
			Ti	13.71	13.80				

The reliability of the first four analyses is doubtful because the first two were made in the 1870's and 1890's, and in the latter two it is uncertain exactly which oxides of the elements were calculated. All the analyses seem to contain very high Fe_2O_3 values and it is not unlikely that the specimens used were rather weathered.

Shanton Ore Deposit.- This is a body of ilmenite-magnetite similar to the Iron Mountain orebody. According to Diemer (1941) the deposit contains 11,890 tons of ore per foot of depth.

Analyses of the ore given by Diemer are as follows.

	B_2 %	1 %	2 %
TiO_2	25.0	21.08	19.98
Fe	51.0	51.5	52.98
V_2O_3	0.53		
P_2O_5	0.0		

Taylor Deposit.- This is a small orebody eight miles north of Iron Mountain. It is similar in character to the Iron Mountain deposit.

<u>Fat Sheep Mountain, Laramie</u>.- A titanium and iron-bearing ore body is reported to occur near Laramie at Fat Sheep Mountain. The ore covers an area of 2 x 15 miles and there are supposed to be 228 million tons in reserve, analysing 35% Fe, 28% Ti, and 0.04% V (Min. J. <u>243</u> (1954) 11). The Metal Bull. (Feb. 1954) reports that this orebody contains 46% Fe, 19% Ti, and 1% V.

WEST COAST STATES AND ALASKA

There are occurrences of rutile in beach sands and deposits of ilmenite in both beach sands and hard rock in the west coast states of the U.S.A. Both types of deposit have been unsuccessfully worked in the past for their titanium mineral content.

The beach and stream sands of California, Oregon and Washington contain concentrates of heavy minerals at a large number of localities. The mineral content of the heavy concentrates varies widely from place to place and is apparently controlled by the mineralogy of the local country rocks. Heavy silicate minerals such as hornblende, epidote and olivine are common constituents of the concentrates, and there are usually present significant quantities of rock particles. The presence of silicate minerals and rock fragments in the sands indicates that the mineral deposits have not passed through the long and complex stages of concentration which have led to the formation of the commercially important titaniferous mineral accumulations of India, Brazil, Australia and Florida. As a result, there are no large high grade accumulations of titaniferous minerals to be found on these west coast beaches.

Sea level on parts of the Oregon coast was 1,000' higher in the geologically recent past than it is now (Twenhofel 1946). This figure is far too large to be accounted for by Pleistocene sea-level fluctuations and indicates rapid emergence of the coastline. Whereas in Australia fluctuations in sea-level have been of considerable importance during the genetic processes leading to the formation of the heavy mineral deposits, it appears that the fluctuations on the west coast of the U.S.A. have had the reverse effect because of their excessive magnitude, and almost wholly unidirectional character. They have caused the ocean beaches to be left high and dry before the elapse of a sufficient period of time to allow for purification of the heavy concentrates by elimination of undesirable minerals and rock fragments.

California

Beach Sands.- The beach sands of California have been described by Day and Richards (1908), Hornor (1918), Tucker (1927) and Hutton (1952). Hutton carried out an exhaustive study of the sands over the stretch of coast between Golden Gate and the south side of Monterey Bay. Rutile was never present in excess of 1% in any sand studied. Black sand concentrations were frequently encountered but were usually either too small to be of any importance or were of a transient nature. However, relatively stable concentrations were encountered at the following localities;- Princeton beach; on the south sides of the Tunitas, San Gregorio and Ano Nuevo creeks; south of Pigeon Point lighthouse; east of Ano Nuevo point; between the Pajaro river and Moss landing in Monterey Bay, and between the Salinas river and Monterey township. Ilmenite is usually the dominant mineral phase in the heavy opaque concentrates but variable amounts of chromite and magnetite are always present.

Hutton does not give any estimate of the tonnages of ilmenite available at the various localities he studied but, from the manner in which the occurrences are described, it would appear that their commercial value is probably small owing to their restricted areal extent.

A beach sand deposit at Clifton has been mined intermittently for the last twenty-five years (Tucker 1927; Minerals Yearbook 1952), and both magnetite and ilmenite concentrates have been produced. The latter have a low TiO_2 content, and are suitable only for use in the manufacture of roofing material.

The location of the black sand concentrates is invariably controlled by a headland or river effluent immediately to the north of the heavy mineral seams. Headlands and river effluents apparently disrupt the steady southerly longshore drift, possibly by reducing velocity and increasing turbulence, causing the heavier portions of the material being moved southward to be deposited on the beaches.

The minerals in the beaches have been derived directly from granites and other igneous rocks in the hinterland without an intervening stage of sedimentation. Direct derivation from the parent rock in this way is undoubtedly the prime cause of the contrast between the mineral composition of the California sands and that of the exploitable beach sands in other parts of the world.

<u>Hard Rock deposits</u>.- Numerous titaniferous magnetite bodies of various shapes and sizes occur in anorthosite and gabbro in the western San Gabriel Mountains which are located 25 miles north of Los Angeles. The ore bodies have been studied by Hess (1914; 1915); Tucker (1927); Moorehouse (1938) and most recently and most thoroughly

by Oakeshott (1936; 1937; 1948). They are situated in the Acton, Little Tujunga, Lang, Trail Canyon, Mount Gleason and Alder Creek map quadrangles as defined by the United States Geological Survey.

The orebodies, in which the opaque minerals occur as ilmenite-magnetite intergrowths, vary greatly in form and size, ranging from small irregular veins to large dyke-like or elliptical lenses. When occurring in the pyroxenite facies of the gabbro the ore minerals are usually disseminated throughout the silicate matrix. This is comprised of plagioclase (labradorite-andesine) and augite, the latter of which is frequently replaced by chlorite, actinolite and serpentine. Within the anorthosite the opaque minerals are frequently more highly concentrated to form more massive orebodies. All the richest ore accumulations occur in anorthosite in regions where granite pegmatite, aplite and lamprophyre dykes are most abundant. The contacts of the ore bodies are variable and may be completely gradational or absolutely sharp. There is some evidence to suggest that the shapes of the orebodies are controlled by structural features within the anorthosite-gabbro such as foliation and fracture zones.

The opaque minerals are ilmenite and magnetite each containing fine exsolution intergrowths of the other. Two analyses (Oakeshott 1948) are recorded below. The second analysis would appear to be of a disseminated ore type.

	I	II
SiO_2	0.42	
TiO_2	23.13	8.9
Fe	48.9	32.8
V_2O_5		0.04
H_2O	0.07	

It is, apparently, not possible to obtain either an ilmenite concentrate with a sufficiently high content of TiO_2 to be marketable as raw material for the pigment industry, or a magnetite concentrate with a sufficiently low titanium content to render it acceptable as an iron ore. Oakeshott records the following analytical data concerning magnetic and non-magnetic concentrates.

		Wt.%	Fe	TiO_2	V_2O_5	Dist-ribn. Fe	% TiO_2
I	(Non Magnetic	35	54.46	8.7		53.0	17.8
	(Magnetic	65	25.96	21.7		47.0	82.2
II	Strongly Magnetic	14.2	38.54	10.2		29.0	6.9
	Slightly Magnetic	11.7	21.96	32.6		13.5	18.0
	Non-magnetic	66.8	14.36	23.3		50.6	73.2
	Tails	7.3	17.90	5.6		6.9	1.9
III	Magnetite Conc.		50.8	9.8	0.18		
	Ilmenite Conc.		33.52	31.3	0.03		

The localities from which samples I and II were obtained is not recorded. The concentrates in analysis III are from the Live Oak Mill, Sand Canyon which is mining alluvial black sand derived from immediately adjacent oreshoots in the solid rock.

The ore-bodies are regarded (Oakeshott 1948) to have been formed by very late igneous processes. The opaque minerals partly replaced the orthotectic minerals and partly crystallized as a late magmatic residium. There is a close relationship in space and time between the titaniferous magnetite-ilmenite ore bodies and granite pegmatites, and the opaque minerals are considered to be pegmatitic in origin.

History of Exploitation.- The first recorded attempt to utilize the titaniferous magnetite ore was at Russ Siding, Soledad Canyon in 1906. An oil furnace was built and ore was obtained from a nearby small rich orebody. The project, evidently initiated with the idea of recovering the iron was abandoned when the refractory nature of the ore was discovered. The mineral Increment Company of Richmond, California mined ore at a locality 2.5 miles south-east of Lang Station in 1927. E.I. Dupont de Nemours Co. carried out systematic prospecting work between 1927 and 1938, particularly in the Mill Creek area, but were unable to locate a deposit from which an ilmenite concentrate of usuable grade could be obtained.

Alluvial placer deposits of titaniferous magnetite sands were being worked in 1946 in Live Oak Canyon. The magnetic concentrate obtained is used for ships ballast and the ilmenite concentrate is mixed with asphalt and utilized for roofing material.

Ore Reserves.- There are several million tons of ore scattered in low grade deposits throughout the San Gabriel gabbro-anorthosite igneous rock-mass, but there is probably no more than a million tons available containing 20% TiO_2 or above. (Oakeshott 1948). There are, however, probably several million tons of sand deposits containing from 2.4 to 30.8% TiO_2 in Live Oak and Pacoima Canyons.

Oregon

At many localities along the length of the Oregon coast concentrations of heavy minerals are found in both the sands of the ocean beaches and of old raised beaches inland from the present-day coast. These deposits have been worked in the past for their chromite content and, in the case of the inland placer deposits, for gold. The ilmenite, which occurs in variable concentrations in the heavy concentrates, has not yet been commercially exploited owing to its unsuitability as a raw material for white pigment manufacture.

The beach sands of Oregon have been studied by Day and Richards (1908), Hornor (1918), Pardee (1934) and Kelly (1947) but the most comprehensive studies have been made by Twenhofel (1946a; b) who has carried out physical and mineralogical analyses of a widely chosen selection of sand samples representative of the complete Oregon seabord. South of Coos Bay chromite predominates over ilmenite in the heavy mineral concentrates, but to the north ilmenite is the more common mineral. Zircon is present in the sands of some localities. Twenhofel lists the following localities south of Coos Bay as being of possible economic value:- Five Mile creek; Cape Blanco; The Heads, Port Orford; Euchre Creek; Rogue River estuary; and south of Meyers Creek. North of Coos Bay, in particular in Clatsop and Tillamook Counties (Kelly 1947; Twenhofel 1946a) there are a number of localities where heavy minerals have accumulated on the ocean beaches and the most abundant mineral in them is ilmenite.

In the Portland and Salem districts of Oregon large areas of lateritized Miocene basalts form potential ores of alumina and iron oxides. These ferruginous bauxite deposits contain variable amounts of TiO_2, averaging 4.85% for the deposits in Washington County and 5.83% for the deposits in Columbia County. (Libbey, Lowry and Mason 1945; 1946). The titanium content of the bauxite is probably contained in weathered ilmenite grains which, if the deposits are ever worked for their alumina content, would probably be recoverable as a by-product.

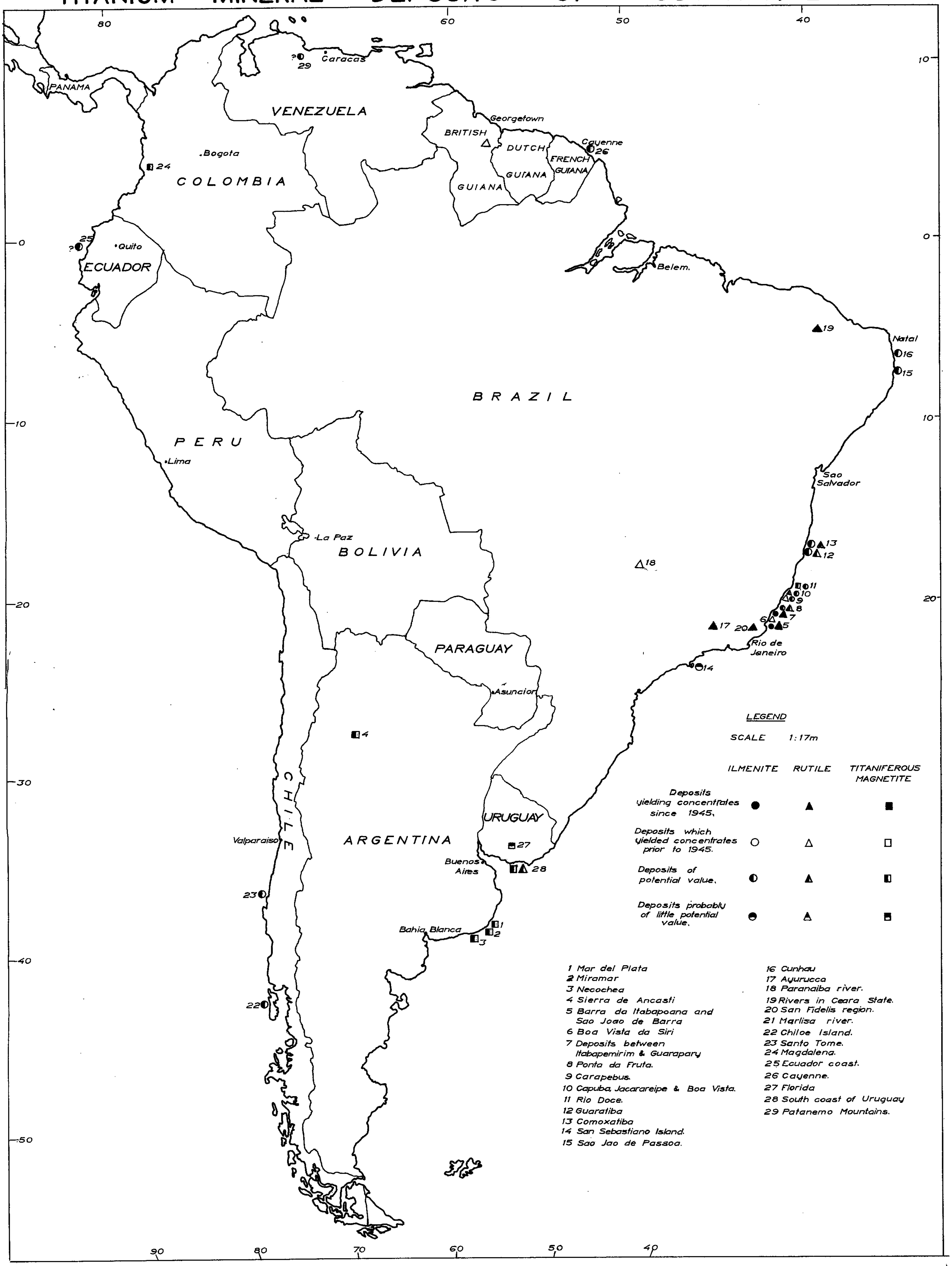
Washington

Black sands containing ilmenite are found on the ocean beaches of Washington state. Kelly (1947) has described a number of the occurrences which are mostly of small size. At Sedro Wooley, in 1920, the black sands were experimentally treated in a blast furnace with a view to utilising their iron content. (Baughman 1927).

Alaska

The only recorded occurrence of ilmenite in Alaska is in the Snettisham region where titaniferous magnetite and ilmenite occur in association with diorite and hornblendite. The content of Ti is 4-5%. (Buddington 1925; 1929).

TITANIUM MINERAL DEPOSITS OF SOUTH AMERICA



CHAPTER IV

SOUTH AMERICA

ARGENTINE

Beach Sands

Ferruginous and titaniferous sands occur on the Atlantic coast of the Argentine in the province of Buenos Ayres on the beaches of Mar del Plata, Mar del Sur, Miramar and Necochea and also in dunes inland. The beaches contain very poor concentrations of no importance. The inland dunes contain from 5.59-7.59% Fe and 1.87-2.35% TiO_2 and consist of very fine-grained sand distributed over wide areas. The average width of the dune belt is one kilometre and the average height five metres and they are supposed to extend over a length of 100 kilometres of coast line. There are estimated to be 220,000 tons of concentrates per square kilometre of sand dunes. No details are available concerning the mineral content of the sands, but the titanium-bearing mineral is probably magnetite though there may be separate ilmenite grains present. (Lannefors 1929). Some experimental concentration work has been carried out and there is a possibility that an iron concentrate, at least, can be obtained. (Carnaveli 1951).

Rock Deposits

In the Province of Catamarca, west of Albigesta in the Sierra de Ancasti, there is a deposit of titaniferous magnetite as a magmatic segregation in a gabbro intrusive. An analysis of the ore is given below:-

FeO	Fe_2O_3	Al_2O_3	MgO	S	TiO_2	SiO_2
65.7	8.6	1.2	2.46	0.04	17.00	5.00

(Imp. Min. Res. Bur. 1922).

Ilmenite and titaniferous magnetite deposits exist in the Department of El Alto. (Bassi 1952).

BRAZIL

Beach Sands

"Brazil has had an industry based on ocean beach deposits of heavy minerals containing monazite, zircon, rutile and ilmenite for well over 40 years, but except at the very earliest period, prior to 1906, and again during World War II, has this industry been at all comparable in size with similar operations in other countries" (Gillson 1950). The restraints on the beach sand industry have been the lower quality of the minerals, the small size of the deposits (until recent discoveries), the lack of Brazilian investment interest and unfavourable Brazilian mining law discouraging foreign capital investments.

The heavy mineral deposits occur principally in a belt about 175 km long extending north from the north-east corner of Rio de Janeiro state into Espirito Santo state as far as the Rio Doce. Further north in the state of Bahia is another belt of deposits about 40 km long and to the south in Sao Paulo state is a small deposit of ilmenite (Guimaraes 1946). Other deposits are known to exist some 20^{o} of latitude farther north in the states of Paraiba do Norte and Natal.

"The limitation of the deposits to specific zones has a direct and positive relation to the local geology. The deposits occur where the bottom beds of the coastal plain are being eroded, or were recently eroded by the sea". (Gillson 1950). (The geological history of the deposits is discussed more fully in the geological section of this thesis).

The economic potentialities of the deposits are restricted by lack of good roads along the coast and lack of port facilities. The port of Victoria, in Espirito Santo state is near only to some of the smaller deposits. The port of Guarapary, 50 km south of Vitoria can be used by vessels up to 3,000 tons but port facilities are inadequate. All other ports are extremely small. An anchorage north of Itapemerim is a potential loading point for the large deposits in the northern part of Rio de Janeiro state, but there are no roads connecting the deposits with the anchorage. Off-shore loading is possible from the beaches in southern Bahia because reefs provide protection.

The deposits in Natal and Paraiba do Norte are either poor in grade or large and badly located for shipping.

<u>Deposits south of Vitoria in the States of Rio de Janeiro and Espirito Santo</u>. (Froes-Abreu 1933; Rocha 1939; Information taken mainly from Gillson 1950).- The deposits south of Vitoria can be divided into those south of Barra do Itapemirim and those to the north, mainly between Anchieta and Guarapary.

Southerly deposits.- Twenty-two large deposits lie between Barra do Itabapoana and Sao Joao de Barra. Most of the deposits are of elevated bar type formed by long narrow ridges in which the rich layers of heavy minerals are usually obscured by about 50 cm of barren or low grade sand. They vary in length from one hundred metres to 2.5 km, and the width of the high grade zone from 20-50 metres. Barren sand lies at a depth of not more than 4 metres. The average grade of the deposits is 32% heavy mineral (over 2.9 Sp.G) of which 55% is ilmenite, 5% rutile, 25% zircon and 5% monazite. The remainder is formed by tourmaline, staurolite, sillimanite, kyanite, corundum and, in the Itabapoana deposits, spinel. An analysis of an average sample of Itabapoana ilmenite is as follows:-

TiO_2	FeO	Fe_2O_3	Cr_2O_3	V_2O_5
57.0	3.6	34.8	0.08	0.22

An isolated bar type of deposit occurs at Boa Vista da Siri, 25 km south of Barra do Itapemirim. The total tonnage available is not large. The deposit was worked from 1910-1912 for monazite and is now owned by "Mibra" (Monazita e Ilmenita do Brasil).

