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The occurrence and paragenesis of the ores of titanium

B. K. Welch

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THE OCCURRENCE AND PARAGENESIS OF THE ORES OF TITANIUM

by

B.K. WELCH B.Sc.(Dunelm) F.G.S.

VOLUME I

Thesis submitted for the Degree of Doctor of Philosophy
in the University of Durham.

The Titanium Mines of Europe:- Otanmaki Oy in central Finland
(above) and Titania A/S near Hauge I Dalane in south-west Norway.

PREFACE AND ACKNOWLEDGEMENTS

The thesis is a critical review and synthesis of the literature concerned with the ores of titanium, expanded with the author's original work on selected aspects of the subject. A new classification of titaniferous ore deposits is submitted based on mode of occurrence, paragenesis and geochemistry. An introductory mineralogical chapter offers new and confirmatory data on optical properties and X-ray characteristics of ilmenite from primary ore deposits.

Titanium ore deposits fall into two major classes, primary and secondary. The most important primary ores are genetically connected with batholithic anorthosites and the ores in this category which occur in the Egersund region of south-west Norway are described in detail for the first time. The genesis of the batholithic anorthosites and their associated titaniferous ore deposits is fully discussed and a new theory is put forward partially reconciling previously antagonistic magmatic and metasomatic theories. The economically important effects of amphibolite facies metamorphism on titaniferous magnetite deposits, causing separation of a free ilmenite phase, is illustrated by the author's description of the Otanmaki orefield in central Finland. Iron-titanium oxide minerals in the gabbro of Carrock Fell, Cumberland are also the subject of original study.

Secondary titanium ore deposits occur principally in ocean beach sands. The factors affecting their distribution are critically examined and attention is drawn particularly to the effects of Pleistocene sea-level changes on heavy mineral

concentration. The mineralogical changes which iron and titanium oxide minerals undergo in secondary deposits are discussed and new data is submitted to account for the TiO_2 variations which occur.

A survey, with an economic emphasis, of world titanium mineral resources is presented in Volume II. Information of both geological and economic interest is included, based almost entirely on published material.

norite complex.

To Mr. E.J. Cobbing B.Sc. for many critical discussions of the subject.

To the workshop staff of the Durham Colleges Department of Geology for the preparation of thin and polished sections of ores and rocks, and for reproducing the thesis photographs.

To Mrs. W. Layton for redrawing four of the maps.

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FOR VOLUME I

CHAPTER I

INTRODUCTION

SOME ASPECTS OF THE GEOCHEMISTRY OF TITANIUM

Titanium is the ninth most abundant element in the earth's crust.   It is, therefore, the most common of the 'rare' elements, those elements which do not play an important part in the major petrogenetic processes.   It is a strongly lithophilic element forming principally titanates, oxides, titanosilicates and titano-niobates.   The average magmatic rock contains 0.64% Ti and the average sediment 0.44% Ti.

Order of Abundance of Elements in the Earth's Crust

(in p.p.m. after Mason)

O	466,000	Na	28,300	Mn	1,000
Si	277,200	K	25,900	Cr	200
Al	81,300	Mg	20,900	V	150
Fe	50,000	Ti	4,400	Ni	80
Ca	36,300			Co	23

Titanium lies in the first long period of the Periodic Table in Group IVB.   The elements which follow it in the long period are vanadium, chromium, manganese, iron, cobalt nickel and copper. Zirconium is found with it in Group IVB.   Vanadium and iron are closely associated with the primary magmatic ores of titanium, as are chromium and manganese though in accessory amount.   Zirconium often occurs with titanium in secondary ore deposits on account of the similar physical characteristics and chemical stability of the two elements' commonly occurring compounds in the environment of erosion, sedimentation and diagenesis.

There are three valency modifications of titanium, di-, tri-
and quadrivalent.   The first does not occur in rocks;   there is
never an adequate redox potential to allow the existence of the
divalent compounds.

Trivalent titanium (ionic radius 0.69Å) is of no importance
in the formation of minerals, existing only in some meteorites as
the nitride, osbornite.   Small amounts of trivalent tianium are
captured by ferromagnesian silicates such as monoclinic pyroxenes and
biotite, where it replaces trivalent iron and aluminium imparting
a distinct colouration to the host mineral.   It also causes the blue
colour of some anatase crystals.

Quadrivalent titanium (ionic radius 0.65Å) requires a sixfold
co-ordination of oxygen ions on account of the moderate radius of the
ion, and thus rarely replaces silicon (quadrivalent, ionic radius
0.39Å) as was earlier assumed because of their similar valency.
Only in schorlomite garnet is titanium known to occur in fourfold
co-ordination as a replacement of silicon.

The minerals ilmenite, rutile, titaniferous magnetite and sphene
carry most of the titanium contained in rocks.   If to this list be
added the silicates which contain small amounts of titanium, certain
amphiboles, pyroxenes and biotites together with perovskite then well
over 90% of the element is accounted for.   Only in the rare alkaline
complexes are any other titaniferous minerals of rock-forming
importance encountered.

In basic magmatic rocks ilmenite and / or titaniferous magnetite
are the most common hosts of titanium.   The earliest minerals to
crystallise are magnesian olivines and magnesian pyroxenes, and the

oxide most commonly associated with these is chromite. Chromium has an ionic radius of $0.64\overset{o}{A}$, compared with $0.67\overset{o}{A}$ for Fe''', $0.79\overset{o}{A}$ for Fe'' and $0.65\overset{o}{A}$ for Ti^{IV}, and as a result chromite crystallises first in the sequence of spinels. Titanium crystallizes with magnetite later in olivine-bearing, or olivine-free, gabbro and norite. The first titanium oxide to crystallise at high temperature is probably a solid solution which on cooling separates into ilmenite and magnetite which may contain ulvospinel (Fe_2TiO_4). If the rate of cooling is sufficiently slow, as in the Skaergaard intrusion of East Greenland, ilmenite exsolves completely from the magnetite, presumably because the temperature at which it ceases to remain in solid solution is too low for it to diffuse beyond the margins of the crystal. At a higher level in a differentiating basic magma, again the Skaergaard intrusion is a good example (Vincent and Phillips 1954), the magnetite contains lamellae of ilmenite in abundance which is taken to indicate a more rapidly falling temperature. Ulvospinel also tends to disappear from magnetite in the higher levels of such a gabbroic mass, probably as a result of a fall in the redox potential. In the Bushveld complex the contrast between chromium on the one hand and titanium and ferric iron on the other is very well brought out (Wilson 1953)

The Composition of Oxide Layers in the Bushveld Complex

		Cr_2O_3	Fe_2O_3	TiO_2
Upper Norite Zone	Upper Magnetite	0.02	59.86	18.2
	Middle Magnetite	0.07	64.09	16.56
	Lower Magnetite	0.39	67.79	11.90
Upper Critical Zone	Merensky Reef	39.1	5.2	
	Upper Chromite	42.5	4.4	
	Middle Chromite	44.7	4.1	1.5
	Lower Chromite	48.0	3.9	

In igneous complexes of the Bushveld type where differentiation has proceeded in quiescent conditions, titanium and iron oxides crystallize in noritic and anorthositic differentiates. However, in many igneous rock complexes in which these oxides are found they are not associated with precisely similar silicates. On the basis of the evidence afforded by the Bushveld complex it might be expected that the more 'acid' the associated silicates the higher should be the titanium content of the oxide phase. In a general way this proves to be true and for the silicate 'indicator of acidity' the plagioclase feldspars are of great value. The higher the albite content of the plagioclase the higher is the titanium content of the oxides. Certain very basic intrusions such as Taberg, Sweden and Iron Mine Hill, Rhode Island are slightly anomalous in that they contain more titanium than expected. However, these intrusions exhibit a number of other unusual features as well. The silicate-titanium relationship in basic magmas is fully discussed in Chapter IV under the heading "Layered Basic Complexes".

The other lithophile elements of the first long period, vanadium and manganese are respectively captured and admitted by ilmenite and magnetite. Vanadium (V''') shows a strong preference for magnetite: with an ionic radius of $0.65\overset{o}{A}$ it replaces ferric iron $(0.67\overset{o}{A})$ but up to 0.3% has been recorded to occur in ilmenite (Vincent and Phillips). Sometimes the mineral coulsonite (Dunn and Dey 1937) is formed in small amount in the vanadiferous magnetite. Manganese (Mn'' I.R. $= 0.91\overset{o}{A}$) is distributed fairly equally between the ferrous iron of both minerals, but it also follows magnesium and calcium in silicates.

Niobium (I.R. = 0.69) is an interesting trace element found in ilmenite where it replaces titanium. [It] is common only in acid igneous rocks where ilmenite is scarce. However, all ilmenites contain a trace of it. As one would expect ilmenite in anorthosites contains only a small amount of niobium, about 0.005% or less, and those from nepheline syenites the most, up to 0.9%. It is the striking contrast between the very low values obtained for anorthosite ilmenites and the values obtained for ilmenite from all other sources which is important. The importance lies in two separate contexts. Firstly it confirms the exclusiveness of the anorthosite environment and provides support for the complete genetic dissociation, argued for in Chapter VI on different grounds, of anorthosite batholiths from granitic rocks. Secondly it emphasises that the ilmenite in beach sand placers is not primarly derived from basic magmatic rocks as has been frequently suggested, but is probably derived largely from basement metamorphic terranes. Unfortunately there are no published analyses of ilmenites from regional metamorphic rocks to confirm the connection.

The Average Niobium Content of Ilmenites

(Niobium values from Fleischer et alia 1952)

Ilmenites from batholithic Anorthosites (14 analyses)   0.006%(approx)Nb
Ilmenites from gabbros (2 analyses)   0.005% Nb
Ilmenites from beachsands (13 analyses)   0.091% Nb
     from three continents.
Ilmenite from granite pegmatites (4 analyses)   0.205% Nb
Ilmenite from nepheline seyenites (3 analyses)   0.504% Nb

In the more siliceous rocks ilmenite and titaniferous magnetite become much rarer and their place is taken by sphene and, to a lesser extent, by rutile. Ilmenite appears to be a comparatively unstable mineral in most hydrothermal environments and the alteration

to 'leucoxene', which is finely divided sphene, rutile and, rarely, anatase, commences in the intermediate diorites and syenites. Sphene is comparatively restricted to acid rocks but rutile does occur rarely in eclogites and anorthosites. There is, however, considerable doubt whether it is a direct crystallizate from a magma in the latter environment. It replaces ilmenite in anorthosites if there is a lack of iron in its immediate vicinity with which it might react to form ilmenite. Ferriferous minerals do not occur abundantly with rutile in unaltered basic rocks.

Although titanium is not concentrated to any marked degree in granites, it is concentrated to a limited extent in pegmatites, alkaline granites and syenites, and carbonatites. In the alkaline and carbonate-rich rocks it forms perovskite ($CaTiO_3$) or varieties of perovskite, such as dysanalyte and loparite, rich in yttrium, niobium and the rare-earth elements. In pegmatites yttrotitanite (keilhauite) may be comparatively common. Many exotic titanium and rare-earth bearing silicates are also known to occur, almost exclusively, in these rocks.

The behaviour of the important titaniferous minerals during metamorphism is a subject discussed directly and indirectly in much of this thesis. The complication of the subject lies primarily in deciding whether certain host rocks are metamorphic or magmatic in origin, no easy task when rocks of the granulite facies are under consideration. The subject will only be outlined in this introduction. Titanium oxides and titanates of iron all seem to be stable in the high temperature, moderate pressure metamorphic facies. In the eclogite facies, rutile may be the only stable phase. In the epidote-amphibolite facies ilmenite becomes unstable, or at least

metastable, and rutile and sphene are the stable phases depending
on the paragenesis. Metamorphism in amphibolite facies can be most
important as an upgrading agent for otherwise economically valueless
titaniferous magnetite ores. If magnetite containing titanium
in lamellae or solid solution is held at the reduced temperature
of the low temperature portion of the facies, the titanium content
has time to exsolve more completely than during crystallization,
presumably at an accelerated rate, from a magma. In lower temperature
and more hydrous facies much titanium enters silicate lattices but
rutile probably remains stable and its allotropes, brookite and anatase,
stable or metastable, are also found in these facies.