Northerly deposits.- The deposits are numerous but of no great size on this part of the coast, yet all of the recent production has come from this group. From south to north as far as Guarapary they are known as Caju, Piuma, Paraty, Ubu, Maiba, Ubahy, Meaipe and Lima. North of Guarapary is a deposit, presumably exhausted, which supplied the bulk of the tonnage produced to date by 'Mibra'. An ilmenite concentrate from this deposit analysed

TiO_2	FeO	Fe_2O_3	Cr_2O_3	V_2O_5
53.9	6.68	28.5	0.05	0.45

Further north at Ponta da Fruta is another deposit. All the deposits are of elevated bar type except Maiba which is a modern beach placer. These deposits are now worked by 'Mibra' and 'Fomil' (Formento

Monazita-Ilmenita) a subsidiary of the Lindsay Light and Chemical Co. of Chicago. The concentrates are shipped by launch or truck to Vitoria.

Deposits north of Vitoria in Espirita Santo state.- Several deposits occur to the north of Vitoria and south of Ara Cruz which are accessible by road. They are known as Carapebus, Capuba, Jacareipe and Boa Vista. Carapebus was worked from 1910-1912 and its ilmenite has the following composition:

TiO_2	FeO	Fe_2O_3	Cr_2O_3	V_2O_5
58.06	5.92	30.46	0.03	0.44

North of Ara Cruz relatively inaccessible deposits occur of which Sai is the only one of reasonable size. It is an elevated beach type of deposit with black sand occurring as a layer at the foot of the "barreira". These deposits contain some magnetite altered almost completely to hematite. The best grade of concentrate obtainable contains 53% TiO_2.

In the delta of the Rio Doce titaniferous magnetite-ilmenite deposits are found. The deposits are coarser grained and the best ilmenite concentrate obtainable contained 37% TiO_2. 20 km up the Rio Doce small high grade ilmenite deposits occur associated with land locked lagoons left inland by the rapid seaward advance of the Doce estuary.

Deposits in Bahia state.- There are two deposits known, separated by about 40 km of coastline. The more northerly is called Comoxatiba and the more southerly, Guaratiba.

Comoxatiba.- This is a modern beach placer 3 km long, 1-2 metres thick and up to 30 metres wide. It is covered at low tide by the sea which, by actively eroding the cliffs of soft Tertiary sand, is constantly renewing the deposit. The monazite content of this deposit is higher than any of the larger Brazilian deposits. The ilmenite contains 57.14% TiO_2. The deposit was worked for monazite about 1903 when approximately 25,000 tons were shipped out.

Guaratiba.- The deposit is in the form of an elevated bar 5.6 km long and 25-200 metres wide. From the analysis below it is apparent but the ilmenite has nearly as high a TiO_2 content as the Trail Ridge, Florida, ilmenites.

TiO_2	FeO	Fe_2O_3	Cr_2O_3	V_2O_5
61.4	2.5	31.9	0.07	0.15

Both these deposits are accessible for loading direct into small craft owing to the presence of an offshore reef which protects the beach. No figures for reserve tonnages of heavy minerals are given by Gillson (1950).

Deposits in Sao Paulo state (Guimaraes 1946).- Ilmenite was discovered in 1945 on the coast north of San Sebastiano island. There are three small deposits containing a total of 10,000 tons of ilmenite:- Cocauha, 500 metres long containing ilmenite with 38% TiO_2; Mococa, 600 metres long containing ilmenite with 33.5% TiO_2 and Preta, a deposit of insignificant importance.

North-east Brazilian deposits.- Two deposits in north-east Brazil have been described.

San Joao de Passoa in Paraiba do Norte state.- Ilmenite occurs in red beds of Cretaceous age which are probably of too low grade to work even though available tonnages must be very large. No important beach sand concentrations have been found (Gillson 1950).

Cunhau in Rio Grande do Norte state.- Black sand containing ilmenite and zircon which together make up 85% of the heavy concentrate, and very small quantities of monazite and rutile occur in the beaches and in dunes near Cunhau. The tonnage in the dunes is "very large", although the average grade of the sand is low. The ilmenite analyses 56.2% TiO_2, 17.8% FeO and 21.6% Fe_2O_3.

Saldanha (1955) has described zircon and ilmenite from Floriana, Rio Grande del Norte state.

Brazilian beach sand ilmenite, although it has a higher TiO_2 content than hard rock ilmenite by virtue of partial leaching of iron from the molecule, does not compare favourably with Floridan (64.0% TiO_2) and Travancore (60.4% TiO_2) ilmenites. There is no record of the existence of a completely 'leucoxenised' ilmenite constituent of the Brazilian sands as there is in Florida. The presence of 'leucoxene' is most important because it increases the tenor in TiO_2 of the final 'ilmenite' concentrate.

Concentration tests on Brazilian beach sands have shewn that the procedure adopted in Florida is also suitable in their case.

Alluvial Deposits

Rutile has been produced from alluvial deposits in many parts of Brazil frequently as a by-product of diamond mining. The deposits are all low grade and most of them are a long way from the coast.

Minas Geraes State.- The deposits are found in the regions of Lima Duarte and Ayurucca. They are derived from talc and sericite schists which are widely distributed in the central plateau of Brazil. The rutile is often intergrown with ilmenite so that grinding and electromagnetic separation are necessary to raise the TiO_2 content of the natural rutile above 70-85%. (Froes-Abreu 1936; Meyer 1938; Zuquim 1935).

Goyaz state.- Alluvial and placer deposits occur in or near the Aragina, Paranaiba and Tocantius rivers. The rutile contains 95-97% TiO_2 and is derived from porphyroblastic masses in schists of Algonkian age. Production from these deposits, some of which was a by-product of diamond mining, was 400 tons in 1937.. (Oliviera 1937; Froes-Abreu 1936; Leonardos 1938).

Ceara state.- Rutile, with a small amount of intergrown ilmenite, has been produced from alluvial deposits containing 1% of TiO_2. The rutile as mined contains 88-96% TiO_2 and is worked by primitive dry placer mining. It is derived from granites and gneisses of the region. (Chambers (1942)).

Bahia state.- Perovskite, containing 58-88% TiO_2, occurs in sands in all streams of the Serra de San Pedro in the Capim Grosso district. It originates from granite veins. (Freise 1937).

Rio de Janeiro state.- Small amounts of rutile have been produced from stream-bed alluvial deposits of the Serra dos Sapateiros near San Fidelis.

Titaniferous magnetite deposits

Jacupiranga and Ipaneama.- Titaniferous magnetite deposits occur in the nepheline syenites of this region. Certain facies of the intrusion are supposed to contain 20% TiO_2. (Beyschlag, Krusch and Vogt 1914).

Ilmenite and rutile production in Brazil from all sources over a period of years has been as follows (Gillson 1949 and other sources). Quoted in metric tons unless otherwise stated.

Ilmenite

1932		1939	10	
1933		1940	12	
1934		1941	4471	
1935	287	1942	3033	'tons'
1936	9	1943	3030	'tons'
1937	234	1944	3250	
1938	317	1945	5000	

Rutile

1932	35	1940	499
1933	96	1941	2369
1934	116	1942	4615
1935		1943	4557
1936	721	1944	1564
1937	654	1945	160
1938	215	1946	
1939	489		

BRITISH GUIANA

Iron sands containing ilmenite were reported to occur in British Guiana. (Evans 1910). The reference was probably to the ilmenite found in various gold placer deposits within the colony. (Smith 1946).

Rutile concentrates occur in the diamond deposits of the Marlisa river, a tributary of the Berbice river. (Smith 1946). An analysis of the concentrate is quoted below:

	TiO_2	Fe_2O_3	SiO_2	P
%	95.00	1.95	2.94	0.08

(Imp. Inst. Bull. 27 (1929) 101).

Uranium-Euxinite with a TiO_2 content of 25% occurs in pegmatites intrusive into basic lavas in the Kanuku Mountains. (Smith 1946).

Ilmenorutile, with the following composition, occurs in pegmatites 110 miles south-west of Georgetown.

Cb_2O_5	Ta_2O_5	TiO_2	FeO	MnO	SnO	ZrO
29.85	8.33	38.4	10.8	2.9	0.33	0.24

(Smith 1946).

CHILE

Ilmenite occurs in recent sands on the west coast at Chiloe island. (Falke 1938). In 1944 a mine near La Seraba produced 5 tons of ilmenite. (Lawthers 1954).

A deposit of titanium is reported to have been discovered at Santo Tome near Concepcion. "According to first reports it should be of considerable size". (Chim. et Industrie 4 (1954) 810).

COLOMBIA

At various times occurrences of titaniferous magnetite have been reported from Colombia, in particular in the Magdalena department (Oppenheim 1941) and in Espėritu Santo, Sevilla, (Mutis 1943).

ECUADOR

The sands of the Ecuador coast contain varying amounts of magnetite and ilmenite. Over a total area of 350-400 sq. kilometres, down to sea level, there is a total of 4,000 million cubic metres of sand containing from 10-60% of iron and titanium oxides. Heavy concentrates from the sands contain up to 35.1% TiO_2. (Private report). The reliability of the source of this information is uncertain.

FRENCH GUIANA

On the beach of Cayenne gold bearing black sands contain up to 15% ilmenite. (Lebedev 1936).

The laterite deposits of Fourgaisie contain up to 4% TiO_2.

PERU

Ilmenite and rutile are supposed to occur in some Peruvian ores (Weckworth 1908) but they are of no economic importance.

URUGUAY

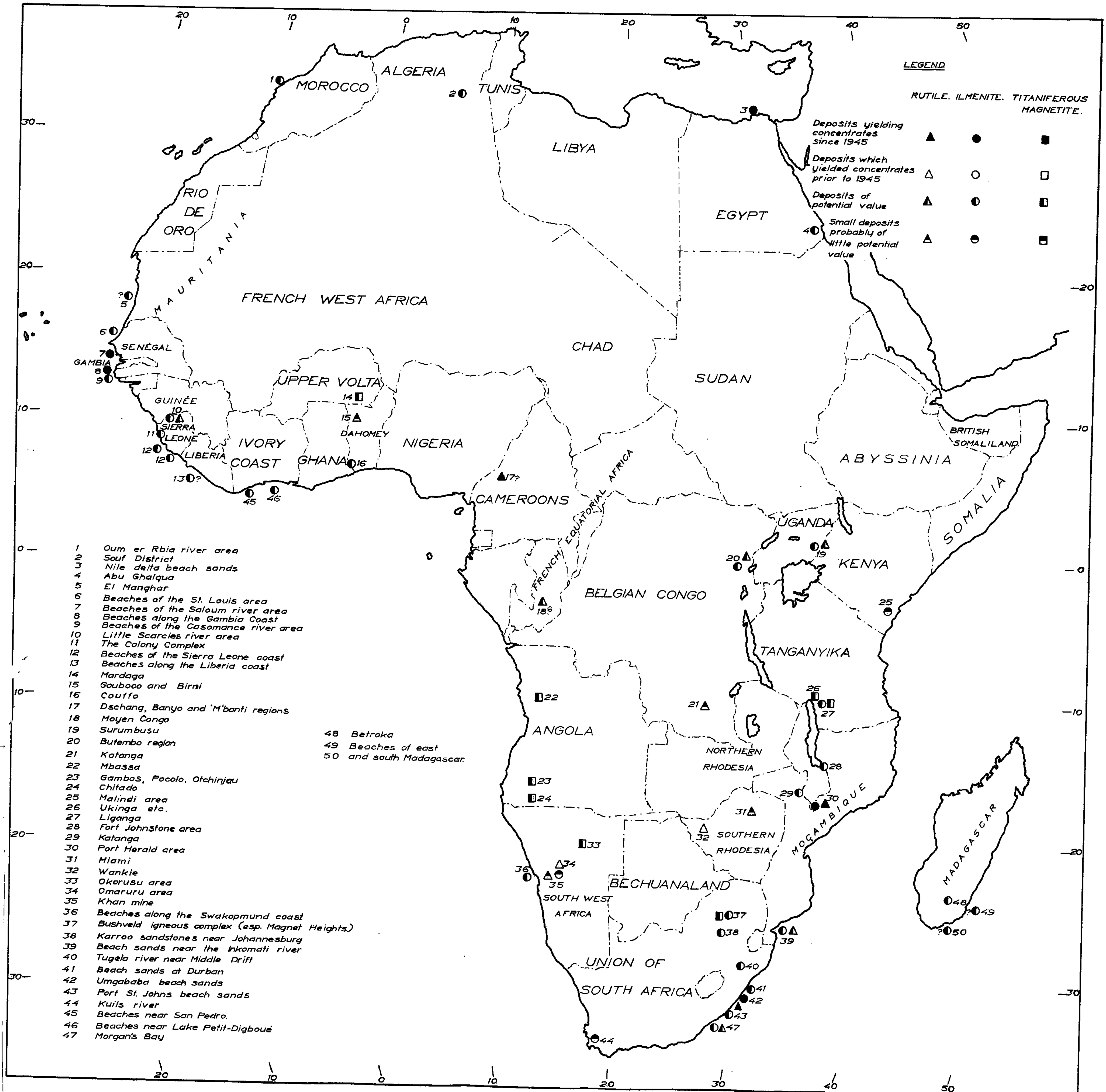
Radioactive black sands are found on the southern shore of Uruguay. They contain monazite, titaniferous magnetite, magnetite, rutile, zircon, garnet and quartz. Other occurrences in the interior of the country are also known. (Goni 1950).

Veins of titaniferous iron minerals occur associated with gneissic granite "a few thousand feet west of the highway to Florida in an open field". They are 2"-8' wide. Analyses indicate a TiO_2 content of 12-23% and an Fe content of 45-56%.

VENEZUELA

Deposits of titanium minerals have been discovered near Puerto Cabello 140 miles west of Caracas in the Patanemo and Borburata mountains. (Chem. World 14th April 1956).

TITANIUM MINERAL DEPOSITS OF AFRICA.



CHAPTER V

AFRICA

BRITISH COLONIES

KENYA

Kenya contains no titanium ore deposits which are being actively exploited though ilmenite and rutile are common accessories in the schists and gneisses of the Pre-Cambrian basement. Brief details of a few local and, as far as is known, unimportant deposits are recorded below.

Kitson (1934) reported the occurrence of ilmenite in stream sands and eluvial material from the following areas:- Wusengi; north of Asembo; South Gem; Rangwe river, south Kavirondo; Awache River; and Nyasola River. Rutile has been found at Asembo Bay, Central Kavirondo, and north of Asembo.

Pulfrey (1952) described black sands from Uyoma, Central Nyanza on the east shore of Lake Victoria, and gave the following analysis:-

FeO	50.21%	Ti	13.80%
Magnetite	56.15%	Ilmenite	26.17%

He also noted the occurrence of titaniferous hematite (3.5% TiO_2) segregations at Homa Mountain, on the east shore of Lake Victoria, associated with carbonatite and alkaline intrusions.

Thompson (1956) reported the discovery of black sands containing ilmenite, rutile, monazite and zircon in the Malindi area.

TANGANYIKA

Titaniferous Iron Ores in the Njombe District

The Liganga Titaniferous-Magnetite Deposits.- These deposits lie forty miles to the east of the northern end of Lake Nyasa. Stockley (1945, 1946, 1948), and more recently Harpum (1952), have described these deposits. An estimate of the amount of ore available (Stockley 1945) and Chem. Eng. News <u>33</u> (1955) is 1.2 billion tons containing 65% magnetite and 26% ilmenite. This estimate of available ore is probably greatly exaggerated because it is based on Stockley's (1946) description of the ore zone as a syncline which, apparently, is incorrect (Harpum 1952).

The following analyses are available.

	Stockley (1945)	Harpum (1952)	Harpum (1952)
	%	%	%
SiO_2	0.45 - 1.4	0.8	1.85
Al_2O_3		10.6	9.51
Fe	57	50.7	49.5
TiO_2	8	13.7	12.61
CuO		-	0.38
MgO		5.1	5.1
MnO	0.2	-	0.4
Cr_2O_3		0.2	0.31
V_2O_5		nd	0.41
P_2O_5		tr	0.016
S	0.05	nd	0.004

The deposits, which occur as sheets of ore injected into leucogabbro and anorthosite, dip at a high angle to the west south-west. The ore seams are concordant with the major joint system and have sharp contacts against the host rocks with intense chlorite development at the margins. Stockley (1945) regarded the ore as a magmatic segregation from the gabbro host rock but Harpum (1952), who found transgressive contacts of ore against gabbro, regards the ore bodies as injections. Harpum attributes the exceptional size of the deposits to the very well developed jointing in this region.

If a method suitable for economic smelting of the ore is ever developed, the proximity of the coalfield of Ketewaka, 34 miles distant from Liganga, and the presence of limestone in the region may provide the basic essentials for a heavy industrial region of the future.

Other magnetite bodies occur associated with gabbro, leucogabbro, and anorthosite eruptive rocks in a sixty mile long belt running north-west to south-east and including the Liganga deposit. The intrusive bodies are all connected genetically with thrust zones. Two intrusive sheets are recognised, the former containing concordant ore deposits and the latter discordant bodies of the Liganga type. No analyses or details of ore reserves are given in the literature except for a gabbro body at South Ukinga (Stockley 1948), said to contain 30 million tons of ore analysing 55.75% Fe and 8.33% Ti.

Central Corridor Thrust.- Metasomatic titaniferous iron ore deposits associated with thrust zones are described by Harpum (1952). They occur at Tandala together with soapstone, and a long the Central Corridor thrust. Three metasomatic zones are recognised:-

a) A chlorite permeation zone with titaniferous magnetite segregations containimg from 20.6% to 2.6% TiO_2. The TiO_2 content of the containing rock is 1%.

b) Titaniferous magnetite-metasomatic permeation rocks. Magnetite is presumably intergrown with ilmenite since the more magnetic ore fraction runs 18.7% TiO_2 and the non-magnetic fraction 22.4% TiO_2. It is thus unlikely that these deposits will be of economic importance for some time because of the difficulties involved in separating the TiO_2 from the Fe.

c) Metasomatic hematite-limonite deposite with 1.03% TiO_2. At Ukisi, in Upangwa, amphibolite has been replaced by calcite with separation of magnetite containing 4.4% TiO_2.

Anorthosite Granulites.- Titaniferous-magnetite containing 11.6% to 15.2% TiO_2 occurs in long narrow bodies associated with anorthositic granulites in the Basement system. They may be genetically connected either with basic igneous rocks or metamorphosed sediments (Harpum 1952).

The geology of these deposits is discussed in Part I of this thesis.

Other Minor Deposits

Baum (1909) noted the occurrence of titaniferous magnetite sands and brookite in old stream beds in the neighbourhood of the Wilhelmstal-Tanga railway line in Usambara. Titanium-iron occurrences in amphibolite and diorite in the same area were also reported.

Schumacher and Thamm (1941) recorded eluvial deposits of ore containing 25.31% TiO_2, which had originated from local gneisses, from Mbakana brook, Hondussi Hill, Uluguru mountains. These have recently been investigated and found to be of no further interest.

McConnell (1953) described a quartz-rutile reef, in granite gneiss of the Basement complex, which contained an average of 1% TiO_2. The rutile occurs in large crystalline masses up to 40 cm in diameter. The occurrence is four miles north-east of Milembule, 5 miles north-east of Namanyere, forty miles east of Lake Tanganyika.

Teale and Oates (1943) report stream concentrates consisting of up to 80% titaniferous magnetite containing 14% TiO_2 at Geita, and eluvial rutile deposits of small size at Nsaja Hill, Dodoma.

UGANDA

Bukusu Hill

The most important titanium ore deposits in the country occur associated with an alkaline volcanic ring complex at Bukusu in Mbale District. The complex is a roughly circular mass four to five miles in diameter consisting of syenites, ijolites and pyroxenites, enclosing a continuous belt of magnetite-apatite-phlogopite rocks and a central core of carbonatite. This belt is normally $\frac{1}{4}$ to $\frac{1}{2}$ mile wide, but to the north-west is $1\frac{3}{4}$ miles wide and includes three hills called Nangalwe, Sikusi and Surumbusu. (Davies 1947; Broughton, Chadwick and Deans 1950).

Analyses of iron ore are given by Broughton et al. 1950.

	Nangalwe Hill	Sikusi Hill	Surumbusu Hill
SiO_2	2.35	1.36	0.49
Al_2O_3	2.96	0.67	0.89
Fe_2O_3	73.75	59.07	59.90
FeO	15.30	24.28	10.68
MgO	0.30	1.03	1.95
CaO	0.43	0.04	1.84
TiO_2	0.35	11.50	21.75
P_2O_5	0.003	tr	tr
SO_3	-	-	-
V_2O_5	0.31	0.04	0.09
MnO	1.43	0.80	0.16
H_2O	3.01	1.29	2.42
	100.19	100.08	100.17

"Mineralogically the iron ores range from fairly pure magnetites, through titaniferous magnetites, to types which are mixtures of titaniferous magnetite, ilmenite, perovskite and leucoxene." In Sikusi the TiO_2 occurs in titaniferous magnetite and exsolved ilmenite; Surumbusu contains perovskite and leucoxene. The vanadium content of the ore is low; the little that is present is concentrated in the purer magnetite ores as would be expected. (Broughton et alia 1950).

Material from Surumbusu was subjected to concentration tests (Broughton et alia 1950) with the following results:-

	Magnetic Concentrate.	Non Magnetic Concentrate
	76.4%	23.6%
	(Titaniferous Magnetite)	(Perovskite, leucoxene and magnetite)
Total Fe as Fe_2O_3	81.44	2.72
TiO_2	14.72	65.98
CaO	-	22.30
Ce_2O_3	nd	1.19
Other rare earth oxides	nd	1.92 including thoria 0.2%
Ign. loss	-	1.52
	96.16	95.63

Recalculating from these results, the original sample must be approximately 76% titaniferous magnetite, 16% perovskite, and 8% leucoxene.

A further sample from the same approximate locality yielded 82% titaniferous magnetite, 15% perovskite, and 3% leucoxene.

Samples of the non magnetic concentrate, treated by National Titanium Pigments Ltd (now Laporte Titanium Ltd), shew that TiO_2 can be made satisfactorily by treatment with oleum.

The perovskite of this deposit is knopite, a cerian variety. An analysis is given by Broughton, Chadwick, and Deans (1950). The "leucoxene" has been shewn to be finely crystalline anatase, a conclusion confirmed by optical and x-ray work.

Taylor (1953) records that the Surumbusu hill magnetite contains over 20% TiO_2, is intermixed with, and underlain by, vermiculite which may be of economic grade. Nameka hill, on the south-west side of the ring complex, contains at least 8.5 million tons of magnetite in granules over ¼" in diameter. Seven analyses are given shewing 7.90 to 9.65% TiO_2 and an average of six other samples gave 13.7% TiO_2. No information regarding ilmenite-magnetite intergrowths is given (Taylor 1953).

Other Deposits

Small alluvial and eluvial concentrations of rutile and ilmenite have been reported in the last thirty years from many areas of Uganda. Wayland (1931) described tin and rutile pegmatites and associated alluvial deposits and Bissett (1942) reported the occurrence of small ilmenite deposits in schist in the Karamoja area. Rutile and ilmenite occur in the Kafa river area (Harris 1943) and ilmenite in alluvial and eluvial concentrations in north-east Acholi (Roe 1944).

BASUTOLAND

According to Stockley (1947) ilmenite is found in kimberlite pipes and in stream sands, where it is derived from lavas and dolerite dykes. Rutile is found in river gravels and sands below sedimentary strata outcrops. It is unlikely that any of these occurrences are of economic value.

SWAZILAND

Rutile is associated with tin deposits according to Rathbone (1904). No other information is available.

ZANZIBAR PROTECTORATE

Ilmenite occurs in the beach sands of Zanzibar and Pemba islands in good concentrations (Stockley 1928) but the largest deposit contains only a few tons and is of no economic importance.

GAMBIA

Very little is known about Gambian titaniferous ore deposits although some, very probably of economic importance, undoubtedly occur. Cooper (1927) recorded the presence of ilmenite, monazite and zircon in stream concentrates. The beaches of Gambia may also contain significant quantities of titaniferous minerals because beach sands are mined for ilmenite to the north and south in French Senegal, and Sierra Leone, and ilmenite-norites outcrop on the coast of the latter colony. British Titan Products Co. Ltd. have a thirty year agreement with the Gambian Government to develop titanium resources. (C.T.J. 135 (1954) 550; New Commonw. 5 (1954) 263; Min. World 167 (1954) 169; Commonw. Surv. 1 (1955) 33).

NIGERIA

Ilmenite and rutile have been found in many stream sands throughout Nigeria but in insufficient quantities to constitute ore deposits. Behrend has recorded the occurrence of ilmenite-magnetite sands in a southern tributary of the Benue river. Ilmenite gravel is abundant near Baicossa, 20 miles north of Obudu station (Bull. Imp. Inst. 15 (1917) 84-5).

Rutile.- The crystalline rocks and gneisses of the Borgu region contain abundant rutile (Tattam 1935).

Titaniferous Magnetite.- Titaniferous iron ores containing 14.7% TiO_2

occur at Mardaga, thirty kilometres south-west of Diapaga.

SIERRA LEONE

Alluvial, eluvial, beach sand, and hard rock deposits of titaniferous minerals are known to exist in Sierra Leone. There are no concentrates being produced at the present time from these deposits, but British Titan Products and Columbia-Southern Chemicals Corporation (U.S.A.) are reported to be planning production in the near future from soft rock deposits in the Imperri chiefdom, Bonthe district. No details concerning the deposit have been published. (Metal Bull. 4052 (1955) 24; C.T.J. 139 (1956) 1224).

Alluvial Deposits

The Report of the Geological Survey of Sierra Leone for 1928 recorded an abundance of rutile in the gravels of the Little Scarcies river below its conjunction with the Mabole river. It is accompanied by granular ilmenite, and a little corundum, zircon and sapphire. When the report was written it was considered to be probably an economic proposition. No reserves were given.

Ilmenorutile has been reported to occur in the Tonkolili river valley (Bull. Imp. Inst. 42 1942). Material from Madondoneh stream, a left bank tributary of the Tonkolili, has been analysed (Pollett 1949).

	TiO_2	Nb_2O_5	Ta_2O_5	FeO	Sp.G.
%	55.7	22.6	9.4	11.0	4.74

Monazite, gold, topaz, ilmenite, and beryl also were present in the concentrate. The country rock is porphyritic biotite granite.

Beach Sand Deposits

There are no references in the literature to beach sand concentrates of titaniferous minerals other than those in the immediate vicinity of the norite-anorthosite Colony complex. These were investigated at various times in the 1930's (Ann. Repts. Geol. and Mines Dept. Sierra Leone (1932-1937) but were thought to be not worth working. Junner (1930; 1938) gave the following partial analyses of black sands.

	Whale Estuary	Beach at York	Toke River	Big Water, York Pass
Fe_2O_3	46.9		50.56	
TiO_2	52.9	52.2	49.5	46.8
Cr_2O_3				0.29

Junner also described the beach deposits at Hastings as, "7 ft thick extending over ½ mile".

Pollett (1951) remarked that the beach sand deposits were abundant but mixed with much boulder material. He said that they had recently been resurveyed by a British Company, who had demonstrated that the ore was coarsely crystalline, containing ilmenite with 48.5% TiO_2 and low TiO_2 magnetite as separable minerals. Bands of black sand outcropping near the top of raised beaches were thought very rich in ilmenite.

It seems probable that the deposits which the British Titan Products Ltd - Southern Chemicals Corporation joint subsidiary plan to work is a beach deposit, but no details are known.

Hard Rock Deposits

The Norite-Anorthosite Colony Complex.- The Colony complex has been described in a number of papers by Junner (1929, 1930, 1932 and 1938), while more recently Wells and Baker (1956) have redescribed the complex dealing in detail with the anorthosites.

The complex is a large, lenticular, centrally sunken, generally concordant intrusive mass. This basin-shaped sheet of basic igneous rocks has been truncated and inundated by the sea to the westward. Four main zones have been established (Wells and Baker 1956) in each of which the general sequence from bottom to top is olivine rich rocks, gabbros deficient in olivine, and leucocratic rocks including anorthosite. Gravity survey proves the mass to be a lopolith, probably seven miles thick at the centre (M.H.P. Bott, personal communication 1957).

The ilmenite-magnetite ores associated with the anorthosite were among the last mineral phases to crystallise. They consist of granular ilmenite, and magnetite which contains exsolved ilmenite lamellae. Very fine lamellae of ulvospinel occur in some of the magnetites.

Each zone of the complex was injected as a separate magma pulse and has differentiated in situ, the ore bands collecting at the top of each phase as a pegmatitic residium.

There are no details of ore reserves given in the literature. The only descriptions Junner gives are of a 2 m thick ilmenite band at Hastings, and a band 4.5 m thick of titanomagnetite at Mount Aureol. The ore reserves in a complex of this size must be enormous, but whether the ore bands are sufficiently consistent to allow economic exploitation is at present unknown. From the brief description of ore given by Wells and Baker (1956) and the analyses of immediately adjacent beach sands (see above), it seems that the ore will probably be suitable for beneficiation to yield an ilmenite product relatively free from magnetite impurity.

The geology of the Colony complex is discussed in Part I of this thesis.

BELGIAN CONGO

Little is known concerning the occurrence of titaniferous minerals in the Belgian Congo, although they have been briefly recorded to occur at a number of widely separated localities.

Hard Rock Deposits

Katanga.- Rutile (Cesaro and Bellaire 1922), ilmenite and titanomagnetite (Verhoogen (1938)), are found in the kimberlite pipes of Katanga. It is not reported whether or not the ilmenite has been concentrated for economic purposes. Evrard (1949) quotes the following partial analyses from Verhoogen.

	Titanomagnetite	Ilmenite
TiO_2	11.54	53.21
Fe_2O_3	56.56	11.90
FeO	25.8	27.99
MgO	6.8	7.20

Secondary Deposits

Lhoest (1939-40) recorded the occurrence of rutile and ilmenite, associated with gold and cassiterite, at Mununzi, near Luhule, in the Butembo region north of Lake Edward. Huge and Egeroff (1948), quoted by Lawthers, reported mineable concentrations of rutile occurring in veins and alluvial deposits south of Lake Albert.

Tyler, in the Minerals Yearbook (1939), reported that a firm were producing titanium oxide-white pigment from Ti-Sn concentrates produced in the north of the Belgian Congo. The location of these deposits is not recorded, but the reference is probably to the Mununzi area.

EGYPT

Beach sand and hard rock deposits of ilmenite and rutile are known to occur in Egypt and the former have been exploited in the past.

Beach Sand Deposits

Black and green sand deposits occur on the seaward edge of the Nile delta at Abu Khashaba, Rosetta, Burullus and Damietta. The existence of these deposits has been known for many years (Griffith Jones 1923) and an unsuccessful attempt to work them was made in 1930. Since 1939 the deposits have been owned and, at least intermittently, operated by the Anglo Egyptian Mining Co. The black sands are moved by camels or fishing boats to Rosetta to a separation plant handling 20 tons per day. It is thence shipped to Alexandria.

The sands are deposited by storms during the winter and they are worked during the summer. They originate in the Ethiopian plateau whence they are transported by the Nile during flood periods. The sands consist of titaniferous Magnetite 22-25%, Ilmenite 40-45%, Zircon 10-12%, Monazite 2-8%, Rutile 1-2%, Garnet 10-15%, Silica 10-15%, Greensand (silicates of rare earth elements) 6-12%.

In 1939, 5,208 tons of concentrates were exported.

Hard Rock Deposits

<u>Abu Ghalqua</u>.- An ilmenite deposit lying within a gabbro mass has been described several times by different workers. The gabbro lies near Wadi Abu Ghalqua in the Eastern Egyptian desert in Lat. $24^{\circ}21'20''$ N and Long. $35^{\circ}3'30''$ E. It is 30 km inland from Abu Chosun on the Red Sea and 85 km south of Mersa Alam.

The deposit was first described by Hume (1907, 1909) who called the host rock hypersthene gabbro. Later workers, Stella (1932), Attia (1950) and Amin (1954), have described the rock as augite gabbro, and the ore as ilmenite with hematite exsolution lamellae.

The ore occurs as bands and disseminated crystals at the top of a gently dipping, highly altered and uralitized sheet of labradorite-augite-ilmenite gabbro. The largest ore zone is 270 m x 90 m in area. There are at least two other smaller ore zones up to 50 metres long making a total of at least 3 million tons of ore in the gabbro. The ilmenite bands strike north-west to south-east and dip gently north-east, parallel to the eastern contact of the gabbro. The intrusion of a later microgranite against the gabbro has caused widespread uralitization but this has not obscured a platy flow structure which is observable in the disseminated ore bands intercalated with the rich ore horizons.

The following analyses of the ore are available.

Attia (1950)

SiO_2	0.85
Al_2O_3	1.16
Fe_2O_3	21.95
FeO	25.94
MgO	2.39
CaO	tr
TiO_2	46.87
P_2O_5	0.009
MnO	0.38

Attia (1950)

	1	2	3	4
TiO_2	50.50	46.55	43.65	47.24
Fe	43.75	36.95	36.40	36.75

	5	6	7
TiO_2	54.00	41.70	32.00
Fe	40.00	51.84	54.22

Hume also quoted analyses, but his description of the ore as hematite, and his analyses, are so much at variance with every one of the later workers that there must be a mistake in his work which it is best not to perpetuate.

Amin (1954) describes the ore as ilmenite with exsolved hematite blebs and lamellae of average width .002 mm and length .04 mm.

However, there is too much titanium in the analyses for it all to be combined with FeO to form ilmenite (Holman 1953). A mineral of unknown composition has been described by Nekhla, quoted by Holman, which may contain the excess TiO_2.

According to magnetic separation tests on the ore, carried out by Holman (1953), 4.8% of magnetite is present in the weathered ore. The residue left after the separation of the magnetite consisted of two ilmenite products one assaying 54.87% TiO_2 and the other 51.44% TiO_2. The disagreement between the results of petrographic, magnetic separation and chemical investigations calls for more careful work to be carried out on this orebody before a definite conclusion concerning its mineral composition can be arrived at.

The texture of the rock in thin section shows that the ore minerals crystallized later than the silicates. "The deposit was formed by liquid gravity accummulation of a late ilmenite-rich residual fluid". (Amin 1954).

FRENCH COLONIES

FRENCH CAMEROONS

Many small alluvial occurrences of rutile and ilmenite have been recorded in Chron. Min. Colon. and Chron. Min. Fr. d'Outre Mer during the last thirty years. The most important appear to be in the Nyong, Dschang, Banyo and M'banti districts (Jacqueton 1933; Behrend; Callot 1950; Haugou 1933). The latter three regions, near the Nigerian frontier, lie in areas of altered gneiss and granulite. The rutile has been collected from streams sands and laterites and primitively concentrated by natives. Callot (1950) gives 16 analyses of Cameroon rutiles of which the maximum and minimum values are given below.

TiO_2	Fe_2O_3	SiO_2
96.5-98.85%	0.9-2.33%	0.1-1.45%

Gillson (1949) quotes the following production figures for rutile from the Cameroons but gives no indication of the precise source of the concentrates. Presumably it has been obtained from stream placers.

In metric tons.

1935	45	1941	1,399
1936	55	1942	2,153
1937	102	1943	2,750
1938	118	1944	2,902
1939	159	1945	1,046
1940	503		

According to l'Usine Nouvelle (Feb. 1956 53) 207 tons of titanium minerals were exported in 1954.

FRENCH EQUATORIAL AFRICA

Brustier (1923) records the occurrence of rutile in alluvial material near Baveke on the Apko river, and rutile in quartzite near N'Dacire. Ilmenite and rutile occur in the river terraces of the Moyen Congo according to Chron. Min. Colon 3 (1934) 218.

Lawthers (1956) states that the production of rutile from the French Cameroons and French Equatorial Africa was 14,720 tons between 1941-50.

DAHOMEY

Rutile, ilmenite, ilmenorutile and titaniferous magnetite are all found in Dahomey. None of them has been commercially exploited.

Rutile Deposits

Djougou.- A small rutile deposit in gneiss is recorded to occur at Djougou, cercle de Parakou. It is 150 km from the railhead at Parakou. An analysis is given:- TiO_2 95.5%, SiO_2 1.8%, Fe_2O_3 2.1%, N.D. 0.65% (Chermette 1938).

Birni.- Rutile of low grade is found in amphibolite and quartz veins in biotite gneiss over an area of 20 sq. km at Birni, cercle de Natitingou. (Chermette 1938).

Gouboco.- At Gouboco, cercle de Natitingou, eluvial rutile of grade 100 gr./sq. m. covers an area 6 km x 200 m. The deposit probably contains only a few hundred tons of rutile. The bedrock is amphibolite veined with quartz (Chermette 1938).

Rutile Analyses	TiO_2	SiO_2	Fe_2O_3	N.D.
	96.6	1.6	1.3	0.42
	95.0	2.4	1.8	0.79

Kouande.- Workable rutile deposits are reported to occur at Kouande (Mathews Min. Yrbk. 1943). Chemische Ind. 722 (1956) reports that this deposit will be worked by the Soc. M du D-N.

Ilmenorutile Deposits

Ilmenorutile, which is almost certainly a mixture of ilmenite and rutile and not a separate mineral identity, occurs in small concentrations in the Bassin du Keran (Chermette 1938).

Analyses	TiO_2	SiO_2	Fe_2O_3	FeO
	69.5	1.87	6.8	20.2
	76.3	0.35	3.9	19.5

Ilmenite Deposits

An ilmenite deposit associated with a band of amphibolite outcrops at Couffo, cercle d'Abomey. (Rev. de l'Ind. Min.(1932)pt. 2 442; Chermette (1938); Chron. Min. Colon 16 (1933) 355). The deposit is 2 km long and 500 yds wide. It is 150 km from the coast.

Analyses (Chermette).

	TiO_2	SiO_2	Fe_2O_3	FeO	Al_2O_3	CaO
1.	44.1	0.4	16.1	39.6	-	-
2.	36.8	3.1	23.7	33.1	2.5	0.6
3.	34.8	0.6	32.2	31.4	0.4	0.4
4.	29.7	-	43.1	26.8	-	-

Chermette describes the ilmenite as an intergrowth of crichtonite and hematite.

Titaniferous Magnetite Deposits

Mardaga.- Titaniferous magnetite ore associated with a gabbro massif is known to exist at Mardaga, cercle de Fada N'Gourma, Niger, just over the Dahomey border. It is 600 km from the railhead (Chermette 1938). A similar deposit has been found at Firu near Atacora (Lat. 11°N 2°E long). (Behrend).

Analysis (Mardaga ore)

TiO_2	SiO_2	Fe_2O_3	FeO	Al_2O_3	CaO	MgO	NaO	P
14.7	4.2	70.3	0.62	3.96	0.3	3.2	1.05	.07

FRENCH TOGOLAND

Chermette (1949) records the presence of rutile in the Bafilo region and suggests hand picking by natives as a method of concentrating the material.

IVORY COAST (COTE D'IVOIRE)

Deposits of ilmenite lying between the Cavallé and Sassandro rivers were briefly described by de la Rue (1927). The principal deposit is near Blieron, between the Nero river and lake Petit-Digbou, and contains 37.1% TiO_2, which could be raised to 52% by magnetic concentration. Other deposits near San Pedro (Bas Cavally) and between Victory and Monogaga (Bas Sassandra) were also mentioned. Ilmenite sands between the Cavalle and Bandoma rivers at Grand Rabon are mentioned by de la Rue (1932).

A sample of residual sand containing 19% TiO_2, obtained after preliminary panning, is mentioned by de la Rue (1927). It was obtained from Bondouku in the northern Ivory Coast.

SENEGAL

Beach Sands

Beach sands containing ilmenite and zircon have been worked in Senegal since 1912. Three groups of deposits are known:- 1) near St. Louis 100 miles north of Dakar; 2) the Petite Cote from Rufisque near Dakar to the mouth of the Saloum river, a distance of approximately 70 miles; 3) near the Casemance river south of the British territory of Gambia.

The Senegal deposits have been described in varying detail by Leyrat (1932); Orcel (1934); Legoux and Faucheux (1935) and Leyrat and Chartier (1936). The following description is taken principally from Legoux and Faucheux (1935).