In the cycle of erosion and sedimentation titanium minerals,
especially ilmenite and rutile, tend to concentrate together on
account of their common high specific gravity, hardness and relatively
high chemical stability in the conditions. Ultimately and
inevitably the minerals are broken down and some of the titanium
enters clay minerals where it is bonded to hydrous silicates of
aluminium. However, TiO_2 as rutile, and possibly some hydrous TiO_2,
survive to accompany the clay minerals as a separate phase.

TITANIUM ORES: A GENERAL CLASSIFICATION

Titanium ores fall into two principal classifications, primary
(magmatogenetic) and secondary (exogenetic). There are also
two important titanium-bearing ore-minerals, ilmenite and rutile.
Small quantities of other titaniferous minerals are mined, notably
those containing rare-earth elements, but not for their titanium
content, although in some cases this may be recovered as a by-product.

The primary titanium ore deposits are very largely composed of ilmenite, although a few contain subsidiary amounts of recoverable rutile. Primary rutile deposits are of small size and, of recent years, have assumed a position of no economic importance. Many secondary deposits contain both ilmenite and rutile in economically important quantities. They are concentrated together on account of their hardness chemical stability and high specific gravity in the environment of erosion and sedimentation. It is, in part, this association of the two minerals, and the ease of mining this type of deposit, which has provoked an increasing interest in secondary deposits in recent years. Many mining operations, which have commenced with the primary intention of producing ilmenite, have found the presence of a small amount of recoverable rutile, a mineral of considerably greater value, to be most useful in providing a reasonable profit margin.

In Volume I of this thesis the geology of the primary and secondary deposits is discussed separately since, for various reasons which will become apparent, it is more convenient to treat them in this way rather than deal with them on the basis of a mineralogical classification. The primary deposits are subdivided under two main headings (i) (Chapter III) those associated with large areas of anorthositic rocks and (ii) (Chapter IV) those associated with other magmatic or metamorphic/metasomatic rocks. They are discussed in this way not because titaniferous minerals are more abundant in anorthosites, so being deserving of special treatment, but because rock masses of this type contain actual or potential orebodies with remarkable frequency. In other magmatic rocks the titaniferous minerals are, in general, not to be considered

actual or potential titanium ores and so merit a less extended discussion. The basis of discussion in each category has been the presentation in some detail of first-hand results of example areas followed by a consideration of other ore deposits in a comparative fashion, the length of description in individual cases depending ideally on economic and geological importance but, only too often, actually on the volume of published results which is frequently meagre.

Primary Titanium Ore Deposits

The primary titanium ore deposits can be broadly classified in the following groups:-

A **Deposits associated with 'batholithic' anorthosites, leuconorites and leucogabbros.-** These deposits can be subdivided into i) massive and vein deposits in which the ore minerals comprise over 66% of the orebody and occur in ore-rich stringers (e.g. Blaafjell, S.^{W}. Norway) and ii) disseminated deposits in which the ore-minerals are spread evenly throughout the host-rock (e.g. Storgangen, S.W. Norway). The deposits are not normally _in situ_ derivatives of the enclosing anorthosite but are, or occur in, a melanocratic variant of it, usually a melagabbro or melanorite with or without olivine. The orebodies are found within (rarely at the margins of) the main mass of the anorthosite and frequently appear to be associated with zones of tectonic dislocation.

Ilmenite is the titanium ore mineral in all deposits in this group. Normally it contains abundant exsolution discs of hematite which lower the TiO_2 content, but it may be free from all exsolution phenomena. Magnetite usually occurs with the ilmenite

but in most ores only in small amount, up to approximately 20% of the opaque minerals. However, some deposits contain as much magnetite as ilmenite (Lake Sanford, New York State) and in this circumstance the ilmenite may contain exsolved magnetite as well as hematite. Graphite in small quantities may also be present. A rather rare variant of type (ii) contains rutile in sufficient quantity to be an ore mineral. The only known occurrences are in North America at St. Urbain, Quebec and Roseland, Virginia but another example which may be of this type occurs in Nyasaland.

B <u>Deposits associated with gabbros and gabbroid derivatives.-</u> The host rocks to deposits which fall into this group include pyroxenite, peridotite and rarely olivinite. Morphologically the deposits vary from disseminations of low concentration to vein, massive, lensoid and tabular bodies of varying size. High concentrations of opaque minerals are usually associated with considerable hydrothermal alteration of the host rock. Complementary intrusions of granophyre are not uncommonly found nearby. The opaque minerals of the 'ores' may be ilmenite, usually free from exsolution structures but sometimes containing exsolved hematite or magnetite, which is commonly accompanied by magnetite usually containing exsolved ilmenite, sometimes ulvospinel, and almost always a magnesian spinel. Magnetite is frequently the dominant opaque mineral, the titanium content of the 'ore' being concentrated entirely within the magnetite's crystal boundaries. Deposits of this type are of no economic value at present. The titanium content of the ores is often linked closely to the composition of the host rock in a manner described and discussed in the earlier part of this chapter and in Chapter IV. Metamorphism may affect the economic potential of a deposit (see Group F).

C   <u>Deposits in large layered basic complexes</u>.-   Deposits of this
type are really a special case of the preceeding group **or**, perhaps,
more correctly the members of the preceeding group are all special
cases of this group.   However, the distinction is made on account
of the genetic importance of the complexes in this group.   They are
so large that their displayed features must represent close
approximations to fundamental processes of rock differentiation in
the lithosphere, and must contain a key to the behaviour of
titanium within the crust.

Economic ores are not found within complexes of this type
such as the Bushveld and the Colony Complex Sierra Leone.   They
consist predominantly of titaniferous magnetite with subsidiary ilmenite.
The overall titanium content is usually about 18-20% at maximum.
The ore minerals tend to accumulate with anorthositic and leuconorite
or leucogabbro, in which the plagioclase has a more calcic
composition than that in the batholithic anorthosites, where the
titanium content of the ores is normally much higher.

D   <u>Titanium mineral accumulations associated with granites</u>.-   This
is an unimportant group as far as ores are concerned.   Ilmenite
is only an accessory mineral in this group, rutile or sphene
replacing it.   Concentrations of the minerals do not normally
occur as magmatic crystallizates with the granites, in contrast to
the anorthosites, but are either contact metasomatic in origin
(Adirondacks) or are found in late differentiates of an intrusive
nature (Kragero; South-west Africa).   There is no clear-cut division
between some occurrences of this type and those of group E.   It is
significant that non-titaniferous magnetite and titaniferous minerals
occur together in this paragenesis.

E <u>Deposits associated with alkaline intrusions.</u>- Titanium is concentrated in certain alkaline and peralkaline rock complexes (Kola Peninsula; Arkansas) in association with rare-earth bearing minerals. Four subdivisions of the group can be delimited.

(i) Ultrasic alkaline masses containing knopite and titaniferous magnetite.

(ii) Lujavrites-foyaites-urtites containing loparite.

(iii) Alkaline and feldspathoidal syenites containing sphene and ilmenorutile.

(iv) Carbonatite intrusives containing titaniferous magnetite and sphene (particularly East Africa).

F <u>Deposits in metamorphosed gabbroic complexes.</u>- This group should strictly be considered as a subdivision of group B but is classified separately on account of its economic importance. Metamorphism, particulaly in the amphibolite facies causes recrystallization of titaniferous magnetite and liberates the trapped ilmenite as a discrete mineral phase. However, as ilmenite is only metastable in at least part of the amphibolite facies in contact with silicates, orebodies may become dispersed if their constituent minerals are exposed to reaction during the metamorphic process. Among metamorphogenetic ores there is probably a connection between group F and group A, if some of its deposits are, as suggested elsewhere in this thesis, of metasomatic origin. This emphasizes the importance of metamorphism as an ore-forming process. There is some evidence which suggests that prolonged metamorphism in the chlorite facies including perhaps minor metasomatism, can produce a magnetite-rutile bearing rock from a titaniferous magnetite-rich gabbro. There are no actual ores of this type known but the process may prove to be of some

importance.

The Secondary Titanium Ore Deposits

Secondary titanium ore deposits, which are discussed in detail
in Chapter V can be classified into three main groups.

A Lateritic soils - residual deposits.- Lateritic soils, formed
on and from basement complexes of metamorphic or igneous origin
which contain only normal amounts of titaniferous minerals,
retain and concentrate stable titanium compounds such as rutile, anatase
and leucoxene. In themselves these deposits are of no immediate
economic importance although methods of extracting the titaniferous
minerals, allegedly economically, have been described. Their
importance lies in their role as an intermediate stage in the
process of concentration leading to the formation of widespread heavy
mineral deposits on ocean beaches.

B Eluvial and alluvial deposits.- Deposits of this type, to be
of any great value must be derived from igneous and metamorphic
deposits already considerably enriched in ilmenite or rutile (Brazil,
French Equatorial Africa, Malaya).

C Ocean beach and bar deposits.- Both present-day and fossil
ilmenite and rutile concentrations are important ores in this group.
They provide most of the world's rutile production. (E. Australia;
Florida). They are formed from large basement complexes of
igneous and metamorphic deposits containing low concentrations of
the ore minerals via intermediate sedimentary formations or laterites.
Factors of importance for their formation are 1. A suitable
hinterland containing the titaniferous minerals. 2. A long period
of tropical weathering to release the minerals from bedrock and to
destroy undesirable silicates. 3. Rapid transport to the ocean

caused by uplift of the land or a fall in sea-level. 4. Constant winds causing the sea to re-work the sand over considerable periods of time.

Ilmenite in beach deposits has distinct characteristics rarely encountered in ilmenites in primary deposits. It has always suffered leaching of iron and is, in fact, in transition to leucoxene, here a mixture of ilmenite and crypto- and microcrystalline rutile. The TiO_2 content of the ilmenite is often above the theoretical amount on account of this. Other economically valuable minerals such as monazite and zircon are often concentrated with the titanium minerals.

CHAPTER II

THE MINERALOGY OF TITANIUM.

This chapter is intended to be introductory in character and does not set out to present a detailed mineralogical account of the naturally occurring forms of titanium.   Most of the minerals are only briefly mentioned since they are of little importance in titaniferous ore-deposits, but where possible references are given to other works where mineralogical details are available.   In the case of minerals of importance to the main body of discussion in this thesis a more extended treatment is presented.

There are six main groups of titaniferous minerals, simple oxides (RO_2), double oxides (ABO_3), multiple oxides, titan-niobates, titan-borates and titansilicates.   Each group is examined systematically in the following pages.   Two important works of general reference are "Dana's System of Mineralogy" by Palache, Berman and Frondel Volumes I (1944) and II (1951), and "Gmelins Handbuch der Anorganischen Chemie: Titan".

SIMPLE OXIDES (RO_2)

There are three principal natural modifications, rutile, anatase and brookite each of which has a similar fundamental lattice structure - (TiO_6) of which each three shares in each oxygen atom. In special cases trivalent iron or chromium may substitute for titanium as in pseudobrookite and nigrine.

Divalent titanium oxide has been recognised in furnace slags (Carstens 1928;1931) but is unknown in rocks.

Rutile (TiO_2)

Rutile is the most commonly occurring oxide of titanium and may be the most abundant titanium mineral.   It is particularly widespread in metamorphic rocks especially in granulites and eclogites. It is the only stable titanium mineral in a pegmatitic-pneumatolytic environment and it is in rocks in this category that most of the few hard-rock ore deposits of the mineral have been found.   It is also abundant in hydrothermal veins but anatase may, in part, take its place here.   Rutile is a very common inclusion in many minerals, notably quartz, micas and feldspars.   It is often found enclosed in minerals where it has been formed,possibly by exsolution, during meta-morphism.   Intergrowths with hematites are often caused by the dis-integration of ilmenite.