In the Rufisque area the black sands are deposited on the beach during high, and particularly storm, tide periods. They occur in bands and lenses of varying thickness (15-40 cms average) which alters annually. The main band usually lies at a depth of 1.5 m. The bands are separated by varying thicknesses of barren or low grade sand. The following ilmenite analyses have been published:

	Rufisque	Casamance
TiO_2	55.8	58.88
FeO	9.3	7.49
Fe_2O_3	32.45	32.90
ZrO_2	-	0.70
SiO_2	0.2	0.30
Al_2O_3	1.42	-
CaO	0.55	-
	99.72	100.27

Other minerals found in the sands in small quantity include magnetite, staurolite and rutile while zircon is an important constituent.

The ilmenite analyses indicate a tenor of TiO_2 above the calculated TiO_2 content of ilmenite. This has led Legoux and Faucheux to describe the mineral as ilmenorutile. Other workers, who have found similarly high TiO_2 contents in secondary ilmenite deposits, have called the mineral arizonite. It has recently been shewn that the mineral is ilmenite which has suffered alteration with loss of Fe and consequent increase in TiO_2 percentage (see beach sand section of geological report).

At Joal near the mouth of the Saloum river, the sands are carried over an offshore bar during storm periods, accumulating over the years into large deposits. (Youngman 1930).

The composition of the black sands varies somewhat from locality to locality but ilmenite is always the dominant mineral with zircon next in abundance. The following figures are given by Legoux and Faucheux:-

Petite Cote sands

Ilmenite	Zircom	Other constituents mainly quartz
27-62%	7-23%	20-59%

The sands of Casamance are of equally high grade but do not appear to occur in sufficient quantity to justify exploitation.

Origin of the Deposits.- De la Rue (1932) stated that the minerals originate from submarine basalts off the Senegal coast, but Legoux and Faucheux have shewn that the sands cannot have originated from the basalts exposed on the peninsula of Cap Vert because of the grain size of the ilmenite in the basalts which is less than 0.1 mm, while the size of the sand grains varies from 0.12-0.20 mm and these are weathered and rounded grains. Also the basalts contain no zircon. Legoux and Faucheux know of no coastal rocks in Senegal capable of providing ilmenite and zircon. They sum up thus "....une origine differente doive etre recherchee, sous-marine et peut-etre lointaine." Legoux and Faucheux were looking for an ilmenite-rich rock as the source for their sands whereas in fact that is not necessary. It is most probable that the Tertiary rocks of the coastal areas of Senegal, perhaps with additions from the Colony complex of Sierra Leone, are the source of the ilmenite.

Reserves and Exports.- Considerable reserves of ilmenite must exist on the Senegal beaches and it appears that the region near Joal at the Saloum river mouth is the richest. Youngman (1930) describes in detail the history of the deposits up to 1929. Two new plants to provide ilmenite, rutile and zircon concentrates have since been built, one at Rufisque and the other at St. Gomer near the Saloum River mouth. (C.T.J. 133 1953 822). Chem. Eng. News (1955) 5064 reports the construction of a plant at Joal which is to treat 60,000 tons of sand per annum to yield 30,000 tons ilmenite, 2,000 tons rutile and 4,000 tons zircon. At Djifere the Soc. Gaziello is producing ilmenite concentrates. "In 1955, 80,000 tons of titaniferous sands were treated and more than 25,000 tons of ilmenite concentrates were produced." (Chemische Ind. No. 12 1956 722).

The following export figures of ilmenite and zircon are available.

		Metric Tons			Metric Tons
1	1912	350	1	1931	370
1	1913	52	2	1932	0
1	1922	5	2	1933	375
1	1923	492	1	1934	487
1	1924	436	3	1935	3,810
1	1925	181	3	1936	3,912
1	1926	5,745	3	1937	3,176
1	1927	5,200	3	1938	8,436
1	1928	6,100	3	1939	0
1	1929	7,240	3	1940	5,798
1	1930	2,300	3	1941	895

1. Legoux and Faucheux (1935).
2. Chron. Min. Colon. 16 (1933) 355.
3. Gillson (1949) (ilmenite concentrates only).

11,741 metric tons of titanium mineral were exported from French West Africa as a whole in 1954. (L'Usine Nouv. 1956 Feb. 53).

FRENCH SUDAN + MAURETANIA

The occurrence of ilmenite was reported in the Bafoulabe districts of French Sudan and Mauretania in Rep. Ann. Serv. Geol. Af. Occ. Fr. (1935) 144. Dropsy (1943) carried out a granulometric study of some sands in littoral dunes at El Manghar (Mauretania) and recorded the presence of the following minerals; zircon, ilmenite, garnet, tourmaline, monazite, sphene, hornblende and biotite. The El Manghar deposit was considered to be a possible commercial proposition.

ALGERIA

Sand Deposits.- Ilmenite and magnetite are supposedly accumulated in the sand dunes of Biskra in the Souf district of north-east Algeria

(Bellair 1940 quoted by Lawthers).

Rock Deposits.- Numerous bodies of ilmenite and titaniferous magnetite are associated with various basic intrusive masses in Algeria (Lawthers). According to Chimie et Industrie (155 1956), titanium minerals have been reported in the Hoggar region. Ilmenite 'enclaves', projection products of the Hoggar volcano, have also been described.

MADAGASCAR

Hard Rock Deposits

Ambatofinandrahana.- Rutile was worked here during the 1914-18 war, a total of 200 tons of $TiCl_4$ being produced from it. The rutile occurs in micaschist. (Chron. Min. Colon. 16 1933 355).

Rutile, ilmenite and titaniferous iron ore deposits have been mentioned and very briefly described by Lacroix (1920a; 1920b; 1922), and Lawthers. The more important deposits are as follows.

Vangoa River.- A deposit of ilmenite-magnetite lies in the valley of the Vangoa river, a tributary of the Miandiwazo. The ore analyses 51.4% TiO_2 and consists of ilmenite and magnetite each containing exsolution lamellae of the other (Lacroix). Residual deposits, presumably associated with this occurrence, analyse 1-20% TiO_2. There are over 20,000 tons of ore (Lawthers).

Betroka.- A deposit of ilmenite or titaniferous magnetite at this locality contains 27% TiO_2 (Lacroix 1920b) to 40% TiO_2 (Robinson 1922). There are 3.5 million tons of 'ilmenite'.

Other titaniferous magnetite deposits are reported to occur at 1) Volovolo, Bekily region 2) Ankatrafey, Androngovato (Lacroix 1920a) 3) Lavailila 4) Ianakafy 5) Beloza river headwaters. (Lawthers 1956).

Beach Sand Deposits

Beach sands on the east and south coasts of Madagascar have been examined for ilmenite and monazite. (Behier 1954). The reserves are estimated to be 800,000 tons containing 23-65% ilmenite and up to 3.1% monazite on the south coast beaches. Five chemical analyses of ilmenite concentrates are given. Financial groups were supposed to be investigating the economic possibilities of the deposits (Metal Bull. 28 1954).

REUNION

Ilmenite-magnetite sands derived from basalt are found on the island of Reunion. (Lacroix 1932; Blondel 1934). The sands were analysed in 1878 by Velam and in 1874 by Lahuppe.

	TiO_2	$FeO + Fe_2O_3$	SiO_2
Lahuppe	23%	71.6%	3.8%
Velam	20%		

after separation of magnetite.

These sands are unlikely to be of value because they are derived directly from basalt and much of the TiO_2 will be in solid solution and in exsolved lamellae of ilmenite within the magnetite.

GHANA

Ilmenite and rutile are widespread minerals in many of the basement Pre-Cambrian rocks of Ghana, although no potential orebodies are known to occur. Fluvial and beach sand concentrations of both rutile and ilmenite have frequently been recorded to occur, although none are, apparently, of economic significance.

Beach Sands

The coastal beach sands of Ghana contain local accumulations of ilmenite and other heavy minerals. At Mankwadzi, four miles west of Winneba, a beach 600 yards in length contains layers of black sand in the inter-tidal zone which is between 25 and 30 yards wide. At the back of the beach a limited area of dune sands contains no marked concentrations of heavy minerals. The ilmenite in the sands, and probably the bulk of the heavy minerals have been derived from the Upper Birrimian amphibolites of the Winneba-Saltpond area. (Layton private communication).

The heavy mineral content of a sample of these sands taken from a trench through a black lensoid patch, slightly concentrated by panning, was as follows:-

Ilmenite	60%	Staurolite	8%
Magnetite	3%	Garnet	10%
Rutile	4%	Monazite	2.5%
Zircon	9%	Cassiterite	0.5%

Ilmenite also occurs in a number of other beaches along the coast of Ghana but no details of the occurrences are available.

Other Deposits

Ilmenite.- The sands in stream beds of the andesite areas of the Western Province contain ilmenite (Geol. Surv. Dept. Rep. 1921). Ilmenite from the diamondiferous concentrates found in the gravels of Yamawaka Creek, 2 miles east of Asamang has the following composition.

FeO	MgO	TiO_2
22.84%	0.32%	49.48%

(Geol. Surv. Dept. Rept. 1934-5).

Aggolomerates near the Tain river, in the Sunyani and Wenchi districts (Geol. Surv. Dept. Rep. 1933-4 11) and stream concentrates in the Birim gold and diamond field (Geol. Surv. Dept. Rep. 1934-5) also contain ilmenite.

Rutile.- The existence of rutile in stream and river gravels has been reported on a number of occasions. It occurs in the Jagulo area (Geol. Surv. Dept. Rep. 1926-7); in gravels near Matsi, north of Ho, Togoland (Rept. to the Council of the League of Nations (1936); and in the Birim valley gold field and in gravels from Klemm stream and the Bluvu river (Junner 1935). There is no record of any production from these localities.

Kitson (1925a:b) reported that rutile was a constituent mineral of pegmatites in the Tarkwa and Somanya-Agomeda districts.

LIBERIA

"The Columbia-Southern Chemicals Corp. will soon begin exploratory operations.... in search of titanium-bearing ores. The explorations are being carried out under a Concession Agreement, dated June 1956, between the Company, and the Liberian Government." (Chem. Eng. News 34 (1956) 6311) (Wall Street Journ. 148 (1956) 15).

MOROCCO

Beach sands at the mouths of the Oum and Rbia rivers at Azemmour contain 12% TiO_2. The river sands contain 9% and dune sands 4% TiO_2. (Chron. Min. Colon. 4 1935 193): (Agard + Permingeat 1952).

Lamke (1937) reports that sands near Casablanca contain 19% magnetite and 38% ilmenite.

PORTUGUESE COLONIES

ANGOLA

Hard Rock Deposits

Vieira (1952) records the following titaniferous iron ore occurrences.

Mbassa.- Near Mbassa on the Lucale river, north of Dondo, 28 km south east of Zenza do Itombe, at least 6.5 million tons of ore are associated with gabbro norite, peridotite and hornblendite as a magmatic segregation.

An analysis of the ore gave, Fe 56.1%, SiO_2 8.7%, TiO_2 2.8%.

Chitado.- Near the Cumene river, close to the southern boundary of the territory, ilmenite-magnetite ore occurs as a differentiate of a 6,000 sq. km anorthosite massif. The amount of the reserves is unknown but certainly exceeds six million tons.

Analysis %	Fe	FeO	Fe_2O_3	SiO_2	TiO_2	P_2O_5
	48.3	31.3	34.3	2.8	25.6	.02

Several other occurences similar in nature to the Chitado deposit are known in the Gambos-Pocolo-Otchinjau region between Chitado and Chibia.

The region in which all these latter deposits are situated is almost completely devoid of good communications. The only waterway is the Cumene river concerning which no details are available.

CAPE VERDE ISLANDS

Magnetite and ilmenite occur in beach sands of the Cape Verde Islands. (Bebiano 1932). These are presumably derived from basalt lava flows in their near vicinity, in which case they are unlikely to be of much commercial value.

MOCAMBIQUE

Beach sand and hard rock deposits are known to occur in Mocambique.

Beach Sand Deposits

Black beach sands have recently been reported to occur at the mouth of the Inkomati river, 30 km north of Lourenco Marques. The following information is available concerning a Mocambique beach sand deposit (private source).

Composition:- Ilmenite, Brookite, and Columbite 71.0%, Zircon 10.2%, Rutile 5.1%, Monazite 6.1%, Quartz 6.6%, Magnetite 1.0%. These percentages were obtained by wet tabling and magnetic separation.

Analysis of sand.

	SiO_2	TiO_2	Fe	Al_2O_3	MgO	Hf	Ta_2O_5	Cb_2O_5	ZrO_2	SnO_2
%	2.11	48.07	10.16	1.00	2.04	3.00	2.05	1.00	27.6	1.60

Mineral analyses.

	SiO_2	TiO_2	ZrO_2	Fe_2O_3	P_2O_5	ThO_2	CeO_2	Other rare earth oxides
Monazite	0.06	0.49	3.48	1.5	27.6	6.7	10.3	49.8
Rutile	1.08	93.15	-	5.76	-	-	-	-
Zircon	30.7		63.5	0.35	Al_2O_3 5.4			
Ilmenite, brookite etc.	0.64	53.85		FeO 45.4	-	-	-	-

No reserve quantities are known.

Hard Rock Deposits

Two deposits are known; one is at Mawili the other at Kakanga. (Legraye 1939).

<u>Mawili</u>.- The Mawili occurrence is a lenticular mass of ore enclosed in later dolerite, not connected genetically with the ore, which is

in turn enclosed in anorthosite. The ore is described as titaniferous magnetite containing exsolution lamellae of magnetite and ilmenite. From a drawing of the ore, taken from a polished section, the ilmenite appears to be replacing the magnetite and titaniferous magnetite. The intermixing of the constituents occurs on such a fine scale that the ore is unlikely to be of economic value. The effect of the dolerite intrusion is not discussed but may have been of great importance, causing a radical change in the texture of the ore. The following analyses are given:

	SiO_2	Al_2O_3	Fe	Fe_3O_4	TiO_2	MgO	SnO_2	CuO	Loss to Fe correction
1.	6.10	6.21	50.85	70.17	10.82	1.55	0.85	0.26	3.41
2.	2.2	6.21	52.10	71.90	13.29	1.74	1.15	0.23	2.90
3.	6.35	7.43	51.12	70.55	9.72	2.00	0.88	0.28	2.25
4.	3.30	7.16	51.75	71.42	13.08	0.90	1.14	0.21	2.18
5.	5.26	7.95	51.25	70.73	11.26	2.00	0.98	0.21	1.42

Kakanga.- The Kakanga ore body is smaller than the Mawili deposit and no details of the host rock are available. The ore consists of granular ilmenite and titanomagnetite; the grains are 1-2 mm in diameter.

The following analyses are given by Evrard (1949).

	TiO_2	Fe_2O_3	FeO
a)	24.0	38.0	33.0
b)	8.25	56.0	32.0
c)	43.12	19.0	34.0

a) is titanomagnetite and ilmenite ore.
b) is the magnetic fraction after crushing.
c) is the non-magnetic (ilmenite) fraction.

From the analyses it is apparent that either hematite is present in some form, or Fe_2O_3 is present as an oxidation product of the ferrous iron in the ore.

SPANISH POSSESSIONS

CANARY ISLANDS

Mathews (Min. Yearbook 1942) reports the presence of workable beach sands in the Canary Islands. Barcelo (1945) gives analyses of five samples of black beach sands containing TiO_2. The ilmenite in the sands, as a derivative of basaltic lavas, is probably of no commercial value at the present time.

UNION OF SOUTH AFRICA

The Union of South Africa contains the largest known reserves of titaniferous magnetite in the world, and probably the largest reserves of ilmenite-rich beach sands. The titaniferous magnetite deposits are associated with the Bushveld igneous complex. These deposits have been investigated to ascertain their economic possibilities and, despite the enormous reserves, it appears unlikely that they will be used for many years owing to metallurgical difficulties encountered during purification processes.

The beach sand deposits, the most important of which lie on the south and east coasts of the Union, have been fully investigated only in recent years and very little detailed information regarding them has yet been published. Many of the beach sand deposits lie within native reserve areas and as a result it is not likely that the government will make them available for exploitation. In this thesis the beach sand deposits will be dealt with first, since they are potentially the most important economically.

Beach Sand Deposits

Cape Province.- The beaches of the eastern Cape Province may well prove to be the richest ilmenite deposits in the world. Certainly those concentrations of ilmenite which have so far been reported are equal to those of any other known deposit.

Morgan's Bay beaches contain, "a high proportion of ilmenite varying from 8-90% over an area of 1 x 1½ miles down to a depth of 300' in one section and over an area of 4 x 1 miles to a depth of 50' in another." (Chem. Age 68 (1953) 758). The building of laboratories and the installation of machinery is reported to have commenced. According to Chem. Age 69 1028, Morgan's Bay is one of the richest titanium deposits in the world. (See also C.T.J. 130 and 131 1952).

The beach deposits near Port St. Johns, which is halfway between East London and Durban, Natal, are probably similar in character to the Morgan's Bay deposits. The Port St. Johns beaches are grouped into three units from south-west to north-east. 1) Intafufu beaches 2) Ingo beaches 3) Umzunhlava-Umzunpuni beaches. From the description of the deposits, (private source 1954) the ilmenite occurs in bands, of concentration varying from 20%-80% and averaging 50%, beneath the present day beach at a depth of approximately 1', and beneath the foredune and parallel dunes a short distance inland, at varying depths. The highest heavy mineral concentrations occur at the north end of beaches, "on the lee side of the promontaries, presumably as a result of the south-west coastal current." The sand other than that in the black bands contains 0-5% ilmenite.

On the Intafufu south beach 100,000 tons of ilmenite occur in a band 2 ft thick (average) underlying an area 800 yds wide. This is only one beach of several and no account is taken of any deposit beneath inland dunes of which the existence but not the areal extent is recorded. An estimate of half a million tons of ilmenite reserves in the St. Johns beaches was made.

Chem. Ztg. 80 (1956) 331 reports that American industrial articles are already interested in exploiting the black sand deposits which occur halfway between East London and Durban. The Rand Daily Mail (22.11.55) records that deposits of titanium, over a 250 mile stretch of the coast from the Great Kei river to the Natal border, have been prospected.

Recent dune sands of the Cape Flats near Faure contain 1% of heavy minerals of which 30% is zircon, 27% ilmenite, 15% leucoxene and 3% rutile. (Wyo and Reitz 1944).

Natal.- Ilmenite-bearing beach sands have been known to occur in Natal certainly since 1938 when Partridge (1938) analysed sands from beaches and dunes at Durban. The beach sands apparently contained 5-90% of heavy minerals of which ilmenite 70-85%, zircon 7-9% and garnet 2-6% were the principal constituents. The S. Af. Min. Eng. J. 54 (1943) 467 records the occurrence of ilmenite and zircon sands in Natal. The reserves of ilmenite in the coastal sands was thought to be large, but large areas were thought to be unworkable due to town land restrictions and the high cost of land because of a) holiday resorts and b) sugarcane plantations. (Frankel, Schady and Duplessis 1951a, 1951b; Masson 1953).

However, C.T.J. 132 (1953) reported that the Titanium Corporation of S. Africa expected to commence working Durban beach sands in 1953 and Chem. Ing. Technik. 10 (1954) 592, envisaged a production of 6,000 tons ilmenite, 6,000 tons of zircon and 3,500 tons rutile in 1954. A titanium mine at Isipingo near Durban started a production of 30 tons daily in January 1957. (Chem. Zeitung 20.2.57 133).

Metal Bull. 4193 (1957) 24 and Chem. Eng. News 35 (1957) 90 both reported that the Anglo American Corporation of South Africa was shortly to commence the extraction of ilmenite, zircon and rutile from beach sands at Umgababa on the south coast of Natal.

South West Africa.- Deposits of ilmenite sand are found along the S.W.A. coast near Swakopmund. (Frankel, Schady and Duplessis 1951; World Min. 71 1954; C.T.J. 133 1953; Chem. Age 71 1954). The heavy mineral content varied from 4-87%. Ilmenite and magnetite were present in the beach sand in a ratio of 1.6:1 and in the dune sand in a ratio of 1:1. Inaccessibility and lack of local water supplies are likely to militate against economic exploitation of these deposits.