Rutile is very stable during the cycle of erosion, sedimentation and diagenesis and is present in most sedimentary rocks.   It is most frequently a detrital mineral (Rastall 1939) accumulating on ocean beaches and in alluvial and eluvial deposits in economic concentrations (see Chapter V) but can, apparently, also be of authigenic origin

(Gardner 1955). It certainly forms as a decomposition product of ilmenite in a sub-aerial environment (see Chapter V). In certain metamorphic and magmatic environments (Watson 1922; Kokta 1936) it may be converted to ilmenite.

Chemistry.- Naturally occurring rutiles normally contain about 97% TiO_2, ferric and ferrous iron being the commonest contaminants. The black variety Nigrine, usually contains higher proportions of iron, up to 12% Fe_2O_3. Some nigrines have an oxygen deficiency and become almost colourless when oxidised (Golding 1956). Small quantities of Sn, Cr, V, Mo, and Sn have been recorded in certain rutiles (Shilin 1940; Watson 1912).

The niobian variety ilmeno-rutile, may contain up to 33% Nb. It can be regarded as a mixed crystal lying between rutile and mossite. It occurs in granitic and alkaline pegmatites (Sosedko 1939; Chernik 1921; Anda and Nitta 1941; Tavora and Scorza 1948; Fleischer et alia 1952).

Strueverite, the tantalian variety, can be regarded as a mixed crystal lying between rutile and tapiolite. The Ta_2O_5 content may reach 35%. It has a similar paragenesis to ilmenorutile (Nefedov 1941; Lacroix 1922; Prior and Zambonini 1908).

The melting point of rutile is between 1690 and $1700^{\circ}C$. (Watson 1922). Rutile is the stable form of TiO_2 at all temperatures.

<u>Physical Properties</u>.- It is tetragonal with a hexagonal packing structure, and commonly forms stout prismatic crystals, more rarely needle-or hair-like (Sagenite).   Crystal parameters are a = 4.584 $\pm$ .002Å; c = 2.953Å (LeGrand and Delville 1953; Tokody 1927).   It may form intergrowths with magnetite (see Chapter IV), ilmenite (Jarosch 1955), hematite, brookite, anatase, apatite and quartz.

For optical properties in transmitted light see standard works. In reflected light the colour of rutile is grey-white with a reflectivity of 18% (Ramdohr 1950).   It is distinctly anisotropic.   Internal reflections are red-brown.

Anatase (TiO$_2$).

Anatase (octahedrite, captivos) is formed, in general, by the decomposition of other titanium minerals in hydrothermal or pneumatolytic conditions (Brammall and Harwood 1927).   It is unlikely that it can form as a primary magmatic crystallizate.   It occurs and forms in sedimentary deposits (Serdyochenko and Dobrotvorskaya 1949), commonly as 'leucoxene' (see Chapter V; de Lapparrent 1930).

<u>Chemistry</u>.-   It normally contains over 98% TiO$_2$.   It may contain trace amounts of Na, Ca, Al, Si, Sr, Fe and Mg.   At 900°C. and atmospheric pressure it converts to rutile in under two hours.   With a pressure of 7 tons/sq.cm. it converts at 850°C. in eighteen hours (Thienchi 1946; Schroeder 1928). A reversible change from an α to a β form occurs at 915° $\pm$ 15° (Schroeder op.cit.).   Practical experience in the titanium oxide pigment industry has shown that the temperature of transformation of anatase to rutile is modified by the addition of very small percentage of impurity and that the transformation temperature can be depressed or

elevated.   Experience has also shown that rutile cannot be converted

directly to anatase without an intervening stage in which the titanium

passes into solution.

<u>Physical Properties</u>.- It is tetragonal with cubic packing, generally

pyramidal in form (see Magistretti 1945; 1953 for crystallographic details).

Crystal parameters are a = 3.777A ± .003;   c = 9.5-1A ± 0.004 (LeGrand

and Delville 1953).

For optical properties in transmitted light see standard works,

and for reflected light properties Ramdöhr (1954) and Uytenbogaardt (1951).

Brookite (TiO_2)

The paragenesis of brookite is similar to that of anatase but

it may occur as a primary magmatic minera l (Landes 1931; Reed 1949;

Kornetova 1954).

<u>Chemistry</u>.- It normally contains between 94 and 99% TiO_2 with iron the

most common impurity.   It may also contain Sn, Pb, Si, W and Nb; (up to

2.4% Fleischer et alia 1952).

<u>Physical Properties</u>.- It is orthohombic with unit cell dimensions

a = 9.166A; b = 5.436A; c = 5.135A.   For crystallographic and optical

details see Holzgang (1930); Ikornikova (1946; 1948); Melon (1949);

Pauling and Sturdivant (1928); Phillips (1932) and Rudolph (1944).

Pseudobrookite (Fe_2TiO_5)

Pseudobrookite is classified with the simple oxides for

convenience since it occupies a position between them and the double oxides.

Pseudobrookite occurs principally with eruptive rocks associated especially with fumaroles and rarely as an oxidation product of ilmenite in other paragenesis (Ramdohr 1956). It has not been certainly recorded as a primary magmatic crystallizate. Ernst (1943) prepared pseudobrookite by fusing Fe_2O_3 and TiO_2 together in vacuo. In air ilmenite predominated over pseudobrookite in the product.

Chemistry.- It contains 38 to 52% TiO_2 and 42 to 61% Fe_2O_3 with up to 7% MgO. The variable values have been attributed (a) to rutile intergrowths (Palache 1935), and (b) to the assimilation at high temperature, without variation in the unit cell dimensions, of TiO_2 and FeO (Ernst 1943).

Physical Properties.- The unit cell dimensions are a = 9.78A; b = 9.80A; c = 3.65A (Mark and Rosebaud 1926) or, a = 9.79; b = 9.93A; c = 3.725A (Pauling 1930). It is orthohombic.

For optical properties see Starraba (1942; 1950); Gliszczynski and Stoicowici (1937); Palache (1935) and Ramdohr (1954).

Anosovite (Ti_2TiO_5)

The synthetic mineral anosovite, which has been found in furnace slags, has the pseudobrookite type of structure (Rusakov and Zhdanov 1950-1952; Ostrogorskaya 1956).

DOUBLE OXIDES

Under the heading double oxides are included hematite, and the ilmenite series. The former combines divalent and trivalent cations and the latter divalent and quadrivalent.

Hematite (Fe_2O_3)

Hematite is very widespread in many types of rock from high

temperature magmatic to sedimentary.   Here only a selection of the properties and relationships will be considered in so far as they bear upon occurrences with titaniferous minerals.

Structure.- Hexagonal rhombohedral a_O = 5.029; c_O = 13.79 (Palache, Berman and Frondel).   The oxygen atoms lie in hexagonal close packing with the Fe ions lieing between six oxygens forming an octohedron.

Optical Properties.- In polished section pure hematite is white or pale bluish-white in colour with a reflectivity of about 26% in white light. It shows very weak pleochroism and distint anisotropy.   Titaniferous varieties are less reflective and usually show a slightly brownish-white colouration - in fact the optical properties are intermediate between Fe_2O_3 and $FeTiO_3$.

Chemistry.- The relationships between Fe_2O_3 and Fe_3O_4 are rather complicated and extremely dependant on the environment.   Gheith (1952) found that in natural magnetites the change commenced at 625^OC in dry air and was incomplete at 1100^OC.   Greig, Posnjak, Merwin and Sosman (1935) have shown that at 1452^OC hematite containing less than 1% of Fe_3O_4 is in equilibrium with magnetite containing 30% Fe_2O_3.   In vacuo hematite melts at about 1380° but the temperature rises rapidly with increase of pressure. With slow cooling hematite exsolves from magnetite along the 111 cleavages planes.   It is interesting, and of some importance in ore formation, that Grieg et alia found that exsolution was hastened more by relief of strain within the solid solution than by slow cooling.   The presence of water vapour catalyses the change $Fe_3O_4 \rightarrow Fe_2O_3$ which then commences at 258° (Gruner 1926; 1931).

Gheith (1952) observed that synthetic Fe_3O_4 converted in dry air first to maghemite (γFe_2O_3) at varying temperatures between 375° and 280^OC, the change to hematite (αFe_2O_3) occurring at between 590° and 650^OC.

Water vapour again catalysed the reaction, lowering the temperatures to 210° and 460°C. respectively. The different behaviour of synthetic and natural Fe_3O_4 is thought to be due to differences in the unit cell, the synthetic variety being deficient in divalent iron and containing (OH) in partial replacement of oxygen (Gheith 1952; Starke 1939).

The temperatures of transformation to the hydrous oxides goethite (α Fe_2O_3) and lepidocrocite (γ Fe_2O_3) also depend on the environment of transformation. Synthetic lepidocrocite converts to maghemite at 320°C and this converts to hematite at 560°C (Gheith 1952) in air. Natural lepidocrocite converts at $350^\circ \pm 10^\circ$C (Kulp and Trites 1951) to maghemite, and goethite to hematite at 395°C. Maghemite apparently alters to hematite at $390 - 450^\circ$C in natural specimens. In aqueous neutral solution goethite alters to hematite at $125^\circ \pm 15^\circ$C and in alkaline solution at $165^\circ \pm 5^\circ$C (Smith and Kidd 1949).

Between hematite and ilmenite there exists a solid solution series which is probably continuous (Ramdohr 1926; 1956) at magmatic temperatures, although other writers (Chevallier, Bolfa and Mathieu 1955; Buddington, Fahey and Vlisidis 1955) think there is an immiscibility gap from Fe_2O_3;$FeTiO_3$, 2:1 to 1:2. Ramdohr's evidence, photographs of 1:1 exsolution intergrowths, is very strong and is supported by Millman (1957) and observations made by the present writer. On cooling the solid solution separates into two components, a titanhematite and a hemato-ilmenite, each of which contain exsolution bodies of the other. As cooling proceeds, if at a sufficiently slow rate, the components exsolve more and more completely from one another. The maximum TiO_2 content of hematite at normal temperature is 10% (Edwards), whereas ilmenite contains 6% Fe_2O_3.

Hematite not uncommonly contains exsolved rutile in 2243 directions. This exsolution texture can only occur at a high oxidation potential and is encountered in low temperature quartz-veins and

metamorphic rocks.   Ilmenite exsolved in the 2243 direction allegedly

occurs in emery ores (Bray 1939) but it is doubtful whether the ilmenite

was diagnosed correctly.

Secondary hematite ('martite') is commonly formed in titaniferous

ores either by low-temperature hydrothermal alteration or by weathering

of magnetite.   In such cases it is often possible to compare it with

titanhematite exsolved from nearby ilmenite where it is always whiter

and has a higher reflectivity.   Rutile is often formed with it from

the titanium contained in the disintegrated magnetite.

ILMENITE ($FeTiO_3$)

Ilmenite (menaccanite, crichtonite) is probably the only

natural form of $FeTiO_3$ although Bannister, Claringbull and Hey (1953)

allege the existence of a separate mineral crichtonite, having the large

unit cell dimensions of a = $37A^O$ and c = $21A^O$.   Titanium in ilmenite

is quadrivalent (Hamos and Scherbina 1933; Jakob 1937).

Ilmenite, or as it was originally termed, menaccanite, was dis-

covered by a Cornish clergyman, the Reverend William Gregor in 1791 and a

description of it was published in Crell's Annalen.   Klaproth, who has

often been credited with the discovery, also described it some years

later.   Other obsolescent names which were later applied to it are

Kibdelophan (Kobell) ; Mohsite (Levy) ; Hystatite (Breithaupt) ;

Basnomelane (Kobell) ; and Axotomous Eisenerz (Mohs).