Hard Rock Deposits

Large and small hard rock deposits of ilmenite, rutile and titaniferous magnetite have been recorded from a wide variety of localities within the Union. So far as is known none of these have been worked on any but a very small scale and while the beach sands of Natal and Cape Province are available are unlikely to be worked for their titanium content.

Transvaal. Titaniferous Iron Ores in the Bushveld Complex.- The Bushveld lopolithic igneous body is a saucer shaped mass of basic igneous rocks containing actual and potential ores of chromite, platinum and titaniferous magnetite. Titanium bearing minerals "occur as persistent sheets or short stout lenses of solid ore following one or more horizons in the upper part of the norite zone." (Wagner 1928). The layers range in thickness from 0-10' but at Magnet Heights they reach a thickness of 20'. They dip towards the centre of the complex at angles of 5–30°. A typical section at Magnet Heights (Hall 1932) is as follows.

Pyroxenitic norite	
Magnetite bands	1'
Norite	20'
Magnetite band	1'
Pyroxenitic norite	12'
Magnetite band	6'
Mottled anorthosite	

The ore reserves at Magnet Heights, which lie 100 miles to the north-east of Pretoria, are 560 million tons. The estimated iron-titanium ore content of the whole complex is 2,376.6 million tons.

Analyses (Wagner (1928) and Walker (1930)) of ore from Onderspoort, Mamagalieskraal, Rhenosterfontein, and Magnet Heights show the following variations in titanium, iron, chromium and vanadium content.

	TiO_2	FeO	Fe_2O_3	Cr_2O_3	V_2O_5
%	15.5–20.1	5.0–28.5	49.4–73.75	0.0–0.65	0–1.2

Hall (1938) quotes many analyses of Bushveld ores from Onderstepoort in which the TiO_2 content varies from 2.04–20.1%.

The mineralogical content of the ore is very variable but always contains magnetite, titaniferous magnetite and ilmenite and may contain maghemite, hematite, possibly coulsonite and secondary iron oxide minerals. The high content of Fe_2O_3 in the analysed specimens is in part due to the presence of maghemite γ Fe_2O_3 which is now thought to be a secondary oxidation product in contrast to the views of Wagner (1928); Frankel and Grainger (1941) and Schwellnus and Willemse (1944).

Frankel and Grainger (1941) record the presence of two different ore types (1) equigranular polygonal ore grains, of average diameter 3 mm, fitting closely together with little intergranular material and (2) larger grains with ill-defined shape, with interstitial material consisting of ilmenite and hydrated iron oxides. The bulk of the grains consists of magnetite with ilmenite lamellae, and maghemite. Ilmenite occurs in three ways (1) as interstitial lathe shaped particles 5-6 mm long and 1 mm wide; (2) as individual grains, occasionally twinned, up to a size of 5 x 13 mm and (3) as inclusions in magnetite and maghemite 5 microns x 18 microns size.

Schwellnus and Willemse carried out concentration tests on ore material from a number of different localities with unpromising results. After magnetically separating ore crushed to 60 mesh they found that on average only 12% of non-magnetic material remained which analysed (approx. average) 26% TiO_2. Very little admixed silicate was present. Only one sample, taken from an ore band at Lydenburg, showed any promise as a titanium ore. The non-magnetic concentrate, 17.8% of the original, and the magnetic fraction analysed as follows:

%	SiO_2	TiO_2	V_2O_5	Cr_2O_3	FeO	Fe_2O_3
Non-Magnetic fraction	2.42	42.70	0.36	0.03	33.05	14.37
Magnetic fraction	0.76	10.56	1.50	0.46	9.20	70.42

The analysis of the non-magnetic concentrate shows that it is possibly just of commercial value.

The origin of the titaniferous magnetite ores of the Bushveld complex has been and still is a matter for controversy. Wagner (1928) considered them to be gravitative accumulations of early formed crystals but Hall (1932) showed that the ore minerals crystallised after the silicate minerals. Many workers considered the ores to be later injections, others have put forward a metasomatic origin for them. Bateman (1942) has summarised the views which are more carefully considered in the geological section of this thesis.

Van Eeden (1939); Mendelsohn (1939) and Hall (1912) have described titaniferous magnetite in the Murchison range, Transvaal.

Wagner (1928) mentions the occurrences of ore containing 18% TiO_2 in a small offshoot of the Bushveld complex at Dwarsfontein and Brakfontein and ore containing 13% TiO_2 at Kaffirskraal fourteen miles south-west of Heidelberg.

Other Hard Rock Deposits in the Transvaal.- Wagner (1928) records the occurrence of a gabbro, intrusive into Pongola beds near Piet Retief, which contains titaniferous magnetite with a TiO_2 content of 5-6%.

Karroo sandstones, 55 miles from Johannesburg, contain concentrations of ilmenite and leucoxene. High grade rock containing 35-44% TiO_2 is present at a depth of 0-10' below the surface. Reserves 250,000 tons. Low grade rock containing 20-35% TiO_2 is present down to depths of 25'. Reserves 350,000 tons (Private report). A similar deposit near Argen has also been described.

Chem. Comm. Journ. Aug. 1924 reports the occurrence near Barberton of rutile in 50 lb. lumps in lateritic soil overlying a corundum, tourmaline, rutile, talc, epidote hornfels. The occurrence is not thought to be of economic significance.

Consolidated black sands of Cambrian age containing magnetite, ? ilmenite, hematite, rutile and zircon, with estimated reserves of 12 million tons, have been reported from the Keemanshoop District. (Iron Deposits in the Union S. Africa XIX Int. Geol. Cong. VI. 261).

Natal.- Rich, lenticular deposits of titaniferous magnetite have been described from Insumbene hill on the river Tugela below Middle Drift. The ore body is 75 metres thick in places and contains 100 million tons of ore (Harvey 1951-2). According to Wagner (1928) the ore reserve was 15 million tons. The ore consists of ilmenite and magnetite 'coalescences' which presumably means exsolution intergrowths of one in the other. The grain size of the ore is 0.3-1.2 mm. The ore body is an injection associated with anorthosite. (Du Toit 1918).

South West Africa.- At Okurusu 48 km north of Otjiwarengo, 19 km west of Otjikongo, titaniferous magnetite now altered to hematite occurs as a replacement deposit in crystalline limestone. It is developed at the contact of extensive replacement sheets of fluorite. The ore reserve is estimated to be 40 million metric tons. An analysis of the ore is given below (Joubert 1952; Berg 1942).

Total Fe as FeO	MnO	SiO_2	CaO	TiO_2	Pb,Cu,Au
78%	1%	1%	0.42%	7.33%	Traces

The ore is genetically associated with alkaline intrusive rocks.

At Giftkuppe in the Omaruru region a quartz-albite-pegmatite containing 5% TiO_2 as rutile was worked in 1936-1937 when 74 tons of rutile analysing 95% TiO_2 was produced. (Berg 1942, Frommurze 1942).

At Otjisongati, Damaraland and at the Khan mine, Arandis, ilmenite, rutile and sphene are recorded to occur in copper bearing pegmatites. It is not recorded whether or not concentrates have been produced. Berg (1942).

Alluvial Deposits

Alluvial concentrates in sands from the Kuils river, Cape Province contain zircon 57%, ilmenite 27%, cassiterite 2%, and tourmaline 2%, with many other minerals in very small quantities. The minerals are derived from the Table Mountain sandstone, and granite intrusive into the Malmesbury series (Conradie + Rabie 1944).

UNION OF SOUTHERN RHODESIA, NORTHERN RHODESIA, AND NYASALAND

Southern Rhodesia

Ilmenite.- Ilmenite and titaniferous magnetite occur in kimberlite in the Benibesi diamond field (Rhodesia Mus. 9th Ann Rept. 1910 43; McGregor 1916). The ilmenite is often intergrowth with diopside. The occurrence is unlikely to be of economic significance unless there are concentrations of ilmenite on mine dumps.

Ilmenite is supposed to be abundant in many river gravels. (Rhodesia Mus. Rept. 1910).

Rutile.- Occurrences of rutile are marked on the Provisional Mineral Map of Southern Rhodesia (Geological Survey 1956). A deposit near Wankie in the western part of the state has yielded an unknown quantity of concentrate. Rutile also occurs near Miami, about 100 miles north-west of Salisbury.

Nyasaland

Port Herald Area.- Sand deposits of economic grade occur in the Shire river valley near Port Herald, and hard rock occurrences of ilmenite are known in the nearby Port Herald hills.

The occurrence of ilmenite and magnetite in "quartzite" of the

Nachipere series along the Naminjale and Nankande streams in the Port Herald hills was first described by Dixey (1930). However before that, in the Imperial Inst. Bull. 15 (1917) 84-5, the receipt of samples of ilmenite and rutile from a vein in gneiss on the Nankande river is recorded. The results of analysis were TiO_2 75.04%, Fe_2O_3 11.86%, FeO 11.56%. The samples were described as "50% rutile the remainder chiefly ilmenite". Brief reference to the occurrence of ilmenite was made in a report on the Mineral Survey of Nyasaland 1906-9.

Savage (1935) described the mineral deposits of the Port Herald hills in some detail. He mentioned three separate deposits the Naminjale, Chiradzulu, and Nkande, and reproduced maps of each deposit with a key map for their general location. The deposits were described as ilmenite-magnetite veins and stringers enclosed in "quartzite" which is now known to be anorthosite. Sometimes bronzite occurs with the ore minerals. The 'quartzites' were found to be interbedded with nepheline-bearing gneisses. Considerable quantities of eluvial and alluvial ore-bearing material were found in the stream beds and on the hillside. Savage estimated conservatively at 1,000,000 tons of ore of all types.

The following analyses of eluvial rubble ilmenite are given in Ann. Rept. Geol. Surv. Nyasaland (1936) 19-20.

SiO_2	TiO_2	FeO	Fe_2O_3	Al_2O_3	MnO	Cr_2O_3	V_2O_5	MgO	H_2O
0.62	45.71	34.65	16.06	0.2	0.2	0.24	0.42	1.9	0.41
0.78	43.76	35.6	16.69	0.24	0.2	0.27	0.43	2.03	0.34

Two samples of sand from the Nkande stream contained

Ilmenite conc. %	Magnetite conc. %	% Non-magnetic (garnet)
41.9 (50.78% TiO_2)	1.2	56.9
37.0 (48.4% TiO_2)	0.7	62.3

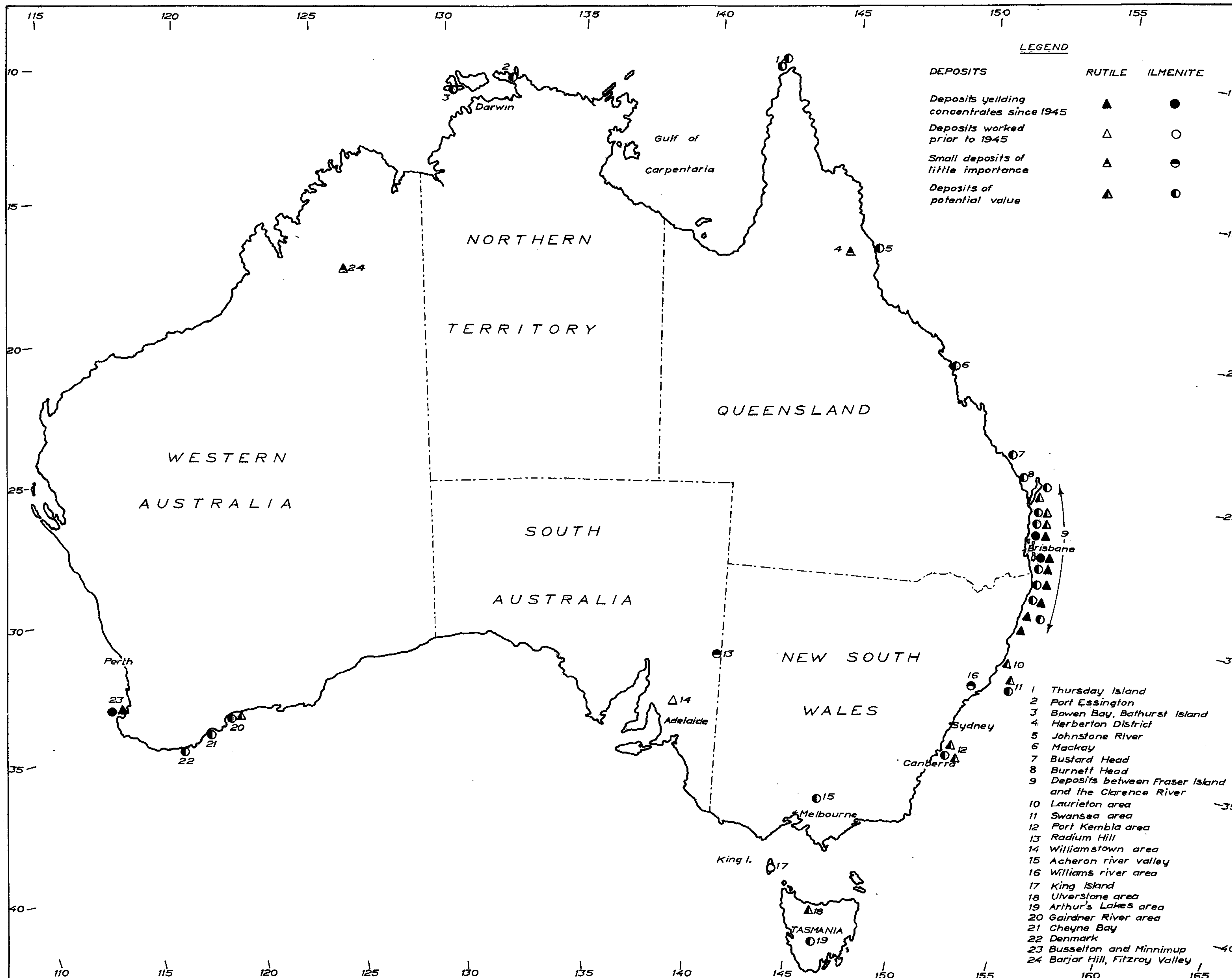
To the east of the Port Herald hills, in the broad flat valley of the Shire river, there are at least 200 ft of unconsolidated fill forming the floor of the valley. It has been demonstrated that this colluvium, as in the case of the valley floor sediments throughout the length of the Shire river's course, has been derived directly from the adjacent rocks in the hills. The mineralogy of the colluvium reflects the mineralogy of the hard rocks with remarkable precision. As a result of this unusual similarity the valley floor sediments in the neighbourhood of Tengani contain appreciable amounts of rutile and ilmenite. These potential ore deposits were investigated by Minerals Reserve Syndicate (Rhodesian Min. Rev. 20 (1955) 23) who held an E.P.L. for the area. This has since lapsed and prospecting is now being undertaken by Laporte Titanium Ltd. An analysis of an ilmenite concentrate is given below.

TiO_2	FeO	Fe_2O_3	MnO	Cr_2O_3	V_2O_5	P_2O_5	Insol.
46.6	31.9	14.4	0.6	0.21	0.16	0.05	6.7

Fort Johnstone Area.- Chem. Age 125 (1956) 579 reported the existence of radioactive sands near Fort Johnstone containing 59% ilmenite and magnetite, and smaller quantities of monazite.

Blantyre Area.- Stream sand concentrates in the Blantyre-Limbe area consist of approximately 60% ilmenite, 30% magnetite and some zircon (Nyasaland Geol. Surv. Ann. Rept. 1950 3-5).

TITANIUM – MINERAL DEPOSITS OF AUSTRALIA.



CHAPTER VI

AUSTRALASIA

AUSTRALIA

The Commonwealth of Australia is the world's largest producer of rutile, which is mined from the beaches of New South Wales and Queensland. Ilmenite, largely useless on account of its high chromic oxide content, is produced as a by-product of the rutile mining. Ilmenite of acceptable commercial grade is being produced in increasing quantities in West Australia.

Beach Sand Deposits

Eastern Australia.- All the rutile produced in Australia is obtained, together with zircon and ilmenite, from naturally concentrated sources on or adjacent to the beaches of the eastern coast. The most southerly deposit which has been worked is at Swansea, New South Wales, 60 miles north of Sydney, and leases have been taken up as far north as Fraser Island, Queensland 170 miles from the New South Wales border. Most of the production has come from the stretch of coast between Byron Bay and Stradbroke Island.

The zircon, rutile and ilmenite is mined from the beaches and from deposits lying beneath dunes just inland from the beaches. The heavy mineral deposits in the beaches are flat lying seams which have been formed between low and high tide levels. They are thickest on their land-ward side against the foredune and thin seawards. The deposits are formed during storm periods by concentration by wave action, the lighter minerals being washed away leaving the heavy minerals on the beach. These are later covered by sand deposited during calmer weather. The set of the surf, from the south-east, is important in forming the richest deposits which are usually found built up on the south side of a headland whence they have been swept by the general longshore drift instigated by the south-east winds. Deposits such as these may be five feet thick near the headland.

For a more detailed consideration of the geology and genesis of the deposits, the mineral distribution within them, and the factors controlling the distribution, the reader is referred to the geological section of this thesis.

The Beach Sand Heavy Mineral Deposits of Eastern Australia and their reserves in tons according to the latest published information.

Locality	Worked by	Zircon	Rutile	Ilmenite	Monazite	Total
Queensland N-S		22,500	15,000	51,000	500	90,000
Frazer Island beach.+		22,500	15,000	51,000	500	90,000
Hook Point.[2]	Reserves unknown.	Min. % 25	17	56		
Middle Rock.[2] Waddy Point.[2]		22,000	17,000	46,000		87,000
Inskip Point.+		4,100	3,200	12,400	200	20,000
Double Island Point.+		1,600	1,600	6,700	60	10,000
Noosa Head (Paradise Caves)+		3,400	2,800	13,700	140	20,000
Moreton Is-land+	J.Scott Moffatt 1949[1]	17,600	5,900	19,000	300	33,000
North Stradbroke Island Beach+	Tit.&Zirc. Inds.1951[3]	12,800	14,700	14,400	100	42,000
Parallel Dunes	"	156,000	156,000	282,000	2,400	600,000
Transgressive Dunes (low grade)	"	1,680,000	1,620,000	2,580,000	18,000	6,000,000

South Stradroke Island.						
Beach[3]		13,000	14,000	12,000	200	40,000
Foredune		3,400	3,500	3,000	50	10,000
Parallel Dunes, 1000 yds inland.		1,450	1,800	1,700	20	5,000
Southport to Clarence River						
The Spit, Wharfe Road	Min.Dep. Synd. 1951[3]	76,800	71,500	49,300	1,020	204,000
Surfers Paradise to North Nobby	Assoc. Min.Pty. 1951[3]					
North Nobby to South Nobby	"	9,400	7,500	5,900	160	23,000
Burleigh	Min.Dep. Synd.1951[3]					
	Min.Res. Bur.1948[1]	9,200	6,160	10,300	200	26,000
Palm Beach	Rutile Sand Pty.1951[3]					
	Min.Res. Bur.1948[1]	18,900	16,800	10,500	250	47,000
Currumbin (Flat Rock Creek)	Bur.Min. Res.1948[1]	2,850	2,600	1,650	40	7,200
Tugun	Rutile Sands Pty. 1951[3]	20,100	17,800	23,500	110	62,000
New South Wales (North to South)						
Tweeds Head to Fingal Point	Porter & Derrick 1939[1]	23,150	13,250	10,200	285	47,500
Fingal Point to Cudgen Head	Cudgen R.Z. 1951[3]	26,500	22,300	14,100	330	64,000
Cudgen Beach	Tweed Rutile Synd. 1951[3]. Tit. Alloy Div.Nat. Lead 1951[3]	260,000	223,000	136,000	3,500	630,000
Norries Head to Hastings Point.	Alluvial Gold Ltd.?[1]	101,500	62,900	43,900	750	211,000
Inland Dune complex++	Zinc Corp. Ltd.,[3]	19,500	20,400	9,600	180	51,000
Hastings Pt. to Brunswick Head.		38,000	24,800	15,500	570	80,000
Potts Pt. to Brunswick Heads	Metal Recov.Pty. 1951[3]	81,600	68,200	39,300	1,140	193,000

Brunswick Heads to Cape Byron Beach	Metal Recov.Pty. 1951[3]	74,400	35,900	25,100	900	139,000
2¼ miles south ½ mile inland.		2,600	1,675	600	25	5,000
Tallow Beach	Zircon Rutile Ltd. 1951[3]	107,000	55,500	37,200	1,200	206,000
Broken Head to Lennox Head		11,900	6,400	4,000	180	23,000
Seven Mile Beach(Fossil Beach 1¼ miles inland).	Zircon Rutile Ltd. 1951[3]	5,600	4,300	2,100	90	12,000
Ballina to Evans Head		1,900	1,350	1,150	45	4,500
Evans Head to Woody Head Beach	Tit.Alloy Div.[1] Nat.Lead	13,200	8,350	5,900	210	28,000
Macaulays Lead		41,500	27,500	19,000	850	89,500
Cement Lead) Jerusalem Creek)		10,500	7,000	4,900	1,205	(11,500 (10,500
Other Areas South of Clarence River.						
Yamba to Angourie	Porter & Derrick 1939[1]	17,000 tons of concentrates have been produced.				
Wooli	"	11,000 tons of concentrates have been produced.				
Woolgoolga	Coffs Harbour Mins. 1944[1]	1,997 tons of concentrates have been produced.				
Swansea Area[x]	Nat.Mins. Ltd.1951[3]	4,300	4,300	1,400	150	10,000
Laurieton Areas[x]		4,000	3,900	2,000	140	10,000
Perpendicular Point North of Laurieton[x]		9,400	7,000	3,600	80	20,000
Bulli to Port Kembla[x]		1,900	1,850	1,200	35	5,000

Total 3,055,000 tons not including 6,000,000 tons of low grade on North Stradbroke Island.

The above table has been adapted from Gardner (1955) with additions as follows quoted by Lawthers 1954 [x]

1 Fisher (1948)
2 Anon report (1939)
3 Gardner (1951)

Notes + Based on details given by Connah 1948.
s Estimate based on inadequate data.
++ Lowgrade deposits. Estimate only, not included in totals.

Gardner (1955) gives detailed descriptions of the following areas.

1 North Stradbroke Island.
2 Southport to Coolangatta.
3 Tweeds Heads to Potts Point.
4 Potts Point to Brunswick Heads.
5 Brunswick Heads to Broken Head.
6 Seven Mile Beach.
7 Lennox Head to Evans Head.
8 Evans Head to Woody Head.
9 Frazer Island to Moreton Island.
10 South Stradbroke Island to North Labrador.
11 The Spit, Southport.
12 Laurieton Area.
13 Clarence River to Sydney.

Gardner's information is drawn from the following sources Beazley (1948;1950); Connah (1948); C.S.I.R.O. (1948); David (1950); Fisher (1953); Gardner (1951); Morton (1948); Stillwell (1949); Stillwell and Baker (1948); Whitworth (1931).

For further details the reader is referred to Fisher (1948 a:b); Poole (1939); Carlson (1950); Paterson (1953); Jones (1946; 1953).

According to Chem. Age (Jan. 1957 165) an Australian Survey ship has discovered rich submarine heavy mineral deposits off Nambucca Heads north south-west, extending over the ocean floor up to 15 miles from the coast.

East Australian rutile is purer than any of its commercial competitors from other beach sand deposits. It contains, on average, slightly over 97% TiO_2 .

Ilmenite from the East Australian beaches is usually rich in Cr_2O_3 occurring as discrete grains of very small size within the ilmenite. Ilmenite from the beaches at present in production varies in Cr_2O_3 content from 2.5-5.5% and the future for such concentrates does not appear to be very promising. However, ilmenite from the North Stradbroke Island deposits which contain 1.37% Cr_2O_3 (Gardner 1955) have been subjected to magnetic concentration, and it has been shewn that an ilmenite concentrate representing 54% of the original can be produced which contains under 0.3% Cr_2O_3. Ilmenite from the deposits north of Stradbroke Island contains less Cr_2O_3. The following analyses are taken from Donaldson & Stuart (1948), and Gardner (1955):-

Partial Analyses of Ilmenite from various Queensland beach sands.

	TiO_2	Cr_2O_3%
Moreton Island	49.68	1.35
Noosa Heads	50.9	0.35
Inskip Point	52.6	0.9
Bundaberg	51.55	0.01
Facing Island	42.17	0.12
Curtis Island	52.55	0.08
Thursday Island	56.2	0.30

The deposits from Bundaberg to Curtis Island are "too small to be worth working." (Gardner 1955).

Ilmenite from the New South Wales deposits has been studied mineralogically by Curnow and Parry (1955) and, Blaskett and Dunkin (1948). The ilmenite concentrates studied by the former workers were provided by National Minerals Pty. and, although the location of their parent deposit was not quoted, reference to the table (above) listing deposits and mineral reserves, reveals that they probably were derived from the Swansea area. If this assumption is correct then the concentrates may be a-typical of the East Australian deposits because they are located south of the Clarence river. However, an important result of their investigations is that they have managed to shew that, by careful magnetic concentration using an industrial separator, an ilmenite concentrate containing only 0.2% Cr_2O_3 and 50% TiO_2 could be obtained with a recovery of 80%. By roasting this concentrate in air for 15 min. at 700°C and separating it magnetically a concentrate, representing 65% of the original sample, containing 0.05% Cr_2O_3, was produced. However, a study of other experiments which they carried out reveals that some of the TiO_2 of the concentrate thus obtained would be in the form of rutile and not ilmenite, which would not always be an advantage in certain ilmenite treatment processes.

Tasmania.- Ilmenite sands occur in a raised beach deposit on King Island, where known reserves amount to 45,000 tons. In 1933 five hundred and fifty tons were produced but no further work was carried out until further exploration commenced in 1951. A concentrate containing 44.8% TiO_2 is reported to have been produced in 1933. (Gardner 1951; Tasmania Rep. Secretary. Min. 1933 25; Ind. Austr. 80 1928 227; 82 1929 26).

Rutile occurs in the Lewis river gravels (Tasman. Dep. Min. 65 Bull. 44 (1938)) but details concerning grade and quantity are lacking.

Ilmenite occurs in black sands on the north coast of Tasmania (Mathews 1941), but again no details are available.

Victoria.- A deposit containing 200,000 tons of heavy minerals, of average grade 1.5% of heavies, occurs in the Acheron river valley 45 miles east north-east of Melbourne. The concentrates contain 84.5% ilmenite (probably including some magnetite) and 1.5% zircon.

The ilmenite contains 52-55.5% TiO_2 and less than 0.03% Cr_2O_3.

A small deposit containing about 2,000 tons of heavy minerals, averaging 62% ilmenite and 11% rutile occurs at Cape Everard 20 miles south-east of the Camm river. The ilmenite contains 0.45% Cr_2O_3. (Fisher 1949; Gardner 1951).

Northern Territory.- The beaches of Bowen Bay, Cape Fourcrey on Bathurst Island 70 miles north-west of Darwin contain heavy mineral deposits containing 40% ilmenite, 31% rutile and 27% zircon. (Fisher 1949). Dowsett Holdings expect to commence production from these deposits in 1957-8 (Chem. Age 75 (1956) 122).

Deposits of heavy minerals occur on beaches near Record Point, Reef Point and Knocker Bay in Port Essington 120 miles north-east of Darwin. Their content is, approximately, zircon 32%, ilmenite 45.5%, rutile 15% and magnetite 7%. No reserve tonnage figures are available (Fisher 1949).

Western Australia.- Until 1949 there had been no production of titanium minerals in Western Australia. In the years 1949 and 1950, seventy-two and eightyfour tons respectively of ilmenite concentrates were produced for test purposes from, it is believed, Wonnerup. By 1957 Western Titanium No Liability and Cable (1956) were producing ilmenite concentrates. Their combined production capacity was 120,000 tons which was to have been expanded. (Financial Times 156 May 1957 2).

Ilmenite-bearing sands are found on the west coast in the Busselton-Capel-Bunbury area and on the south coast east of Albany. The west coast deposits are those undergoing active exploitation. The south coast deposits are of low grade and are inaccessibly situated.

The heavy minerals of the deposits are derived from the basement schist and gneiss complexes which are either exposed, or covered by only a thin veneer of recent sediments, in both areas. Concentration of the heavy minerals has been effected during a period in which sea level has fluctuated intermittently. The evidence for these fluctuations is afforded by the raised beaches which occur in both areas. In the Busselton area, however, recent emergence has occurred with the development of haffs which has resulted in larger areas of sand being locally available. On the south coast drowned river estuaries indicate a recent submergence which may account for the more limited extent of those deposits.

Busselton Area (McMath 1949).- Heavy mineral accumulations are known to exist and are now being exploited in the Busselton area between Minnimup and Bunker's Bay. The principle deposits are at Bunker's Bay, Wonnerup, Siesta Park and Minnimup. They are found in both the present-day and fossil beach sands immediately behind the beaches.

The beach at Bunker's Bay, 25 miles south-west of Busselton covers an area of about 900 x 80 yds and was estimated (1948) to contain 200,000 tons of sand. A sample of this sand contained 46% ilmenite, 3% zircon and 0.3% rutile. The black sands are concentrated in a seam 9" thick in a fossil beach but are evenly distributed in the sands of the tidal zone.

The deposit at Wonnerup, on the Wonnerup and Vasse estuaries, was being actively investigated by Enterprise Explorations Co. Ltd in 1949 and was shewing definite signs of being of economic value. No details of the size of the deposit were given by McMath (1949) but concentrations of ilmenite of up to 46% were reported to occur.

Miles et alia (1955), who carried out laboratory tests on a sand sample from Minnimup, obtained an ilmenite concentrate, 35.95% of the sample, which contained 55.4% TiO_2 and 0.08% Cr_2O_3. 2.8% zircon and 0.96% rutile were also present. Cable (1956) Ltd are at present mining at Wonnerup.

A fossil beach at Siesta Park, 5 miles south of Busselton, contains unknown quantities of ilmenite, probably in low concentrations. One sample taken contained 7% ilmenite.

At Minnimup, 11 miles south of Bunbury, the ocean beach and a fossil beach immediately inland from it both contain concentrations of ilmenite. The area covered by the sands was (1949) of a size sufficient to justify further investigation. It is probably the Minnimup deposit that Western Titanium No Liability are working. Two samples of ilmenite concentrates from Minnimup have been analysed by Laporte Titanium Ltd. with the following results.

TiO_2	FeO	Fe_2O_3	MnO	P_2O_5	Cr_2O_3	V_2O_5	Residue
53.8	25.0	16.6	1.5	0.063	0.034	0.11	0.26
54.05	22.95	14.51	1.27	0.033	0.033	0.014	0.99

Deposit near Denmark.- Johnson, W. (1948) has described deposits of heavy minerals containing ilmenite and zircon on Dredging Claim 20H near Denmark in, approximately, longitude 117°11'E and 35°1'S. The heavy minerals are present in both the actual ocean beach and in fossil beach and dune deposits landward from the ocean beach. In three small deposits on the ocean beaches there was estimated to be 1,156 tons of heavy minerals of which 32-34% were ilmenite, 18-48% zircon and 7-19% garnet. The residue was quartz and kyanite.

The fossil beaches are much more extensive than those fringing the sea and only rough estimates of their sand content has been made, although it was thought likely that there would be insufficient sand available for economic exploitation to be feasible. The heavy mineral content of the fossil black sands was 15-41% ilmenite, 14-49% zircon and 6-10% garnet. The ilmenite contained 0.04% Cr_2O_3.

Cheyne Bay.- Beach sands containing concentrations of heavy minerals occur at Cheyne Bay near Cape Riche in longitude 118°50'E and latitude 34°35'S. The sands containing the heavy minerals ilmenite, zircon, garnet and rutile (nigrine) form beaches at the foot of cliffs composed of Tertiary sediments; they rest upon Tertiary strata or an injection gneiss basement complex. The beaches are completely removed during winter storms so that exploitation could only be a seasonal occupation. It was thought that winter storms might replenish the beaches' content of heavy minerals if these were mined, since sand was visible below water level. (McMath 1947).

The total available tonnage was estimated to be 155,000 tons in the beaches of Dredging Claims 9H, 10H and 12H and 30,000 tons in windblown dune deposits. The heavy mineral content of sands containing 30% or less of quartz varied from 34-60% ilmenite, 9-27% zircon, 2-12% garnet and 0-9% nigrine.

The ilmenite in the beach sands was analysed with the following result.

	%		%
TiO_2	52.12	CaO	-
FeO	29.04	MgO	0.28
Fe_2O_3	16.15	Cr_2O_3	0.04
MnO	1.61	V_2O_3	0.14
SiO_2	0.18	P_2O_5	N.D.
			99.56

From this analysis it appears that the ilmenite is probably in a slightly altered condition.

Torbay.- At Torbay, 16 miles west of Albany, an area of fixed dune sands and a cemented fossil beach contain low concentrations of ilmenite and zircon. The total heavy mineral content of the bulk of the sands is less than 2% rising, in rare black-sand streaks, to 17%. (McMath and de la Hunty 1949).

Doubtful Island Bay and Gairdner River. (McMath and de la Hunty 1949).- The coastal beaches of Doubtful Island Bay and the Gairdner river mouth lie 115 miles east of Albany in longitude 120°E and latitude 34°20'S. They are 14 miles in length and, including the inland dunes, up to a mile wide. Only the present-day beaches were considered to contain concentrations of heavy minerals of economic value, although no detailed examination of the dunes and fossil beaches was carried out. Eighteen samples were studied to determine their heavy mineral content; ilmenite values varied from 0-11%, zircon from 0-4%, and rutile 0-1%. The total content of heavy minerals in the ocean beach was estimated to be 366,000 tons but no estimate of the volume of inland sands was made.

Hard Rock Deposits

New South Wales.- Deposits of titaniferous magnetite occur as stratified bodies in carboniferous sandstones and tuffs near the Williams and Karuah rivers. Total reserve-100,000 tons containing 2.16% TiO_2 (Imp. Min. Res. Bur. Rept. Mineral Industry Brit. Emp. Pt. 5 1922 27).

Queensland.- Rutile, rimmed and penetrated by ilmenite, occurs in nodular form in gneissic biotite granite in the Kingaroy district.

Alluvial deposits, of no commercial importance are associated with the occurrence (Cribb 1943).

Rutile occurs in quartz veins in granite at Mt. Perry. The veins are 6" wide. (Queensland Govt. Min. J. 42 1941).

Rutile is commonly found in the mines of the Herberton district (Youngman 1928).

Western Australia.- Rutile occurs at Barjar Hill, Fitzroy valley in a rock containing 5.85% TiO_2. (Simpson 1928).

Near Gabanintha, 400 miles north north-east of Perth, a deposit of titaniferous iron ore, with reserves of 176,000 tons per foot of depth, outcrops as a ridge 2 miles long. A sample, assaying 76.1% Fe oxides, 15.7% TiO_2, 0.72% V_2O_3 and 0.54% V_2O_5, consisted of a mixture of magnetite, ilmenite and vanadium-bearing magnetite (coulsonite?) (Gardner 1951).

South Australia.- According to Gardner (1951) 20 tons of rutile have been produced in S. Australia in 1906, 1938, 39 and 40.

Rutile.- Rutile-quartz veins near Williamstown, 25 miles north-east of Adelaide in the hundred of Barrossa, have been mined in the past, producing a concentrate containing 96% TiO_2 (Min. Rev. South Aust. Dept. Min. 59 1933 59; 60 1934 43 and 65 1936 48). The rutile forms up to 20% of the veins and up to 3% of the schists.

Lenses of rutile occur in micaschist 40 miles south-west of Adelaide in Yonkalilla Hundred in association with pegmatites. The rutile body is over 65' long and 1' wide (Jack).

Rutile has been mined in association with, and as a by-product of, kaolin in Para Wirra Hundred. (Broadhurst 1944).

Ilmenite and Rutile.- Radium Hill. In the Radium Hill uranium mine ilmenite and, to a lesser extent, rutile occur with the uraniferous mineral davidite. The ore lode is in a shear zone in potassic granite gneiss, which has been metamorphosed to a quartz biotite sericite schist with chlorite and biotite augen.

During the first metallization period iron and titanium were introduced centripitaly replacing the biotite-chlorite augen, and forming rutile, hematite and ilmenite. In a later stage of the first period further much larger quantities of Fe and Ti were introduced together with a little Mg, forming intergrowths and single crystals of rutile, ilmenite and hematite. Quartz and biotite recrystallized.

The second metallization period saw the introduction of uranium, which as the mineral davidite preferentially replaced hematite-ilmenite-rutile intergrowths.

The number of different intergrowths of the ore minerals which occur is a remarkable feature of this deposit.

Granular intergrowths are common between all three constituents (hematite, ilmenite, rutile) and exsolution intergrowths of the latter are frequently encountered. The reverse relationship is also quite common. Granular intergrowths of hematite-ilmenite and ilmenite-hematite occur when both constituents are present in approximately equal quantity.

Rutile occurs as separate crystals intergrown with ilmenite and hematite, and as thin rodlike exsolution lamellae along the 0001 cleavage directions of the same minerals. Magnetite is rare and when seen is homogenous but contains 3.74% TiO_2.

A rare eutectic intergrowth of rutile and ilmenite on a very fine scale has also been observed (Dickinson, Sprigg et al. 1954).

Mawson (1944) and Alderman (1925) have also described this deposit.

Mount Painter. A small quantity of rutile and ilmenite occurs in the Mt. Painter uranium field. Sphene is common as massive segregations in the granite of the area. (Mawson 1944; Gardner 1951).

Mount Jagged. Rutile, ilmenite and titaniferous iron ore are reported to occur near Mount Jagged 34 miles south of Adelaide (Gardner 1951).