Ilmenite which is hexagonal rhombohedral has a structure cell

with the dimensions a_O = 5.083A and c_O = 14.04A (Palache, Berman and

Frondel; Barth and Posnjak 1934).   It commonly forms compact granular

masses; single crystals are usually tabular.   Twinning occurs on 0001

and lamellar twinning on 1011 is common.   The hardness is between 5 and

6 and the observed density 4.72 $\pm$ 0.04 (Palache, Berman and Frondel),

In very thin fragments it transmits red light and is optically negative (Ramdohr 1950).

Optical Properties (Reflected Light).- The properties of ilmenite in reflected light are described and illustrated in later chapters and, except for measurements of reflectivity, only a summary will be given here.   It varies in colour from grey-white to rosy-brown white to a pale stone colour; most probably the variations are caused by other mineral phases in solid solution with the $FeTiO_3$.   Reflectivity also varies with composition and a list of values obtained by the writer using a Cooke, Troughton and Sims microphotometer are given in Table 2.1. In taking each set of readings care was exercised that a stable current was being applied to the instrument during the period of observation. Ilford Spectrum Filter Yellow 606 ($\lambda = 581$) was used for the measurements. At that wavelength the reflectivity of the basal section of quartz used for comparison (R.I. = 1.5446) was 4.581 (calculated).

Table 2.1

No.	Locality	Reflectivity n0 $\lambda = 581$	Remarks.
F673	Carrock Fell	18.5	Ilmenite without exsolution
1G30	Carrock Fell	18.7	lamellae
40	Skaergaard, Greenland.	18.5	Some interference from fine magnetite lamellae.
II7066.9	Otanmaki, Finland.	18.3 -18.6	Some interference from very fine magnetite and hematite lamellae.
B13	Blaafjell, Norway	17.3	Some interference from fine hematite lamellae. Coarse lamellae also present in the specimen.
K3	Koldal, Norway	17.9	As B13.
Od6	Odrevann, Norway	19.4 -19.5	Interference from hematite lamellae.
St1	Storgangen, Norway	19.3	Some interference from fine hematite lamellae.
T13	Tellnes, Norway	19.2	As St1.

A point of interest which emerges from the table is the general similarity in values for ilmenites from similar rock-types in different deposits. Thus FG73, 1G30, 40 and II7066.9 are all from gabbroic ores. B13, K3 and Od6 are from vein ores in anorthosite and St1 and T13 are from massive norite ores in anorthosite. Values for nE at λ = 581 were generally between 2.3% and 2.8% lower than for nO.

A series of readings were taken of nE for specimen Od6 at varying wavelengths by two different observers as a check on the human element. It provided interesting preliminary results, for it showed that although similar values were obtained in light of long and medium wavelengths, towards the blue end of the spectrum results differed markedly. This was attributed to differences in colour vision of the two observers.

Table 2.2

λ	685	600	581	550	520	492	470
Observer 1 nE	17.5	16.3	17.1	15.8	16.2	15.2	16.3
Observer 2 nE	18.3	16.8	17.2	16.5	16.1	17.9	19.0
Observer 1 nO	20.6	20.7	19.5	18.2	19.2	19.1	19.9

It was hoped that measurements of reflectivity taken in light of different wavelengths might provide diagnostic data if correlatable with analytical data. However, from the provisional results it appears that the method is not sufficiently objective for the purpose.

Pleochroism is an important diagnostic characteristic of ilmenite. Weak in air, it is quite marked in oil and serves to distinguish it from magnetite: nO is grey-white to stone colour and nE is a more distinct brown. The anisotropy is marked, the colours varying for specimens from different localities. Most commonly the colour is similar to the rosy-brown observed in plane polarised light but some specimens show a blue-grey, and rarely a slight greenish tint is visible.

In observing these colours it is of paramount importance that the light should be _precisely_ cross-polarised otherwise anomalous colours are observed. Many descriptions in the literature are undoubtedly of low reliability on this account. The maximum angle of rotation of the plane of polarisation observed by the writer, measured parallel to the c crystallographic axis, is 2.4°.

Chemistry and Exsolution Textures.- A great deal has been written concerning exsolution textures of ilmenite and genetic theories developed from such studies are manifold. It is not intended to review all these works here. Important contributions, mostly of a general nature, to which direct reference is not made elsewhere in this text are as follows:-
Bastin, Graton et alia; Cathrein (1884;1887); Cooke; Lindgren (1930); Newhouse (1936); Capdecomme (1941); Chirvinski (1928); Greig; Labuntzov (1926); Magistretti (1912); Orcel and Jouravsky (1938); Short (1940).

Pure ilmenite, in which the theoretical values of 52.66% TiO_2 and 47.34% FeO are closely approached, is a comparatively rare mineral. There are commonly varying amounts of MgO, MnO and Fe_2O_3 contained in solid solution and exsolved Fe_2O_3 and Fe_3O_4 may also be present. At normal temperatures and pressures there is probably complete solid solution between ilmenite and geikielite $(Mg,Fe)TiO_3$, which may extend to $MgTiO_3$ (Bonshedt-Kupletskaya 1952). Similarly there appears to be complete solid solution between ilmenite and pyrophanite $(MnFe)TiO_3$ at normal temperatures. In titanium ores the magnesium and manganese contents are not commonly over 2% of the respective oxides. On the other hand trivalent iron is a common and often abundant constituent of most ilmenites.

Between Fe_2O_3 and $FeTiO_3$ there is probably complete miscibility at magmatic temperatures, as discussed under the heading hematite. With falling temperature the hematite molecule exsolves from the

ilmenite as lobate and irregular discs on the 0001 cleavage plane.   In section they are spindle-shaped.   It has been suggested (Ramdohr) that the exsolution proceeds in two distinct stages giving rise to a generation of coarse discs and a later generation of much finer discs, the second stage being initiated by a change in the symmetry of the ilmenite.   This has been criticized by Edwards (1938 and later) and it seems that in some specimens the difference in size of the exsolved discs is not distinct the change being rapidly transitional rather than sharp.

There are, apparently, two different modifications at the $FeTiO_3$ end of the solid solution series, which though similar chemically have different magnetic properties and probably slightly different structures.   Most ilmenites are paramagnetic (Pouillard and Michel 1949:1950) but synthetic and natural specimens of a ferromagnetic variety have been investigated by Chevallier, Bolfa and Mathieu (1955). These ilmenites, homogenous to X-rays and often deficient in FeO, have been called ferri-ilmenites on account of their Fe_2O_3 content which is frequently as high as 20%.   The natural specimens have long been called 'iserine', a term of general application to minerals whose composition falls between ilmenite and rutile and which may be ferro-magnetic.   Most of them are probably mixtures but those investigated by Chevallier were quite homogenous and their properties were attributed to a different arrangement of iron and titanium in the ilmenite lattice. Ramdohr (1956) has observed a myrmekitic intergrowth of, apparently, ilmenite in ilmenite in 'iserine' which he has suggested may be the cause of the magnetic properties.   He is also of the opinion that it may be composed of two different modifications of ilmenite.

The system Fe_2O_3 - TiO_2 - $FeTiO_3$ is not thoroughly understood

but, as pointed out elsewhere (Chapters I and V), at a high oxidation potential ilmenite becomes unstable. This instability causes the development of rutile exsolution bodies in $Fe_2O_3 - FeTiO_3$ mixed crystals (Edwards 1947; Ramdohr 1956) and in ilmenite (Baker 1952). Baker noted that rutile lamellae in ilmenite stopped abruptly against magnetite crystal boundaries which suggests that TiO_2 cannot exsolve as such direct from magnetite. Jarosch (1955) has described a number of examples of the formation of rutile and hematite from ilmenite and has noted that rutile never occurs in close proximity to ilmenite in the absence of hematite. TiO_2 also separates from ilmenite during sub-aerial weathering not as oriented exsolution bodies but irregularly in a microcrystalline state (see Chapter V). At high temperatures, found only in volcanic rocks, pseudobrookite becomes a component of the system.

Ilmenite and magnetite form at very high temperature a poly-component system developing magnetite, ulvospinel, ilmenite and titanate ($2Fe_2O_3$. $3TiO_2$)phases (Pouillard 1950). At normal magmatic temperatures it seems unlikely that a complete solid solution series exists between magnetite and ilmenite, there is probably a gap between magnetite:ilmenite 1:1 to 1:4. Exsolution textures to fill the hypothetical gap have not been observed.

Ilmenite exsolves from magnetite along the 111 cleavage planes and magnetite from ilmenite along the 0001 direction. Both types of exsolution body are thin and tabular in form. Ilmenite lamellae very rarely contain a few hematite discs (Ramdohr 1956). As well as forming lamellae both minerals show a strong tendency to form irregular blobs within each other. These are sometimes located at twin-plane intersections (see Chapter IV) The degree of miscibility of magnetite in ilmenite is uncertain, being complicated by the fact that many magnetite lamellae have been formed from exsolved hematite discs by reduction. Within a

single ilmenite crystal magnetite and hematite lamellae are always separated by an area of ilmenite devoid of exsolution structures (see Chapter IV) For the same reason it is also uncertain whether magnetite and hematite can both exsolve from a single ilmenite phase.

At lower temperatures the stability relationships of ilmenite and magnetite seem to vary depending on the redox potential, and probably other factors as well.   Magnetite is sometime quite unstable (see Chapter Iv, Carrock Fell) yet in other circumstances it is stable and may replace ilmenite.   It is possible that the titanium content of the magnetite is very critical and that titaniferous magnetite is more unstable than ilmenite and much more unstable than titanium free magnetite. Jarosch (1955) has described some unusual replacement phenomena involving a) the liberation of ilmenite from titan-hematite after replacement by magnetite, and (b) the development of magnetite and rutile intergrowths from ilmenite.   Replacement of ilmenite by sphene is a common phenomena in certain metamorphic rocks formed at low to moderate temperature (see Chapter IV, Otanmaki).

The replacement of other minerals by ilmenite is a subject considered in the genetic discussions in Chapter III where the relationships with silicates are important.   Replacement of rutile is known to occur (see Rutile page 16) and replacement of perovskite has been described (Lebedev and Rimskaya - Korsakova 1949).

Ilmenite does not always bear a replacement relationship to silicates for limited miscibility seems to occur with pyroxenes and perhaps olivine at high temperature.   Ilmenite is, in particular a common inclusion in 'bronzite' and it is quite probable that in many cases these inclusions have actually been exsolved from the pyroxene. Intergrowth textures with silicates have been observed by, amongst others

Palmunen (1925; Odman (1932) and Vaasjoki (1947). Immiscibility of ilmenite and silicates has often been suggested and could account for many textural features of ores, but experimental evidence is completely against such a hypothesis.

<u>Geikielite (MgFe)TiO$_3$</u> .- Geikielite or 'picroilmenite' is ilmenite in which magnesium has replaced part or most of the ferrous iron. The unit cell dimensions (Palache, Berman and Frondel) are a = 5.54A^o and c = 14.093. It is of no economic interest, occurring as a rare associate of ilmenite and accompanying gem stones in some gravels (Efremov 1954).

<u>Pyrophanite (MnFe)TiO$_3$</u>.- Pyrophanite or 'manganilmenite' is a rare constituent in pegmatites, usually those associated with alkaline intrusions. It has unit cell dimensions of a = 5.62A^o and c = 14.333 (Simpson 1928; Omori and Hasegawa 1955).

<u>Silicoilmenite</u>.- Silicoilmenite is a name which has been given to a red-brown mineral alleged to represent a solid solution of ilmenite and silica (Pilipenko 1930).

<u>Davidite</u>.- The uraniferous-titaniferous mineral davidite is probably not a true species, the TiO$_2$ content being contained in admixed ilmenite and/or rutile.

MULTIPLE OXIDES

This group contains the two minerals hoegbomite and perovskite and the spinel group of which only magnetite and maghemite are of interest in the present context. Perovskite, essentially a simple oxide of calcium and titanium, is however not very similar to ilmenite. It occupoes an intermediate position between the multiple oxides and the

complex columbates, tantalates and niobates.

Hoegbomite (AB$_4$O$_7$ type)

Hoegbomite Mg (Al,Fe^{111},Ti)$_4$O$_7$ where Al:Fe^{111}:Ti = 6:1:1 is a rare accessory mineral in certain titaniferous magnetite deposits, notably Routivare, Sweden (Ramdohr 1945).

Chemistry.- The TiO$_2$ content apparently varies from 5.53% in a natural spec- imen to a theoretical value of 13.36% (Palache, Berman and Frondel). Moleva and Myasnikov (1952) has also obtained values near 5%.

Physical Properties.- The mineral probably has a structure similar to that of ilmenite. nO = 1.853 nE = 1.803. It polishes well and has a reflect- ivity of about 9% similar to many silicates (Ramdohr 1950). Reflection pleochroism is weak, anisotropy is marked.

Perovskite Group ABO$_3$

Minerals of the perovskite group occur mainly in basic alkaline m rocks, both in the magmatic and deuteric stages, and in contact metam- orphed limestones. It also occurs very rarely in metamorphosed ilmenite- magnetite ores (Ramdohr 1956).

Pure perovskite contains 58% TiO$_2$ and naturally occurring varieties of considerable purity approximate to that value (Palache, Berman and Frondel; Sigismund 1948) Iwase and Fukusima (1932) have experimented with melts.

Physical Properties.- Perovskite is pseudoisometric, possibly monoclinic. Crystals consist of parallel twin lamellae. It may be isotropic or birefringent. In polished section it is similar to ilmenite. There is some doubt concerning the size of the unit cell (Palache, Berman and Frondel; Murdoch 1951).

Dysanalyte.- In dysanalyte columbium replaces titanium up to 26% Cb$_2$O$_5$ of the mineral and a few percent of iron usually accompanies it. At the same time calcium is partly replaced by sodium and rare-earth oxides.

Loparite.- Loparite, so far reported only from the Kola area of the U.S.S.R. may be richer in columbium than dysanalyte and probably has a lower iron content.

Knopite.- Knopite is probably the most common of the rare-earth bearing members of the perovskite group. It occurs in sufficient concentration to constitute ore and potential ore in the U.S.S.R. (Kupletskii 1936,1938; Florovskaya 1940), and in some of the African carbonatite centres (Broughton et alia 1950). North American occurrences are also known (Ellsworth and Walker 1925). The cerian replacement of calcium may reach 25% (Ce,La etc)$_2$O$_3$ of the mineral.

Irinite.- Irinite (Borodin and Kazakova 1954) contains sodium, cerium and thorium in almost complete replacement of calcium and niobium in partial replacement of titanium. There is also minor replacement of oxygen by hydroxyl ions.

Magnetite (Fe_3O_4)

Magnetite is the most common oxide mineral found in igneous rocks. Normally it is only an accessory but it becomes a major component in a few rocks and also in magnetite orebodies. In this account only titaniferous magnetite will be discussed, thus excluding the magnetite orebodies such as Kiruna.

Titaniferous magnetite accompanies ilmenite in many titanium 'ores' and frequently is the only important oxide mineral present (see Chapter I). Two series of titaniferous magnetites are recognised, those containing an excess of FeO, the ulvospinel-magnetites, and those without an FeO excess, the ilmenite-magnetites. The two series are not entirely separable since one magnetite crystal may contain both titaniferous phases.

Magnetite has a cubic structure cell containing $Fe_8''Fe_{16}'''O_{32}$, with dimensions $a_o = 8.374 \pm 0.003$A^O (Palache, Berman and Frondel) It has an inverse spinel structure (Barth and Posnjak 1934).

<u>Optical Properties (Reflected Light)</u>.- Pure Fe_3O_4 is a faintly brownish-grey colour and has a reflectivity of about 21%. With increasing content of titanium the reflectivity falls and the colour becomes more brown, often with a rosy tint. The blue colour (which may be due to the formation of maghemite) observed in some preparations is caused by dry polishing. The mineral is normally isotropic but anisotropy, usually caused by strain, has been reported (Ramdohr 1950).

<u>Chemistry and Exsolution Structures</u>.- For the purpose of the present discussion there are three solution series, Fe_2O_3 - Fe_3O_4, $FeTiO_3$ - Fe_3O_4 and Fe_2TiO_4 - Fe_3O_4, and the relationships of magnetite with coulsonite and maghemite, of importance.

The relationships of Fe_2O_3 to Fe_3O_4 have been discussed in the section on hematite. Martite or secondary hematite forms from magnetite in oxidising conditions at a low to moderate temperature. At low temperature hydrous iron oxides form directly from magnetite. Martite often follows the 111 cleavages of the magnetite as though exsolved from the host mineral and may be difficult to distinguish from exsolved Fe_2O_3. The relationships of hematite to magnetite have been discussed by Mugge (1911); Broderik (1919); Gruner (1926); Gilbert (1925,1926); Edwards (1949) and Ramdohr (1950 etc.)

It is appropriate here to briefly consider the relationship between maghemite (γFe_2O_3) and magnetite. Maghemite is a compound the occurrence and identification of which in rocks was long the subject of controversy, the course of which can be followed in the following works:- Gruner (1927,1929,1931); Newhouse and Callahan (1927); Newhouse (1929); Twenhofel (1927); Wagner (1927); Winchell (1931); Sosman and Posnjak; Frankel and Grainger (1941); Schwellnus and Willemse (1944) and Strauss. It is now established that it has a defect spinel structure with a cubic unit cell of size $a_o = 8.31A^o$. It is slightly more blue

than magnetite and isotropic in reflected light.   The conditions for maghemite, instead of hematite, development from magnetite are uncertain. So far it is only known to be common as a weathering product but the writer has once observed it in unweathered ore in minute quantity.   It is quite common in some sands (Takenchi 1953).

Coulsonite, the 'species' first described and named by Dunn and Dey (1937) may be a vanadiferous maghemite $(FeV)_2O_3$.   However, its validity as a separate mineral has been questioned by Roy (1954).   In appearance it is similar to maghemite, being isotropic and blue-grey in colour with a reflectivity of about 22%.   It has been recorded to occur only in titaniferous magnetites from Singhbhum, India and the Bushveld, South Africa.

A complete solid solution series exists between Fe_2TiO (ulvospinel) and magnetite at high temperature (Ramdohr 1956) as is evidenced by a study of certain exsolution intergrowths of the two minerals.   Ulvospinel is only found as an exsolution intergrowth with magnetite where it only rarely forms more than 50% of the mixed crystal.   It can form only in reducing conditions and hence is not found in company with hematite-ilmenite inter-growths, except where the hematite is secondary after magnetite.   However, both ulvospinel and ilmenite can exsolve from a single magnetite crystal, the ilmenite exsolving first along 111 planes, followed by ulvospinel along 100 planes.   This observed order of crystallisation (Ramdohr) contradicts Foslie's (1928), theoretical assumptions.   The magnetic properties of these mixed crystals have been described by Chevallier et alia (1955) and Akimato (1951) although the results of the latter are abnormal. The cell size of ulvospinel serves to emphasize its similarities with magnetite.   The occurrence of ulvospinel has been very thoroughly des-cribed by Ramdohr (1953).

The relationships between ilmenite and magnetite have been des-cribed in the section on ilmenite.   It is however worth mentioning here

the conclusions of Buddington, Fahey and Vlisidis(1955) who consider

that the TiO_2 content of magnetites in the presence of ilmenite is largely

controlled by temperature.   Their results indicate that this may often be

the case but the redox potential of the environment, stressed by Vincent

and Phillips (1954), must be recognised as a strong modifying influence.

TITAN-NIOBATES AND TITAN-COLUMBATES

The titan-niobates are of no importance in titanium ores and are

listed here for the sake of completeness only.   According to Palache, Berman

and Frondel they are more correctly regarded as multiple oxides.   They

are grouped below according to that type of classification.

ABO_4 Type

Pyrochlore - Microlite Series.- Several members of this series are titanium

enriched, notably titanian pyrochlore, hatchettolite and scheteligite.

Titanium occupies the 'B' position in the general form.   The minerals

occur in alkaline pegmatites and carbonatites.

Fergusonite Series.-   Risorite, a titanian variety contains about 6% TiO_2

Brannerite.-   A mineral of uncertain formula containing up to 35% TiO_2

(Hess and Wells 1920; Pabst 1954).

AB_2O_6 Type.

Euxenite - Polycrase Series.- The TiO_2 content of this series varies from

14% at the euxenite end to 34% at the polycrase end (Palache, Berman and

Frondel).   The variety tant-euxenite also contains a considerable pro-

portion of TiO_2 (Simpson 1928; Ellsworth 1928).

Aeschynite - Priorite Series.- The TiO_2 content of this series varies from 20%

to 34%, occupying the 'B' position (Palache, Berman and Frondel; Hermann).

Blomstrandine (Bjorlykke 1930) falls in this series.

Samarskite.- True samarskite contains less than 2% TiO_2 (Palache, Berman

and Frondel).   Samarskite which contained 4.29% TiO_2 (Hess and Wells 1930) has proved not to be samarskite.   Wiikite (Lokka 1928;1950) and Nuolaite (Lokka 1928) are ill-defined mixtures containing between 3 and 14% TiO_2 which consist mainly of samarskite.

AmBnOp Type.

Betafite.-   Titanian varieties of betafite contain up to 35% TiO_2 (Palache, Berman and Frondel) Lacroix 1922).

Ampangabeite.- Various indefinite minerals are grouped under this name. Some contain several percent TiO_2 (Palache,et alia; Chernik 1926).

Delorenzite.- Of uncertain formula, delorenzite contains 66% TiO_2.

TITAN-BORATES

Only one titan-borate is known as a naturally occurring mineral. Warwickite.-$(Mg_1Fe)TiO_3 . (BO_3)_2$ (Gmelin).

TITANSILICATES

The titansilicates are those silicates in which titanium is found as an independant quadrivalent cation forming in most instances between 10% and 50% by weight of the mineral.   Most of the titansilicates are rare minerals and many of them are only found in alkaline igneous rock complexes, where locally they may be relatively common.   They are not of any importance as ores of titanium although the element may be recoverable where the mineral is mined for its rare-earth content.   In view of their limited importance they are, in general, considered only briefly here.

Many rock forming silicates contain small amounts of titanium, rarely as much as 7% TiO_2.   They are not discussed here but their

effect on ore genesis is discussed in Chapter VI.

Nesosilicates.

Mermanite.- $(Na,Ca)(Ti,Mn,Mg,Zr)(OH)(SiO_4)$.   Kola Peninsula, U.S.S.R.
Gutkova (1930).

Ramsayite.- $Na_2Ti_2O(SiO_4)_2$. Gmelin 'Silicaten'.

Lorenzite.- $Na_2(Ti,Zr)_2 O(SiO_4)_2$. Gmelin 'Silicaten'.

Sphene.- $CaTiSiO_5$ or $CaTiSiO_4(O,OH,F)$, Sahama (1946).

Sphene is the most common richly titaniferous mineral found in
a wide range of acid igneous and metamorphic rocks.   In the epidote-
amphibolite metamorphic facies (see Chapter IV) it forms by replacement
of ilmenite.   It is a common accessory in granites and many pegmatites.
It is not a titanium ore-mineral, but may be mined on the Kola Peninsula,
U.S.S.R.   It contains between 33 and 44% TiO_2 in naturally-occurring spec-
imens.   Yttrium, cerium and manganese may replace calcium to form Keilhauite
and Greenovite and some aluminium and iron commonly replaces some of the
titanium at the same time.   Substitution of calcium by sodium leads to
Ramsayite.