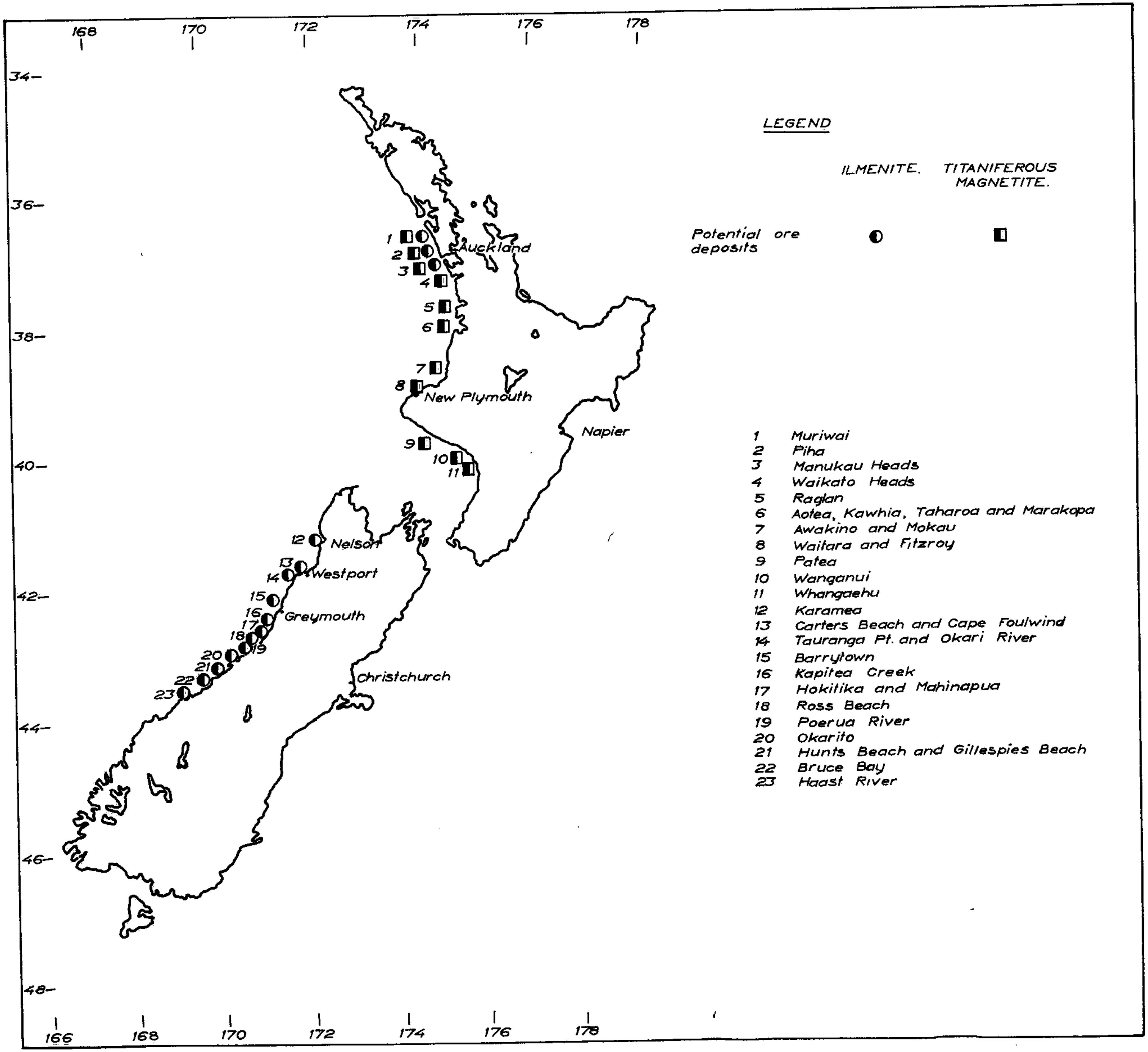
Australian Rutile and Ilmenite Production in Tons
(Gardner 1951)

	Queensland		New South Wales		Total	
	Rutile	Ilmenite	Rutile	Ilmenite	Rutile	Ilmenite
1906					9+	
1933						550[s]
1934			12	8	12	8
1935			139	133	139	133
1936			592	666	592	666
1937			1099	660	1099	660
1938			450	325	458‡	325
1939			705	672	707‡	672
1940			1615	1514	1617‡	1514
1941	263	254	3493	3465	3756	3719
1942	991	992	4425	3593	5416	4575
1943	1872	1629	4752	3755	6624	5384
1944	4179	3639	4524	3534	8703	7173
1945	4536	4120	5208	4240	9744	8360
1946	3353	3073	4799	3537	8152	6610
1947	4269	3702	8925	6608	13194	10310
1948	6310	4250	9167	7075	15477	11325
1949	4937	3950	9045	6869	13982	10869
1950	7643	4683	10466	7549	18089	12291

All, except for a very small percentage, of the ilmenite produced on the east coast has been dumped as useless because of its high Cr_2O_3 content.

\+ From S. Australia.
s From Tasmania.
‡ Includes a small amount from S. Australia.
Includes W. Australian production 50 tons in 1949, 59 tons in 1950.

TITANIFEROUS MAGNETITE AND ILMENITE DEPOSITS OF NEW ZEALAND.



NEW CALEDONIA

Titanium ores have been reported to occur on the north coast of New Caledonia (Chron. Min. Colon. 16 1933 355) but no details of the occurrence are known.

NEW ZEALAND

Titaniferous magnetite-bearing sands are found along the length of the west coast of North Island in enormous quantities. Luke (1955) estimates a recoverable tonnage of 775,900,000 tons assaying 50-58% of Fe and 7-9% TiO_2. The titaniferous magnetite contains too low a percentage of TiO_2 to be of interest as a titanium ore at the present time, and ilmenite is not a constituent mineral of the sands except on the beaches north of Waikato Head. The only way in which the TiO_2 content of the titaniferous magnetite could ever become available to the titanium industry of the world would be as a titanium enriched slag produced as a by-product of steel manufacture. At the present time the New Zealand Government is interested in developing a process of steel manufacture whereby high titanium iron ores can be utilized, and if a process similar to that employed to smelt the Allard Lake ore of Quebec ever becomes practical, then titanium slags suitable as a raw material for white pigment manufacture may come on to the market in the Southern Hemisphere.

Ilmenite bearing sands occur on North Island north of Waikato Head where there is an estimated reserve of 8,600,000 tons ilmenite. The presence of ilmenite in the sands was only discovered in 1949 (Nicholson 1949 unpublished report of the Dominion Laboratory quoted by Luke 1955).

In the South Island of New Zealand ilmenite sands are of more frequent occurrence. They are found on the west coast as recent and raised beach deposits. Luke (1955), gives a preliminary estimate of 43.5 million tons of recoverable ilmenite,but he emphasises that this is based on inadequate data.

North Island Deposits

Titanomagnetite is present in the following beaches in amounts varying from 5-90% (Luke 1955). Whangaehu; Wanganui recent beaches, recent dune sands and low grade pleistocene beach deposits; Patea, beach and dune sands; Fitzroy, beach and dune sands; Waitara, beach, dune sands and raised beach deposits; Mokau, beach and dune sands; Awakino, beach and dune sands; Marakopa, beach and dune sands; Taharoa, beach and dune sands; Kawhia, beach and dune sands; Aotea, beach and dune sands; Raglan, beach and dune sands; Waikato, beach and dune sands.

For further information on the titaniferous magnetite deposits the reader is referred to Luke 1955 and the following authors. Aubel (1920); Beck (1947); Finch (1948); Fyfe (1952); Fleming (1946); Donovan (1917); Hutton (1940; 1945a; 1945b); Kidson (1948); Mason (1945); Monro and Gibbs (1938); Wylie (1938).

The Titaniferous magnetite-ilmenite deposits.- A reconnaissance survey undertaken in 1949 shewed that deposits north of Waikato Heads all contained ilmenite in varying quantities (Fyfe and Nicholson, unpublished report quoted by Luke 1955). The deposits with their ilmenite content and total heavy mineral content are listed below.

Ilmenite content of sands north of Waikato Heads

Locality	Approx. % ilmenite in parent sand	Total % ilmenite and titanomagnetite
Waikato Heads Av. of 3 samples.	0.6	7.6
Piha	12.1	72.1
	6.8	37.8
	3.5	9.5
	3.4	22.4
	3.0	15.0
Muriwai (south end)	11.0	55.0
	8.2	46.2
	7.1	25.1
	6.5	18.5
Muriwai (½ to 2½ miles north of).	7.4	40.4
	1.8	14.8
	3.1	13.1
	3.5	13.5
Three to twenty miles north of Muriwai (Av. of 5 samples).	0.27	0.77

The most important deposits are at Muriwai (south end) and Manukau heads. The Muriwai deposits, extending two miles north of Muriwai, contains, assuming an average grade of 8% ilmenite, 7 million tons of ilmenite. This ilmenite assays 45% TiO_2 which, although low by comparison with beach sand ilmenites from Florida and India, is as good as commercial hard rock ilmenite concentrates. The Manukau Heads deposit is smaller; assuming 8% ilmenite in the sand the reserves are 1.4 million tons. Both the Manukau and Muriwai ilmenites contain only traces of chromium. The Piha deposits contain only 1 million tons of heavy minerals and are therefore of less importance (Luke 1955).

South Island Deposits

Less reliable information concerning the South Island deposits is available than for those on North Island. The accessibility by rail and sea to the deposits is very poor except for the Cape Foulwind (Westport) deposits. The quality of the ilmenite is probably sufficiently good for commerce; it analyses 44.5% TiO_2 with traces only of Cr_2O_3 and V_2O_5, but it does contain 2.5% MnO which is not usually considered to be a desirable impurity. Magnetite, monazite, thorite and rutile accompany some of the deposits in very small quantity.

The following table is given by Luke (1955).

Locality	% ilmenite	% TiO_2 ilmenite	Extent of Deposit	Estimate of ilmenite tonnage to 40' assuming grade of 5%
One mile north of Haast River	21.6		8 miles x 14 chains	3.1 mill. long tons
Bruce Bay	(* 16.0 (+ 9.0		4 miles x 9 chains	1.1 "
Hunts Beach	+ 15.5		4 miles x 18 chains	2.1 "
Gillespies Beach	(+ 20.0 (+ (+ 10.0	44.5	3 miles x 14 chains	1.5 "
Okarito Five Mile Beach	* 28.6		3 miles x 14 chains	1.1 "
Three Mile Beach	* 43.7		1½ miles x 14 chains	0.6 "
Okarito Beach	* 25.0	44.5	7 miles x 9 chains	1.8 "
Poerua River Mouth	* 24.0		8½ miles x 9 chains	2.2 "

Locality		% ilmenite	% TiO_2 ilmenite	Extent of Deposit	Estimate of ilmenite tonnage to 40' assuming grade of 5%
Ross Beach	+	7.0)		8 miles x 14 chains	7.9 mill. long tons
Mahinapua	*	14.0)			
One mile south of Hokitika river	+	8.0)			
Kapitea creek	+	8.6		27 miles x 9 chains	7.2 "
Barrytown	‡	28.4		6 miles x 18 chains	4.0 "
Addisons Flat Westport	s	5.6			
Nine Mile Beach Cape Foulwind	*	25.0		7 miles x 14 chains	2.7 "
Castors Beach Westport	*	14.0		5 miles x 14 chains	1.9 "
7 miles south of Karamea River	+	8.0)		16 miles x 14 chains	6.3 "
5 miles south of Karamea River		27.0)			
					43.5

* surface concentrate.
\+ average surface sand.
‡ dredge concentrate.
s surface sand.

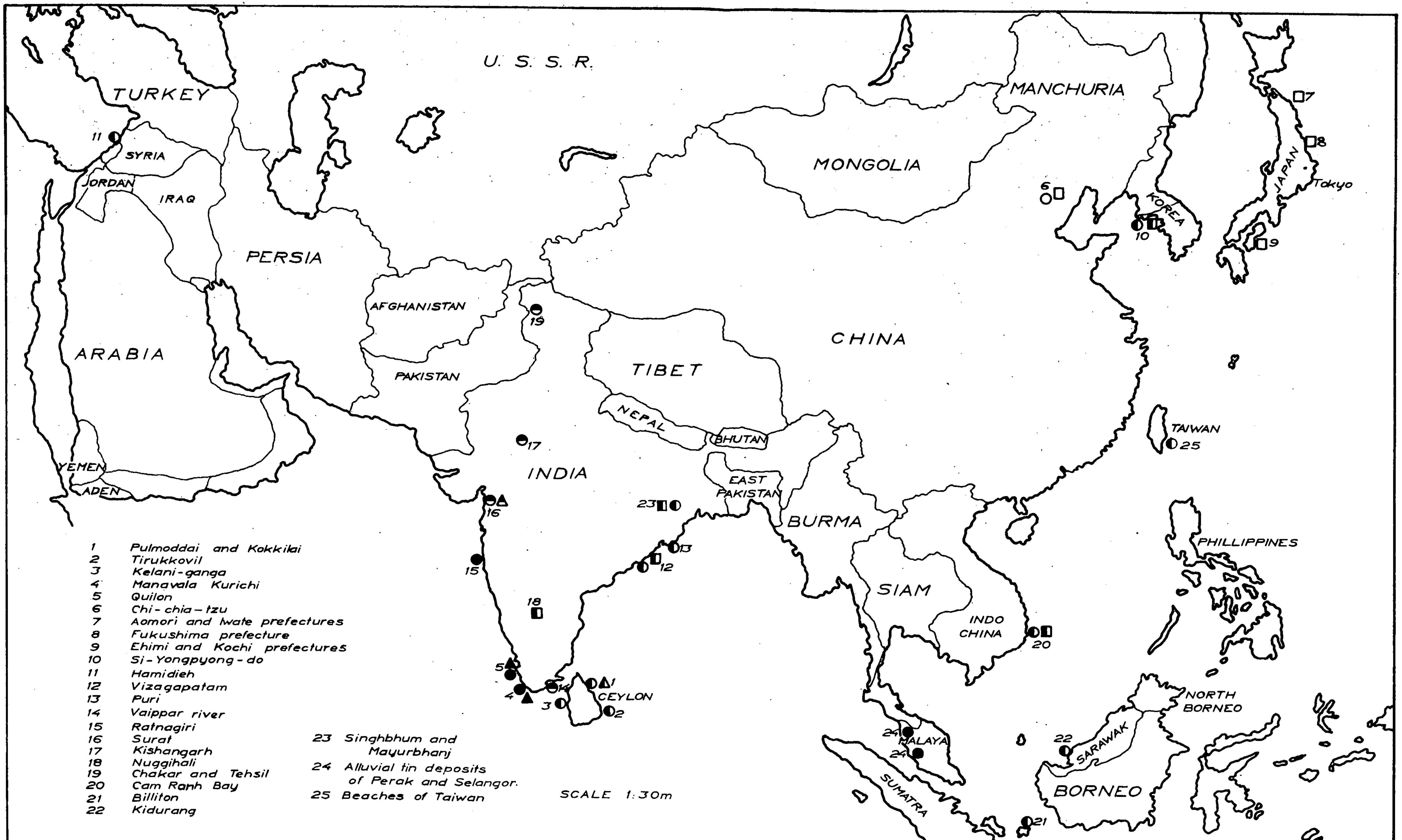
The Cape Foulwind deposits to a depth of 20' are described in the following manner "1.3 million tons of recoverable ilmenite is available above groundwater (10' above sea level).... The dune sand contains an average of 5.5% magnetically recoverable ilmenite, the content varying between 1.7% and 11%. Approximately 30% of the total tonnage of ilmenite estimated is present in sand averaging 8% ilmenite, the remainder averaging 4%". (Unpublished report of Dominion Laboratory by Marshall, Suggate and Nicholson

1949, quoted by Luke 1955).

TUBUAI OR AUSTRAL ISLANDS

Ilmenite is reported to occur in beach sands on Rapa Island in the Tubuai group. (Chubb 1927). It is probably derived from local volcanic rocks and hence is unlikely to be of much commercial value.

TITANIUM MINERAL DEPOSITS OF ASIA



CHAPTER VII

ASIA

SARAWAK

A band of black sand containing 37% ilmenite + 34% zircon, occurs in a beach between Tanjang Batu and Kidurang near Bintulu. The highest concentration of heavy minerals is at Sabatang. The beach is 20-30 yards wide, with dunes extending inland for some distance. The grain size of the ilmenite is 0.15 mm diameter and an analysis gave

TiO_2	FeO	Fe_2O_3	MnO	P_2O_5	U_2O_3	V_2O_5	MgO	Insol.
53.8	34.62	6.86	0.51	0.03	0.24	0.06	2.71	0.82

(Fitch 1952).

BURMA

Samples of ilmenite from an unspecified source in Burma have been examined by the writer. From their physical appearance, x-ray and chemical analysis (see below) they are of alluvial origin.

TiO_2	FeO	Fe_2O_3	MnO	Cr_2O_3	V_2O_5	P_2O_5	Insol.
39.2	13.9	26.4	2.25	0.01	0.08	1.15	14.1

CEYLON

The existence of ilmenite, monazite and zircon-bearing sands in Ceylon was mentioned in a number of the Bulletins of the Imp. Inst. published between 1905 and 1923 particularly in 14 (1916). Chernik (1914; 1915) described the minerals and Coates (1935) redescribed the occurrences. The most complete accounts of the deposits are given by Wadia (1943); Wadia and Fernando (1944); and Fernando (1948).

East Coast Deposits

Pulmoddai and Kokkilai.- The largest deposit in Ceylon lies in a beach over six miles in length which stretches for four and a half miles south of the Kokkilai lagoon and two miles to the north-west of it. This beach is situated approximately thirty-five miles north of Trincomalee. The average width of the deposit which occurs in the modern beach is 70 m, and the average thickness is 0.6-1.8 m. The deposit may also extend to below low water mark and black sands have also been found in dunes behind the beach. The sand consists of 75% ilmenite, 15% rutile, and 9% zircon and there are 3.5 million tons of ilmenite in the beach deposit alone. Wadia and Fernando (1944) quotes the following analysis of ilmenite from Pulmoddai:-

	TiO_2	Fe_2O_3	FeO	Al_2O_3	SiO_2	V_2O_5	Ign. loss
%	62.52	16.5	5.93	1.41	2.32	0.36	0.74

Chemische Ind. (Dec. 1956) declared that Krupp of Essen, National Lead Co., Hopkin and Williams, and two Ceylon firms were interested in developing these deposits. C.T.J. 139 (1956) 1238 indicated that Japanese and Mexican interests had offered to buy Ceylon's total output of ilmenite from Pulmoddai. Chem. Eng. 140 (1951) 620 recorded that a Corporation was to be set up soon to exploit the ilmenite deposit at Pulmoddai. Five million tons of black sand were supposed to be available.

Tirukkovil.- A small high grade deposit containing one half million tons of ilmenite occurs 45 miles south of Batticola.

West Coast Deposits

The west coast deposits are, in general, smaller and of lower grade than the deposits on the east side of the island.

Kelani-ganga.- The beach for several miles north of the Kelani river contains, at certain seasons of the year, a layer of black sand consisting mostly of ilmenite, but with about 2% of monazite. Small deposits of similar type occur at Kalu-ganga, Gin-ganga and Mahamodera.

Kudremalai.- A small deposit totalling about 100 tons, (Coates 1935) of ilmenite with 22% monazite occurs at Kudremalai point.

Kaikawala.- The beach at Kaikawala was worked for monazite between 1918-22 when over 3,000 tons of sand containing 14% monazite, and an unknown percentage of ilmenite were treated. After stripping a few days were allowed to elapse during which the beach was rebuilt of new material of similar grade. The beach in 1941 was, however, suffering from erosion. (Wadia 1944).

CHINA

Hard Rock Deposits

Chengte.- A magnetite-ilmenite deposit at Chi-chia-tsu, Chengte, Jehol Province, Manchuria has been described by Tsuru (1934) and Asano (1938). Sixteen large and eighteen small lense and table-shaped deposits occur in anorthosite and gabbro, the richer deposits being in the anorthosite. The ore consists of coarsely granular ilmenite and magnetite each containing exsolution lamellae of the other. An average of a number of analyses of the ore is given below:-

Fe	SiO_2	Al_2O_3	TiO_2	Mn	P	S
53.21	2.22	5.71	12.26	0.18	0.046	0.091

The ore bodies occur mostly at the contact of anorthosite and gabbro and are sharply differentiated from them. The ore is considered to be a magmatic differentiate, and the ore minerals were the last to crystallize. Kakiuchi (1940) reported that the ore contained 0.3-0.56% of V_2O_5.

The ore was mined during the 1939-45 war, producing a total of 197,359 metric tons. (U.S. Bat. Min. Res. Foreign Min. Surv. 1948).

Beach Sands

Beach sands containing 200,000 tons of black sand averaging 4.4% monazite, 12% zircon, 22.3% ilmenite, and 17.9% magnetite have been recorded to occur in Taiwan Province. (Shen 1956).

FEDERATED MALAY STATES

The Federated Malay States have been for many years important producers and exporters of ilmenite concentrates. The ore is produced as a by-product in the concentration of cassiterite from river alluvials.

The ilmenite is very high grade, because it has been enriched as a result of weathering which has partly leached the iron from the iron titanate molecule. Analyses of ilmenite concentrates given by Ingham (1938) and the Sunkai analysis obtained from a private source are given below:-

	% TiO_2	% FeO	% Fe_2O_3	% $ZrSiO_4$	% MnO	% CaO	% SiO_2	% Cr_2O_3
Bidar	54.0	35.35	5.76	-	3.95	-	1.00	tr.
Langkawai	61.4	8.93	24.0	-	4.48	-	0.5	-
Vlu Yam	52.2	24.2	11.36	-	-	-	-	-
Puchai	55.6	29.5	9.11	-	-	-	-	-
Kalumpaug	54.8	29.08	11.36	-	-	-	-	-
Chenderang	52.4	32.97	7.36	3.00	0.5	1.00	-	tr.
Chenderang	54.0	30.81	8.96	2.3	1.0	1.00	-	tr.
Kuala Lumpur	56.0	28.36	13.11	0.6	0.5	1.00	-	tr.
Penawar	55.8	29.23	9.42	3.00	1.74	0.8	-	tr.
Kuala Lumpur	55.3	30.66	10.08	2.2	1.28	0.7	-	tr.
Rawang	57.6	19.15	16.32	2.8	1.00	1.00	-	tr.
Kampang Lamjat	61.2	18.40	13.06	2.6	1.10	0.5	-	tr.
Tanjang Tualang	58.0	26.6	12.13	1.3	1.38	0.5	-	tr.
Ulu Klang	50.8	27.5	10.08	-	-	-	-	tr.
Tapah	54.3	31.4	8.32	-	-	-	-	-
Sunkai	63.5	7.55	20.77	-	2.45	-	-	.026

Ilmenite 14.1%, anatase 4.7%, brookite and rutile occur in stream concentrates in the river Kemaman. Sands at Karagan contain 39% ilmenite (Scrivenor 1928). Large deposits of ore containing 46.5% TiO_2 occur in the tributary of the Endau river at the boundary of Johore and Pahang states (Youngman 1928). Ilmenite also occurs in coastal sands (Dobransky 1942).