The unit cell (monoclinic) has the following dimensions (Zachariasen
1930):- a = 6.55A ; b = 8.70A ; c = 7.43A.   The crystallography and optical
properties of the mineral have been investigated by the following workers:-
Bonshedt-Kupletskaya (1936); Bianchi (1914); Johnsen (1918); Konta (1949);
Meixner (1937); Morgante (1946); Obenauer (1934); Oberfoll (1931); Parker
1935, 1951); Prince(1938); Stranz (1937) and Webb (1939) amongst others.

Keilhauite.- $(Ca,Y,Ce)(Ti,Al,Fe''')O(SiO_4)$

Greenovite.- $(CaMn)TiO(SiO_4)$

Tscheffkinite.- $(Ca,Ce,Y,Th)(Ti,Fe'')O(SiO_4)$. (Kauffman 1946; Takubo et alia 1953)

Epistolite.- $(NaCa)(Nb,Ti,Mg,Fe,Mn)(OH)SiO_4)$.

Titanolovenite.- $(Na,Ca,Mn)_3(Zr,Ti)F(SiO_4)_2$.   Lovozero, Kola.

Rosenbuschite.- $(Na,Ca)_3(Fe,Ti,Zr)F(SiO_4)_2$.

<u>Rincolite</u>.- $Na(Sr,Ca,Ce)_2(Ti,Ce)F(SiO_4)_2$ or $Na_2O. 3CaO. Ce(F,OH)_3(Ti,Zn)O_2.$ $3SiO_2$ (Fersman 1926). Also known as Lovchorrite, Kola Peninsula.

<u>Rinkite</u>.- $Na(Ca Ce)_2(Ti,Ce)F(SiO_4)_2.$

<u>Johnstrupite</u>.- $(Ca Na)_3(Ti,Ce)F(SiO_4)_2$

<u>Mosandrite</u>.- $(Ca,Na,Y)_{2-3}(Ti,Zr,Ce)(H_2O,F)(SiO_4)_2.$

<u>Lamprophyllite</u>.- $Na_3Sr_2Ti_3(O,OH,F)(SiO_4)_2.$

<u>Fersmanite</u>.- $Na_4Ca_4Ti_4(O,OH,F)(SiO4)_3.$ (Labuntzov 1929).

<u>Lomonsovite</u>.- Allegedly analgous to mermanite with addition of Na_3PO_4 in place of OH (Gerasimovsky 1950).

<u>Scherbakovite</u>.- $Na (K,Ba)_2 (Ti,Nb)_2(Si_2O_7)_2.$ (Eskova and Kasakova 1954).

<u>Vinogradovite</u>.- $Na_5Ti_4 AlSi_6O_{24}.3H_2O$ (Semenov et alia 1956) Kola Peninsula.

Sorosilicates.

<u>Astrophyllite</u>.- $(K_2Na_2Ca)(Fe''Mn)_4(Ti,Zr)OH(Si_2O_7)_2$

<u>Benitoite</u>.- $BaTi(Si_3O_9)$

<u>Titanoelpidite</u>.- $Na(Ti,Zr) H_6(Si_3O_9)_2.$ See also Labuntzovite (Labuntzov 1926; Semenov and Burova 1956) $(K,Na,Ba,Ca,Mn) (Ti,Nb) Si_2(O,OH)_7. H_2O.$

<u>Lozoverite</u>.- $(H,Na,K)(Ca,Mn,Mg)(Zr Ti) H_6 (Si_3O_9)_2.$

<u>Neptunite</u>.- $(Na_2 Fe Ti (Si_4O_{12}).$

<u>Joaquinite</u>.- $NaBa(Ti,Fe)_3(Si_4O_{12}).$

<u>Leucosphenite</u>.- $Na_4Ba Ti_2 (Si_{10}O_{27}).$

<u>Tchlingusuite</u>.- $2(Na,K)_2 \frac{1}{2}(MnCa)O. \frac{1}{3}(TiZr)O_2. 14SiO_2. 9\frac{1}{2}H_2O.$ (Gerasimovsky 1938). Metamict. Kola Peninsula.

<u>Belyankinite</u>.- $2CaO. 12TiO_2. \frac{1}{2}Nb_2O_5. ZrO_2SiO_2. 28H_2O.$ (Gerasimovsky 1950) Kola Peninsula.

<u>Narsarsukite</u>.- Phyllosilicate. $Na_2(TiFe)(O,OH,F)(Si_4O_{10}).$ (Warren and Amberg 1934; Belyankin 1949).

CHAPTER III

PRIMARY TITANIUM ORE DEPOSITS

DEPOSITS ASSOCIATED WITH ANORTHOSITE MASSIFS

Most of the world's supply of ilmenite which does not come
from secondary deposits is mined from ores associated with the
large anorthosite massifs which are found in Pre-Cambrian rock
terranes. Rutile is not normally obtained from this type of deposit
but in Virginia and at St. Urbain, Quebeck, abnormal anorthosites
contain free titanium dioxide in mineable concentrations.

The name anorthosite is badly chosen since it implies a rock
consisting of anorthite feldspar. The common feldspar of the
anorthosite batholiths is calcic andesine, with variations to sodic
labradorite and sodic andesine. Exceptionally, oligoclase may be
the dominant form of plagioclase present. Apart from the anorthosite
differentiates of stratified basic complexes of the Bushveld type,
in which the feldspar is frequently bytownitic, no anorthosite rock
masses carry feldspar more calcic in composition than labradorite.
Plagioclasite has far greater validity as a name and, with a suitable
prefix such as andesine or labradorite, would be more explicative.
However, the term anorthosite is firmly established in the
literature of geological science and a change made solely in the
present narrow context would be valueless. It is of value, though,
to register a protest, in the hope that it will add strength to the
growing body of opinion in favour of an international re-appraisal
and rationalization of petrological nomenclature.

Batholithic anorthosites have many common characteristics.
Feldspar is always present as phenocrysts, often of quite exceptional

size, set in a groundmass of feldspar which is frequently granulated. It is a distinctive feature of the rock that both phenocryst and groundmass have the same composition, and that, despite their large size, the phenocrysts never show compositional zoning. Within a massif two facies are often distinguishable, one of which is ungranulated and contains feldspar slightly more calcic than the other which is granulated, gneissic, slightly more mafic and often peripherally arranged about a core of the ungranulated variety. The gneissic facies often grades to leucogabbro by increases in the content of mafic minerals. Within the anorthosites there are usually bodies of gabbroic or noritic composition, with which the ores are normally intimately associated, and a genetic connection between them and the anorthosites is accepted by most students in this field. Peripherally the anorthosites are invariably in contact with granitic rocks, but here the genetic connection is less clear and has been the subject for some controversy, which is discussed in Chapter VI.

The pressure-temperature conditions in which the anorthosites were intruded and crystallized has been the cause of some discussion. The Norwegian area has clearly been subjected to long periods of stress at an elevated temperature - conditions typical of the granulite metamorphic facies. Most of the Canadian anorthosites and also those in Wyoming are sufficiently comparable for a similar history to be assumed for them. The evidence is less clear in the Adirondack region where later metamorphism in lower P.T. conditions has obscured much of the evidence. The St. Urbain, Quebec and the atypical Roseland anorthosite of Virginia have not originated by a process of crystallization and ore formation solely within the

granulite facies.

The ilmenite ores which are found within the anorthosite massif fall into two broad categories:- (1) Massive or vein-like ores in which opaque minerals form over 60% of the rock (2) Norite and gabbro ores in which ilmenite is an essential, but not a dominant, constituent. Within each of these categories, two subtypes can be delimited using the character of the ore minerals as a basis:- (a) Dominantly ilmenite containing exsolution discs of hematite (a hemato-ilmenite) with accessoric magnetite which may contain ilmenite exsolution lamellae (an ilmeno-magnetite), forming not more than about 20% of the total opaque mineral content of the ore (b) Between 1:1 and 1:4 proportions of ilmenite:magnetite. The ilmenite may contain either hematite or magnetite exsolution bodies but commonly contains neither; the magnetite contains ilmenite exsolution lamellae and may contain ulvospinel. If ulvospinel is present the ilmenite crystals do not contain discs of hematite.

Categories (1) and (2) above may occur together in a single ore deposit as at lake Sanford, New York state where gabbroic ore gives off veins of rich ore into the adjacent anorthosite. There is no known case of the two subtypes (a) and (b) occurring together. On a world basis categories (1) and (2) are probably equally common but subtype (a) occurs far more commonly than (b). In deposits not associated with anorthosite massifs (mostly in gabbros) the distribution is not the same (see Chapter IV).

Controversy over the origin of anorthosite and of ilmenite ores (although the two subjects have rarely been considered together) has continued for more than half a century. Anorthosites have variously been considered to be:- crystalline differentiates of a basic magma,

either rising (Loewinson-Lessing) or sinking (Bowen) in it; parts of a world-wide primary anorthosite layer (Buddington) injected at a higher crustal level; and para-anatectic residua of a granitization process (Michot). The ilmenite gabbro-ores have been:- early crystallizing constituents of a basic magma which have sunk to rest at the bottom of a magma chamber (Bowen); early crystallizing constituents of a basic magma which have sunk, remelted and been re-injected (Vogt); late crystallizing constituents of a leuconorite or leucogabbro magma which have been concentrated by one of many types of filter-pressing action (Buddington; Balk and Osborne); pneumatolytic and/or hydrothermal metasomatic bodies introduced into the anorthosite (Gillson; Ross) and basic fronts rising in advance of granitizing ichors (Michot).

The whole problem of titanium ore genesis is reviewed in Chapter VI where the present writer puts forward a hypothesis which to a certain extent reconciles the magmatic and hydrothermal-metasomatic schools of thought. In this chapter the genesis of each orebody or group of orebodies is discussed on the basis of the evidence and hypotheses which have been published.

The anorthosites and ore deposits described in this chapter lie in south-west Norway, the Adirondack mountains of New York, Quebec north of the St. Lawrence river, Ontario, and isolated masses in Wyoming and Virginia. The concentration of anorthosites on the eastern and western seaboards of the North Atlantic is marked and probably not entirely fortuitous. There are anorthosite batholiths in other parts of the world, in south-west Angola for instance where there is an area perhaps as large as the Adirondacks

formed of a feldspathic complex.   Its geology has never been described
in detail.   Other similar occurrences probably exist in the
geologically unexplored areas of the earth's crust.   However,
the concentration of the known masses in the Pre-Cambrian of the
North Atlantic margins is real and of some, at present hidden,
significance.

The Anorthosite Region of S.W. Norway (Rogaland) and its Associated Titaniferous Ore-Deposits

The titanium ore deposits of south-west Norway have never been
adequately described in their regional relationships and no descrip-
tions at all have appeared in English.   The account which follows
is based on studies carried out by Belgian and Norwegian workers
published in foreign language journals and observations made in the
field and the laboratory by the present writer.   P. Michot, in a
series of publications which have appeared in the course of the
last twenty years has described the geology of part of the region
but with only slight reference to the ore deposits.   Bugge, Carstens
and Hubaux have studied certain features of individual deposits
but have failed to give a comprehensive view of the ores in their
regional setting.

The anorthosite region of south-west Norway is part of the
great Pre-Cambrian Shield area of southern Norway.   The feldspathic
massif and its associated rock types norite, monzonite and mangerite
occupy an area of 3,000 sq. km stretching from Aalgaard in the north
to Hidra in the south and from the coast inland for a distance of
about 30 km.

The mineral assemblages of this basement complex place the whole

region in a facies whose physical characteristics have developed in

response to pressure and temperature conditions which produced a

constant and uniform environment over the area occupied by the

eruptive rocks during the time in which they were crystallizing.

Such a facies has been given a number of different names including

granulite facies (Eskola) and mangerite or deep catazone facies (Michot).

The characteristics of the facies, with special reference to the

region in question, are an absence of muscovite and biotite and

the widespread presence of/the stable assemblage plagioclase (andesine or

sodic labradorite), potash feldspar, hypersthene, diopside and

quartz. In the more alkaline rocks the dominant feldspar is

mesoperthite, (Michot) a term used to describe an antiperthite or

perthite in which it is not possible to distinguish which is the

host mineral phase. Their overall composition falls in the

solubility gap which lies between the potash and plagioclase feldspars

in a normal epi- or mesozonal granitic rock mass. The widespread

existence of mesoperthite would seem to indicate a regional

temperature of over $675^{\circ}C$ (Bowen and Tuttle 1950) during the formational

period. When finally the temperature fell below the critical transition

temperature dividing the one feldspar and two feldspar fields, it

must have done so at a moderately rapid rate, so that only perthite

and not separate crystal entities of potash and soda lime feldspar

could form. The ubiquity of mesoperthite in the Rogaland rocks

has led Michot (1956) to apply the term monogenetic to the region,

implying that its principal rock masses were all formed in the

same environment. The latest crystallizing rocks of the igneous

complex, the mangerites (essential constituents microperthite,

plagioclase and pyroxene) may contain biotite, indicating that they crystallized under lower P.T. conditions.

Dolerite dykes with no genetic relationships to the anorthosites and cogenetic rocks, later intruded the area to crystallize under typical epizonal conditions.

The Metasediments.- The oldest rocks in the region are the metamorphosed sedimentary rocks into which the eruptive rocks were injected. Two series are recognised by Michot (1955e) the lower 'Charnockitic series' and the upper 'Gjestal series'.

The Charnockitic Series consists of migmatised hypersthene gneisses, rich in noritic material, with intercalations of concordant pegmatitic granite. In areas where there has been less cataclastic and dynamic metamorphism granulites of granite composition occur which are interpreted to have been psammitic sediments. These rocks are believed to be the source of the migmatite material intruded into the gneisses and of the pegmatitic granite.

The hypersthene gneisses consist of agmatites and banded norite, adamellite and charnockite granite gneisses. Homogenous adamellite gneisses have been formed in the most highly metamorphosed areas.

At the top of this series cordierite sillimanite gneisses occur.

The Gjestal series, from base to top consists of:-

a. Quartzites and feldspathic quartzites, 5-10 metres thick

b. Diopsidic granitic granulites, 200-250 metres thick

c. Banded granitic granulites, 200-300 metres thick

d. Granulites and cordierite-sillimanite gneisses, 50 metres thick

e. Granitic granulites with basic intercalations, several hundreds of metres thick.

(The term granulite is used in a textural sense only, implying a rock consisting of equant grains: with increasing metamorphic grade it may recrystallize, developing a porphyroblastic texture. Dynamothermal metamorphism changes granulite into gneiss).

These two sedimentary series have been folded in two separate stages. The first tectonic period occurred as the first act in the development of the intrusive complexes, causing recrystallization and intrusion under catazone conditions. The long axes of these folds lie north-south. A later period of folding followed the last of the intrusive complexes, during which the gneisses were thrown into east-west folds destroying or partly obscuring the effects of the older folding period.

During these intense orogenic stages much endomigmatitisation (Michot 1956a) of the quartzo-feldspathic fraction of the gneisses occurred yielding anatectic granite pegmatites where the mobilized material concentrated together or anatectic migmatites where it remained relatively dispersed within the rocks. The endomigmatitisation process was particularly strongly developed in the charnockitic series. In some cases the anatectic migmatites have been completely homogenised after their formation resulting in the development of bands of 'synkinematically homogenised gneisses' (Michot 1956e).

Although the metamorphosed sedimentary rocks which have just been briefly described may not appear to have a direct connection with the intrusive rocks of the anorthosite complex, they do have a bearing on the problems of anorthosite genesis. Prior to the publication of Michot's work the psammitic and arkosic metamorphosed sediments were regarded as birkremite granite comagmatic

in origin with the anorthositic rocks (Kolderup 1896; Barth 1933).
The latter interpretation of the relationships of the charnockite
gneisses played a large part in the concept of the genesis of the
anorthosite arrived at by Barth, which it seems must now be discarded.
The work of Michot carried out over a period of twenty years must
be accepted as the basis of any genetic theories advanced in
connection with the bodies of anorthosite and allied rock types.
The Igneous Rocks.-   The igneous rock masses in the region are
comprised of the following types:- anorthosites, leuconorites,
norites, mangerite with and without quartz, monzonites and quartz
monzonites.   The birkremites and certain leucogranites associated
with the charnockite gneisses must now, on Michot's interpretation
of the field evidence, be regarded as migmatitization products of an
ultrametamorphic process.   Six structural units are recognised.
Listed in order of their emplacement they are.

1.   The anorthosite massif of Egersund-Ogna.

2.   The massif of Haaland.

3.   The anorthosite-monzonite massif of Bjerkreim-Sogndal
      with its substrate the migmatite massif of Lakssvelfjeld.

4.   The norite-granite zone of Puntevold-Haaland-Lien.

5.   The anorthosite massif of Helleren.

6.   The Josingfjord-Tellnes anorthosite.

1.   The Egersund-Ogna massif.   This is essentially constituted
of labradorite-andesine feldspar of varying grain size.   The rock
is almost perfectly monomineralic containing only remarkably small
amounts of hypersthene.   At the contacts of the massif with the
surrounding structural units a wide belt of gneissic anorthosite and

Plate IV N 1.　The south-eastern end of the Hauge I Dalane depression.
The road to Josingfjord climbs the right-hand valley
wall.　The valley to the left leads to the abandoned
mine at Blaafjell.　The suspended dots over the valleys
are the cablecars which convey the ilmenite concentrates
from Storgangen to Josingfjord.　The low foreground
is underlain by norite;　the hills are anorthosite.

Plate IV N 2.　The head of Josingfjord in the heart of the anorthosite
where vegetation is lacking.　The rock is so nearly
truly monomineralic (andesine feldspar) that elements
necessary for most plant life are absent, and soils do
not form.

leuconorite is developed as a result of dynamothermal metamorphism.

2.   The Haaland massif. This has been divided into three units.

The northern unit is made of anorthosite, and of gneissic leuconorite with a banded and lenticular structure. Michot interprets the mass as a leuconorite which, suffering a process of partial anatexis resulting in the melting up of the mafic constituents, has separated into two distinct rock types:- a) a relict para-anatectic anorthosite and a leuconorite magma or migma, consisting of plagioclase crystals floating in a mafic liquid which has crystallised again under stress conditions forming gneissic leuconorite.

The southern unit consists of leuconorite and norite, gneissic and of fine grain, regarded to be anatectic in character.

The third unit consists of coarse anorthosite with ilmenite. It may actually be part of the Helleren massif.

3.   The Bjerkreim-Sogndal and part of the Lakssvelfjeld massif is a large synclinal laccolithic body which envelops the two preceeding massifs.   It is comprised of a series of units which, from base to top in assumed order of intrusion and crystallisation, are:-

    a.   The Bjerkreim anorthosite with ilmenite

    b.   The Helleland banded leuconorites and norites

    c.   The Eia mangero-monzonite, locally quartziferous

    d.   The mangerites, monzonites and quartz monzonites of
          Heskestad, locally containing iron-rich olivine.

The intrusion of the individual magmas was synorogenic.   The later magmas cut and enclosed the earlier, solidified intrusions and

TITANIUM ORE DEPOSITS AND OUTLINE GEOLOGY OF THE EGERSUND-SOGNDAL REGION NORWAY

SCALE

1:100,000
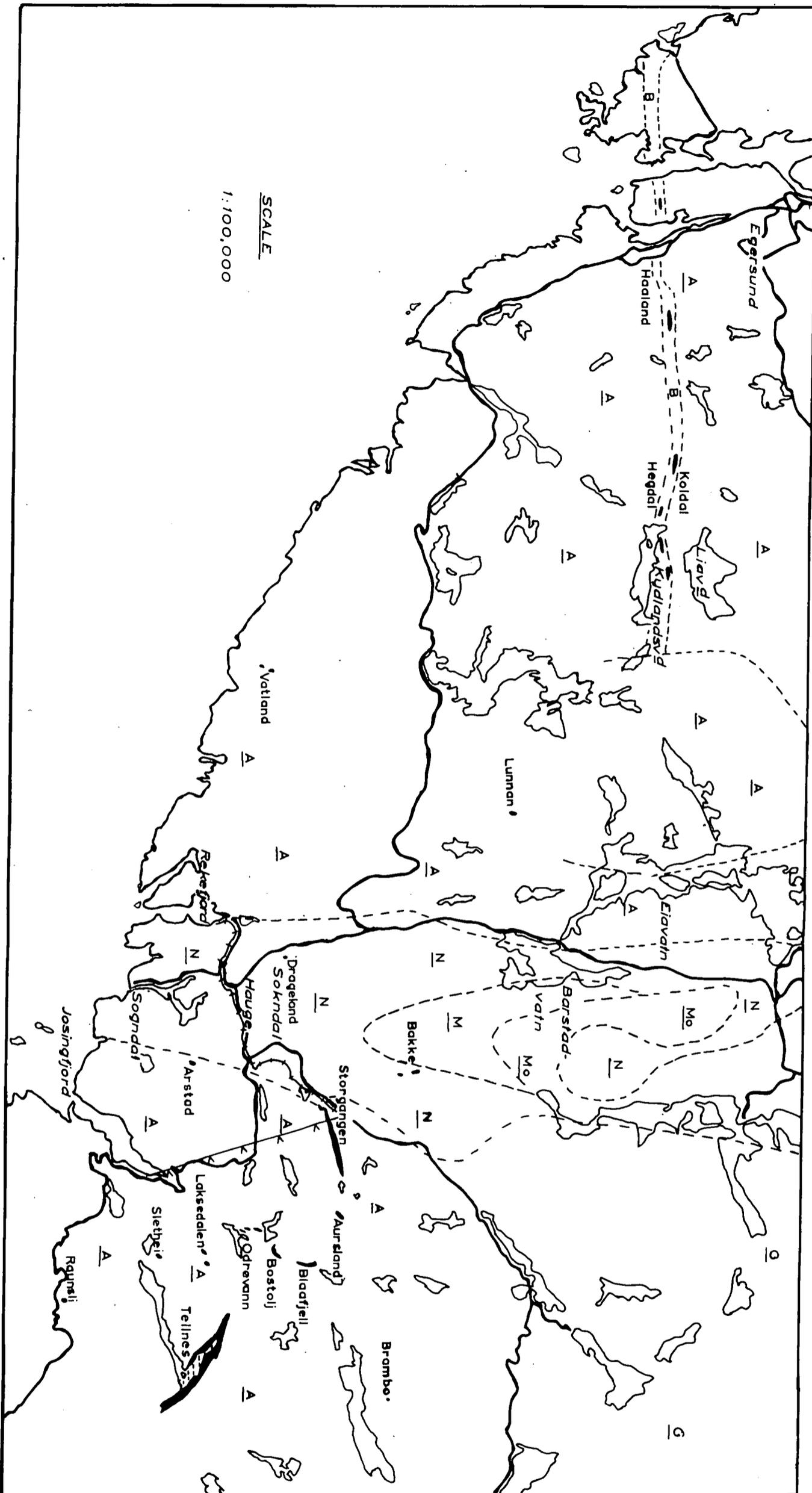
LEGEND

Roads

Railway for Magnetite Concentrates

Cableway for Ilmenite Concentrates

Geology

Geological boundaries based on
the work of P. Michot.

A Anorthosite   G Gneiss

N Noritic rocks

M Mangeritic Monzonite

Mo Quartz Monzonite

B Banded Norite Anorthosite
   Granite

Ilmenite Ore Deposits

Egersund
Haaland
Koldal
Hegdal
Kydlandsvd
Liavd
Vatland
Lunnan
Ejavd
Rekefjord
Drageland
Sokndal
Sogndal
Bakke
Barstad-
vatn
Mo
Mo
Josingfjord
Arstad
Hauge
Storgangen
Aureland
Laksedalen
Slethei
Ogrevann
Bostol
Blaafjell
Tellnes
Brambo
Raunli

crystallisation took place in synkinematic conditions. (Against the field evidence as interpreted by Michot, Bugge (1953) considers that the intrusive magmas differentiated in a quiescent environment).