Until 1933 no ilmenite was exported because of its low market value. The following production figures for succeeding years are taken from Gillson (1949) and Fermor (1949)

	Metric Tons		Metric Tons
1933	204	1938	6,566
1934	51	1939	11,098
1935	2,540	1940	2,596
1936	10,470	1941-1947	No figures available
1937	6,352	1948	12,000

INDIA

Titanium minerals are widely distributed in India, but most of the deposits are of no commercial value and only beach sands are being worked at the present time. The Indian Minister for Natural Resources has stated that ilmenite and rutile reserves total 300-350 million tons (Metal Bull. 4131 1956 24).

Beach Sand and other Secondary Deposits

Travancore.- Production of ilmenite from beach sands in Travancore commenced in 1922 and from that date until 1945 India was the largest ilmenite producing country in the world. Since the 1939-1945 war the United States has been developing its own reserves and, with a fall off in Indian production, has become the largest producer of ilmenite concentrates. Production of monazite commenced in 1900 at which time there was no market for ilmenite. Rutile production commenced in 1939.

The Travancore deposits have been briefly described in many scientific and popular articles during the last 40 years. The most thorough descriptions are those of Tipper (1914), Sallmann (1939), Chambers (1939), Viswanathan (1946; 1949; 1951) and Gillson (1949).

There are two beaches in Travancore, one near Manavalakurichi a few miles west of Cape Comorin, and the other eighty miles to the north extending for a distance of fifteen miles from Neendakara inlet near Quilon to Kayankulam inlet.

"The Manavalakurichi or MK deposit is a modern beach placer, resulting from destruction by the waves, during the period of the south-west monsoon, of dunes built on an elevated bar or spit carrying small percentages of heavy minerals. The accessible reserves at 'MK' are approaching exhaustion, and since the 'MK' ilmenite is lower in TiO_2 than that on the northern beach most of the operations have been conducted at the latter place since 1932". (Gillson 1949).

The beach at Quilon "is a barrier beach extending parallel to the old shore in front of the mouths of two rather large rivers". "The ocean beach is black with layers carrying 80% heavy mineral, and dunes on the elevated bar are grey, with 40-50% heavy mineral, and below them are old beaches buried under dunes formed before the shore retreated (seawards), which are as rich as those washed by the waves." Enormous reserves underlying paddy fields on the adjacent mainland have been claimed to exist, but Gillson considers that if there are any they will not be of such high grade as the known deposits because "sands found at greater depth presumably will never have received any appreciable wave or wind action." The geological history of the deposits is discussed in Chapter V of Part I of this thesis.

Ilmenite and monazite are concentrated from the sands electromagnetically; rutile, electrostatically, while froth flotation is used to obtain zircon, garnet and sillimanite concentrates.

Analyses of Ilmenite Concentrates

	MK			Quilon		
	Hess & Gillson 1937		Private Source	Gillson 1949	Lynd. et al. 1954	Private Source
SiO_2	1.40	1.53	-	-		-
Al_2O_3	nd	1.11	-	-		-
Fe_2O_3	15.50	14.17	16.0	24.6		25.0
FeO	26.00	26.71	23.0	9.55	10.2	10.0
MnO	nd	0.38	0.4	-		0.5
MgO	nd	1.01	-	-		-
TiO_2	54.30	53.56	55.0	60.4	58.2	60.0
Cr_2O_3	0.07	0.09	0.07	0.17		0.08
V_2O_5	0.20	0.03	0.25	0.36	all others 7.3	0.25
P_2O_5	0.26	0.20	0.15	-		0.15

The high TiO_2 content and high Fe_2O_3:FeO ratio of Quilon ilmenite has been shewn to be due (Lynd, Sigurdson, North and Anderson 1954) to both leaching and oxidation of the FeO content of the ilmenite. Only 20% of the Quilon ilmenite concentrate consists of unaltered ilmenite.

Production figures for ilmenite and rutile concentrates are as follows (Krishnan 1942; 1946; Gillson 1949).

	Ilmenite		Ilmenite	Rutile
1924	641	1936	140,477	
1925	328	1937	181,047	
1926	4,236	1938	252,220	
1927	17,809	1939	237,834	
1928	25,307	1940	267,376	934
1929	23,670	1941	131,111	1,891
1930	28,776	1942	49,977	2,295
1931	36,166	1943	38,041	2,396
1932	50,053	1944	102,492	1,672
1933	52,890	1945	102,879	
1934	75,044	1946	197,480	258
1935	127,051	1947	238,204	

Note. 1925-1939 and rutile 1946 given in long tons.
1939-1947 given in metric tons.

<u>East Indian Coast</u>.- Beach sands which contain black sand concentrates are found at a number of places on the eastern coast of India north of the Godavari River. The Vizagapatnam beach between the Yarada and Kailasa hills near Waltair has been the subject of several studies (Mahadevan and Srirama Das (1948); Mahadevan and Nateswara Rao (1950); Mahadevan and Srirama Das (1952); Borreswara Rao (1957)). The seams of black sand concentrates usually vary from between 1" and 8" in thickness. Their composition is variable, depending on the grain size and degree of sorting of the sample. Analysis number 1 is of a sand from Dibbalapalem and number 2 the variation in the constituents of a number of samples taken from the beaches between Yarada and the Kailása hills.

	1	2
	%	%
Magnetite	36	51-88
Monazite	3	1.2-7.7
Ilmenite	5.5	0.5-10
Garnet	15	1.2-17.7
Zircon	0.6	0.2-1.0
Rutile	-	Trace
Others	ad 100	ad 100

The reserve quantities of heavy minerals available in the Dibbalapalem beach to a depth of 5 feet are 5,700 tons but the sands extend to greater depths. In some places between the Godavari and Nagaveli rivers there are sand-dune areas behind the beaches which probably contain further reserves of heavy minerals, but there is no estimate in the literature of the quantities which might be available.

The heavy minerals of the Vizagapatam beach are derived from pegmatites in the immediate hinterland of Waltair (Srirama Das 1952). The deposits are found over a wider area than the Vizagapatam beach and much of the heavy mineral content of the sands undoubtedly is derived from the granitic and charnockitic gneisses which form the drainage area of the eastward flowing Godavari river system. From the river mouth the sands are carried north by the powerful longshore current.

Ilmenite and monazite-bearing sands occurring in black bands in a beach farther north at Puri were analysed with the following result (Sircar 1952).

SiO_2	TiO_2	Fe_2O_3	Al_2O_3	ThO_2	U_3O_8	Rare Earth Oxides
25.64	25.52	30.46	15.39	0.09	0.0022	0.295

No reserve quantities were given.

There are many recorded occurrences in Madras state of small sand deposits containing ilmenite about which little is known. Ilmenite sand has been found near Usur, Arcot district; Arasadi; Tarwarkullam; Ganjam (Rec. Geol. Surv. India 58 1924 30); Vijayapati, Tinnevelly; Kodambakulam (400 tons), Tiruchendur (Rec. Geol. Surv. India 1947-8 51): Combatore (Rec. Geol. Surv. India 1948-9 54): and at the mouths of the Vaippar and Kullar rivers, Tinnevelly where 35,000 tons of sand contains 49% ilmenite (Lawthers).

Beach sands from which 9,000 tons of ilmenite are reported to have been produced in 1953 occur to the south of Ratnagiri port in Bombay state. The Ratnagiri deposits which are formed during the monsoon season, are of unknown potential except that Chem. Age 65 (1951) 465 and 566 remarks on the importance of the Ratnagiri deposits.

C.T.J. 129 (1950) 751 reported that a titaniferous deposit at Malgund, 300 miles south of Bombay, was to be worked. It is uncertain whether the Malgund and Ratnagiri deposits are the same under different names.

Altekar (1956) reported the occurrence of black sands containing magnetite, ilmenite, rutile and zircon near Surat.

Hard Rock Deposits

Titaniferous magnetite-ilmenite deposit of Singbhum (Bihar) and Mayurbhanj.- The existence of titaniferous magnetite in the Dhalbum subdivision of Singbhum district, Chota Nagpur division of Bihar province, and in the adjacent Mayurbhanj state has been known since 1911. The ores were very briefly described by Jones (1934) and more thoroughly by Dunn (1937) and particularly by Dunn and Dey (1937).

Since then they have been mentioned by Nag (1940), Agrawa (1948) and Mitra and Chatterjee. The ore minerals and their textures have been fully redescribed by Roy (1954) and Mitra and Chatterjee (1955). The ore minerals have been well described, but a thorough description of the relationships of the ore deposit to the surrounding and enclosing gabbroic rocks is lacking. This is probably due to the poor exposure of the region.

The titaniferous magnetite-ilmenite ore occurs in veins and lenses in gabbro with quartz anorthosite streaks, and in serpentinized olivine pyroxenite, an ultrabasic variant of the gabbro. Although not specifically described as such the ore bodies occur in what is probably a rudimentary layered complex.

The ore consists of the following primary minerals:- magnetite with exsolved ilmenite and ulvospinel lamellae, titanium-free magnetite, ilmenite and a little pyrite. Secondary minerals developed at the expense of the primary constituents are hematite, rutile, limonite, martite, goethite, and lepidocrosite. Coulsonite is also probably present.

The ilmenite is present mostly as exsolution lamellae in magnetite, but individual grains up to 3 mm in diameter occur. They contain inclusions of hematite, magnetite and goethite. (Roy 1954, 1956).

Dunn and Dey (1937), present 13 analyses of ore of which the following are maximum (TiO_2 content), minimum and average examples.

	Chatterjees Pit Dublabera	Detrital ore Dublabera	West of Dublabera
SiO_2	8.48	1.27	1.00
Al_2O_3	0.79	4.00	0.75
Fe_2O_3	40.24	34.95	60.68
FeO	23.63	28.67	20.01
MgO	0.78	0.13	0.59
TiO_2	21.80	24.7	10.2
P_2O_5	0.51	0.48	0.89
Cr_2O_3	0.13	0.19	nd
V_2O_5	2.01	4.84	1.92
MnO	0.33	0.29	0.13
H_2O	1.73	0.69	2.79

The vanadium content of the ores is abnormally high. No reserves of ore have ever been quoted except that Dunn and Dey estimated there to be a million tons of detrital ore alone. No benefication tests seem to have been made but because of the high percentage of titanium enclosed within the magnetite crystals, without very fine grinding it is unlikely that an ilmenite concentrate with a sufficiently high TiO_2 content could be obtained.

The ore mineral relationships are more fully considered in the first part of this thesis.

Rajputana State.- Ilmenite and titaniferous magnetite occur in quartz-calcite veins at Kacharia, near Kishengarh. These minerals were smelted at some unknown historical period either for their iron content or for copper which occurred in associated copper-bearing minerals. The ilmenite occurs in close association with quartz rather than calcite. (Heron 1935; Crookshank 1948; Sen Gupta 1931).

Sen Gupta quotes the following ilmenite analysis.

SiO_2	FeO	Fe_2O_3	CaO	MgO	TiO_2	H_2O
4.70	13.08	40.18	tr	tr	43.70	0.22

There is probably too small a reserve of ore for this occurrence to be of economic interest.

Mysore State.- Lenticular masses of titaniferous iron ore associated with ultrabasic chromite-bearing rocks caught up in a later granite intrusion are found in the Nuggihali granite-schist belt of the Hassan district, and near Devaranarsipur in the neighbourhood of Bhadrovati. A typical analysis shews Fe 39.8%, SiO_2 9.9%, TiO_2 10.8%, Al_2O_3 6.5%. There are 60,000 tons of ore to a depth of 30' at the latter locality. (Radhakrishna 1951; Lakshamana-Rao 1943).

Madras State.- Ilmenite, in the form of large segregated masses in a pegmatite vein, outcrops a mile north-east of Galimcherla village, Rapur. It is associated with feldspar and biotite and contains 49.82% TiO_2. The mineral is present in "fairly large quantities" (Swanimathan 1928). Titaniferous iron ore is met with in limited quantity in a pegmatite vein near the Patragunta mine. An analysis of it is given below

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	P_2O_5
%	0.65	28.71	0.48	0.00	67.71	1.87	0.9	0	0

Jammu and Kashmir States.- Magmatic segregations of ilmenite occur in rich concentration in veins at Wari Khawah, Viji, Banyar and Naoshera in the Jhelum valley (Middlemiss 1929; Badyal 1955).

The bauxite deposits of Chakar and Tehsil are reputed to contain 5-16% of TiO_2 (Middlemiss 1929). Jha (1955) and Swarup and Sharma (1945) also describe the high TiO_2 content (6-12%) of Indian bauxites which is at present dumped after the extraction of Al_2O_3. The latter authors describe what is considered to be an economic extraction method.

Jashpur State.- Titaniferous bauxite is supposed to occur in Jashpur state.

INDO-CHINA

Ilmenite and magnetite beach sands in Cam-Ranh Bay Indo China have frequently been mentioned in the literature (Dupouy 1913; Echo. Min. 1922 366; Chron. Min. Colon. 16 1933 355) but the only recorded details are that their TiO_2 content is 44.5%. Hematite, rutile, garnet and zircon accompany the ilmenite and magnetite.

INDONESIA

Java

Titaniferous magnetite, ilmenite and hematite occur as lenses in sandstone of Miocene age at Djampangs, West Java. The ore minerals were derived from andesite lavas during the Miocene. The ilmenite in the ores is usually intergrown with the magnetite. The deposits contain, on average, 44% Fe_2O_3, 12% FeO and 12.8% TiO_2. The analyses indicate that most of the magnetite must now be either hematite or hydrated iron oxides. There are over eight million tons of low grade ore (van Bemmelen 1949).

The occurrence of titaniferous magnetite sands is recorded by Molengraaf (1910).

Borneo

The occurrence of ilmenite sand in the rivers of north-east Borneo near Berau is recorded by de Launay.

Billiton

Tyler in Min. Yrbk. 1938 684 mentions the possibility that ilmenite might be produced on the island of Billiton.

JAPAN

The only sources of titanium in Japan appear to be the titaniferous magnetite, or titaniferous hematite, beach sands which are of widespread occurrence. The richest deposits (Neill 1927) occur on the east coast in Aomori and Iwate prefectures. Deposits estimated to total 10 million tons, contained 20-30% Fe, 8-12% TiO_2, and 0.6% V_2O_5. A concentrate containing 60% TiO_2 was supposed to have been obtained. Further reserves of 200 million tons were supposed to exist in old raised beaches.

Staatz (1947a; 1947b; 1948) recorded that the total Japanese iron sand reserves were 41 million tons not 200 million as previously recorded. They contain 1-17% TiO_2, averaging 8-9%. He reported the following mines operating, or recently operating.

Hokkai mine Hokkaido.

Honshu
- Odaka, Onuka, Ozawa, Takachicha, Tomioka mines in Fukushima prefecture.
- Kameji mine, Shimane prefecture.

Shikoku
- Iyo, Kuroshima, Tencho mines in Ehime prefecture.
- Iyahama mine in Kochi prefecture.

The Odaka mine had a reserve of 8,480 tons sand containing 18% TiO_2 and 55% Fe in 1947.

Omati and Suzuki (1955) record that ironsand containing 24-45% Fe and 2.5% TiO_2 is being mined near Horobetsu, Iburi province, Hokkaido. Rept. Geol. Surv. Japan <u>165</u> (1955) record that none of the Fe-Ti sands are being worked.

The titanium in all the deposits occurred in ilmenite intergrowths in magnetite. Umezu (1931) records that titanium occurs only as intergrowths of ilmenite in magnetite or in ilmenite with hematite intergrowths. Kuwabara (1943) records that placer iron in Japan and Manchuria contained 0-51.6% TiO_2 the high values presumably belonging to the Manchurian occurrences.

Kikuchi and Maruyama (1955) have described the titaniferous iron sand deposit of Sugamoshire, Shumokita and Leninsula in Aomori prefecture. Takeuchi et alia (1953) record the occurrence of magnetite in iron placer deposits.

Anda and Nitta (1941) have described ilmenorutile from Hukushima prefecture. It was a solid solution of rutile and mossite, $Fe(Cb\ Ta)_2O_6$. The occurrence presumably was not a commercial proposition.

Oyagi (1955) has described the microstructure of ilmenite in sand from Sabishiro and discussed smelting methods.

KOREA

Hard Rock Deposits

Si-Yongpyong-do.- An ilmenite-magnetite ore in pyroxenite in gabbro, occurs on the island of Si-Yongpyong-do 52 miles north-west of Inchon. The deposit is estimated to contain 2.3 million tons of ore. The ore analyses as follows (Yagyu 1951).

Fe	TiO_2	V	S	P	MnO	SiO_2	Al_2O_3	MgO
50.9	19.0	0.24	0.08	0.03	0.15	3.15	8.03	3.76

Magnetic separation produces three concentrates, a magnetic, an intermediate, and a non-magnetic.

	% of original	Fe	TiO_2	V
Non-Magnetic conc.	55	35	47	0.07
Magnetic	27.5	64	8	0.34
Intermediate	17.5	35	9	0.17

From a recalculation of the analyses it seems that the ilmenite concentrate is ilmenite relatively free from Fe_3O_4. The ore is probably similar to the Lake Sanford ore of New York State.

Sho-eupe-to.- On the island of Sho-eupe-to 38 km south of Ryvtoko, two ore deposits of ilmenite and magnetite, with accessory spinel, chlorite, and other secondary minerals, occur concordantly in hornblende schist. The magnetite contains lamellae of ilmenite. (Ichimura 1931).

	Fe	TiO_2
Av. analysis		
	52%	20.6%

Titanium deposits are known to occur at Kansen-ri (veins in gneiss) and Konan-san (in anorthosite) (Lawthers).

Secondary Deposits

Iimori (1942) records the occurrence of monazite sands containing ilmenite in Korea.

PHILLIPINE ISLANDS

Black sands containing 10% TiO_2 have been reported to occur in the Paracale district of Luzon (Fanning and Eddingfield 1912).

SYRIA

Black sands are found along the beach between the mouth of Nahr-el-Kebir and Hamidieh in Alaouites. The TiO_2 content is 26% (Mines Carr. 10 1931 8).

THAILAND

Titanium minerals have been reported to occur in Thailand (Brown 1952), but no details are available.

TURKEY

Magnetite and ilmenite bearing beach deposits have been recorded to exist at Sile, Vilayet Istanbul (Egeran and Kleinsorge 1941) and at Ordu (Gysin and Kovalev 1940). The former deposits are only one example of many in the district derived from lavas and tuffs in nearby cliffs. The sand contained magnetite 23.4%, ilmenite 32.7%, zircon 18.7% and other minerals 25.2%. The average thickness of the deposit was 20-30 cm over an area of 500 metres by 2 metres. It is unlikely that the deposit is of great economic value if it has been derived from lavas but the presence of 18.7% zircon indicates a different source for at least some of the constituents.

Beach sands at Ciftalen, 18 km west of the Black Sea end of the Bosphorus, contain 10.9% ilmenite and 4.2% zircon. (Granigg 1944).

The chromite deposit of the Guleman Concession, Vilayet Elaziz, contains rutile inclusions. (Wijkerslooth 1947).

Many Macedonian rivers contain titaniferous iron sands (de Launay).

TITANIUM ORES

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