The Lakssvelfjeld massif consists of charnockitic gneisses with interstratified leuconorite anatectites and metasomatic leucoadamellitic migmatites. Michot is uncertain whether these rocks should be part of the charnockitic endomigmatite series or whether they are genuine birkremites, of the type described by Kolderup and Barth (1933), formed by exomigmatitization.

4. The norite-anorthosite-granite zone of Puntevold-Haaland-Lien is a narrow septum of mixed rocks fifteen kilometres long and about 250 metres wide intercalated between the Egersund-Ogna and Haaland anorthosites.

The rock units present are:

a. Banded norite and leuconorite

b. Norite-granite, leucoadamellite and quartz mangerite

c. Banded norite-anorthosite

d. Coarse-grained ilmenite-magnetite norite.

After the formation of this belt of mixed rocks (described below with the ore deposits) the Haaland massif was thrust north over part of it. Following this, 'basic anatexis' produced a homogenous leuconorite from banded norite-anorthosite. Basic anatexis (Michot 1955) is a process of remelting which occurs in leuconorites when the minor mafic constituent melts first, supposedly as the result of a mass action effect exerted by the excess of feldspar.

5. The anorthosite massif of Helleren was probably intruded at

an intermediate stage of the complex intrusion of anorthosite and
monzonitic massifs. It has yet to be studied in detail but
appears to consist of homogenous anorthosite containing inclusions
of most of the rock types of the earlier formed units.

6. The Josingfjord-Tellnes anorthosite which contains the
ilmenite deposits of Storgangen, Tellnesvann and Blaafjell has
not been studied by Michot. The present writer has made brief
observations of the massif in the regions of the orebodies, the results
of which are stated below.

The anorthosite over wide areas is an almost perfectly
monomineralic rock with a remarkably uniform composition. Such a
harshly limited composition gives rise to a very typical barren
countryside (see Plates IV N1 and 2) which is only relieved of its
monotony on account of local areas of leuconorite and norite on
which vegetation can flourish (see Plate IV N5).

The typical anorthosite of the area is a granular rock with
phenocrysts of andesine feldspar, rarely over a metre in length,
commonly several centimetres in diameter (see Plate IV N6), set in
a matrix of subhedral crystals with an average median diameter
of two millimetres. The composition of the feldspar is remarkably
constant throughout. Minimum and maximum values for the lowest
refractive index obtained by the standard immersion method were 1.550
and 1.553 indicating a variation of no more than 5% in the
anorthite content (An_{44-49}). It is particularly significant that
there is no compositional variation between the groundmass and even
the largest phenocrysts.

Locally, by an increase in the hypersthene and ilmenite content,

anorthosite passes into leuconorite or norite. Where the hypersthene content rises above about 10% ilmenite is frequently present as disseminated grains and irregular stringers. There are also many instances of irregular clots of ilmenite in the anorthosite in the absence of hypersthene or any other mineral. Leuconorites of this type are always foliated or 'flow' banded (see Plates IV N7 and 8) in a manner which suggests that the leuconoritic portions of the rock solidified after the pure anorthosite. Plate IV N7 shows particularly clearly the manner in which blocks of anorthosite have been engulfed by the leuconorite. The evidence, unfortunately, is not sufficiently conclusive to distinguish between a metasomatic origin involving intruduction of the ferromagnesian elements, and agpaitic crystallisation produced by the presence of an interstitial liquid of hypersthenic composition. The ortho-pyroxene of these rocks, more correctly described as bronzite, has the following refractive indices:- nZ 1.699 nX 1.688. The ilmenite in the clots and stringers which are found scattered through the anorthosite is coarsely crystalline (up to five millemetres in diameter). It contains well developed hematite exsolution discs of two generations along the 0001 cleavage. The coarse discs, up to 0.3 mm in diameter and 0.04 mm thick, are separated from the small discs by an area, free from exsolution bodies, about 0.01 mm wide. Small inclusions of magnetite, containing ilmenite lamellae along 111 cleavage directions, and pyrite are not uncommon.

Michot summarizes the tectonic history of the region as follows.

1.   Folding and overfolding of geosynclinal sediments in a north-south direction with the development of deep catazone conditions

(mangerite, charnokite or granulite facies).

2. Intrusion of a tholeitic magma and assimilation by it of large quantities of pelitic sediments. Differentiation of this magma to form anorthosite. (This stage is purely hypothetical; Michot offers no field evidence in support of it).

3. Intrusion of the Egersund-Ogna anorthosite.

4. Intrusion of the norite border facies of this mass.

5. Migmatitisation of the nappe superstructure.

6a. Intrusion of the Haaland anorthosite and Bjerkreim ilmenite anorthosite. (The Josingfjord-Tellnes anorthosite is probably of this age or earlier.)

6b. Anatexis of the mafic constituents of the Haaland massif forming para-anatectic anorthosites. (Haaland-Lien banded zone).

6c. Consolidation and differentiation of the Bjerkreim anorthosite.

6d. Thrusting on the northern border of the Haaland massif.

7. Intrusion of the Helleren massif.

8. Intrusion during a period of folding of the leuconorites, norites and mangeromonzonites of the Bjerkreim-Sogndal massif.

9a. Continued synclinal folding and synkinematic differentiation of the mangeromonzonite forming gneissic mangerite and monzonite, and quartz-monzonite. (The intrusion of the Storgangen and Tellnes orebodies probably occurred during this or the preceeding stage).

9b. Recurrence of intense folding in an east-west direction in the superstructure causing migmatitization and the development of anatectic granite.

10. The lowering of P.T. conditions allowing some retrograde metamorphism with the appearance of biotite in some rocks.

11. Intrusion of dolerite dyke rocks in epizonal conditions.

<u>The Ore Deposits</u>.- With this brief consideration of the petrology and tectonic history of the region as a background it is possible to pass on to descriptions of the ore deposits. There are two types of ilmenite-magnetite ore deposits in the Rogaland area. They are massive ilmenite norites and ilmenite veins in anorthosite. The norite ores containing disseminated ilmenite and magnetite are the economically important deposits, even though they are lower in grade than the vein ores, because they alone occur in sufficiently large quantities to make exploitation worthwhile.

Within the region there are only two massive ilmenite-norite orebodies known, Storgangen and Tellnes, and both these lie within the Josingfjord-Tellnes anorthosite east of the Bjerkreim-Sogndal norite-monzonite laccolith (see map). In all the basic complexes of the region small accumulations of ilmenite occur at a large number of widely scattered localities. These are of no economic value but their mineralogy is considered with the vein ores.

The Storgangen ore outcrops about two kilometres north-east of Hauge I Dalane, Sokndal (see map). It is a dyke-like body of ilmenite and magnetite-bearing norite, 1,600 m. long and averaging 60 m wide. It strikes east-north-east and dips to the north north-west at 60° on the surface shallowing to 40° at a depth of about 150 m below the surface (see diagram of serial sections through the orebody).

The dyke lies in anorthosite of almost monomineralic composition. At each end the orebody gradually decreases in width with an increase in ore-mineral content, finally pinching out completely into anorthosite. The western end turns in a southerly direction to parallel for a short distance a valley which separates the anorthosite from the adjacent

leuconorites and mangero-norites of the Bjerkreim-Sogndal laccolithic massif. The orebody is intruded along a fault which offsets the north-south strike of the edge of the norite to the east on the south side of the fault. It could thus be either a tear fault or a reverse fault overthrust from the north.

Along the footwall of the orebody the contact against anorthosite is always sharp. The feldspars in the anorthosite against the ore have been slightly altered over a zone a few centimetres thick. Thin sheets of calcite and micas are found at the actual contact where shearing has caused cataclastic metamorphism. Small slickensides, are common and they generally indicate vertical movement, but divergences from the mean are common. The hanging wall of the orebody (Plate IV N3) shows a complex structure of alternating sheets of norite and anorthosite. Especially in the western part of the mine there is a wide zone, up to 100 m thick, of alternating norite and anorthosite. The selvages of anorthosite are sheets of the country rock separated from each other by the norite.

Along the hanging wall of the orebody two small apophyses of ore embay the anorthosite and a similar structure exists on the footwall side on a smaller scale. The ore-mineral concentrations in the apophyses are as high or higher than the average grade of the orebody. The higher grade of these narrow offshoots and the ends of the orebody seem to indicate greater mobility of the opaque constituents than of the silicates. This is largely borne out by the mineral paragenesis.

The norite orebody is comprised of ilmenite, andesine, hypersthene, magnetite, olivine, biotite, apatite and iron sulphides. Olivine occurs in colourless rounded crystals, usually traversed

THE STORGANGEN OREBODY — VARIATION IN TiO₂ CONTENT

SCALE

0   50   100m

LEGEND

20% TiO₂

12—16% TiO₂

16—20% TiO₂

12% TiO₂

Hanging wall

Foot wall

N
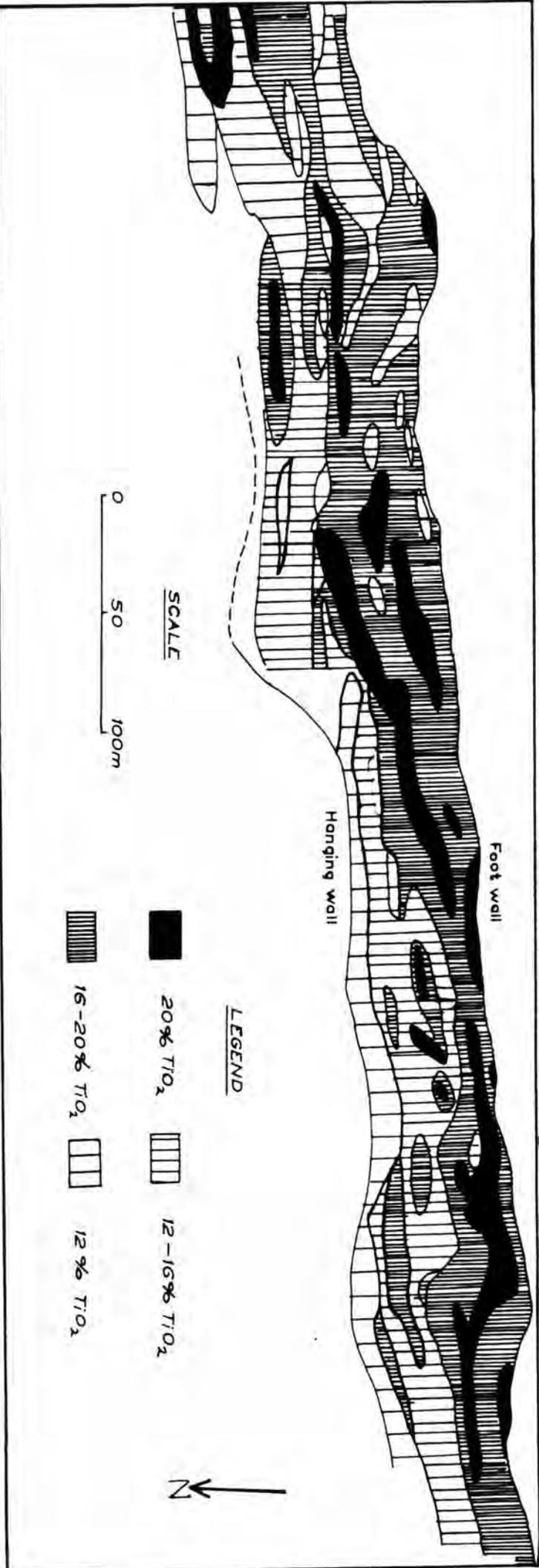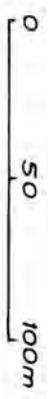
SERIAL SECTIONS THROUGH THE
STORGANGEN OREBODY
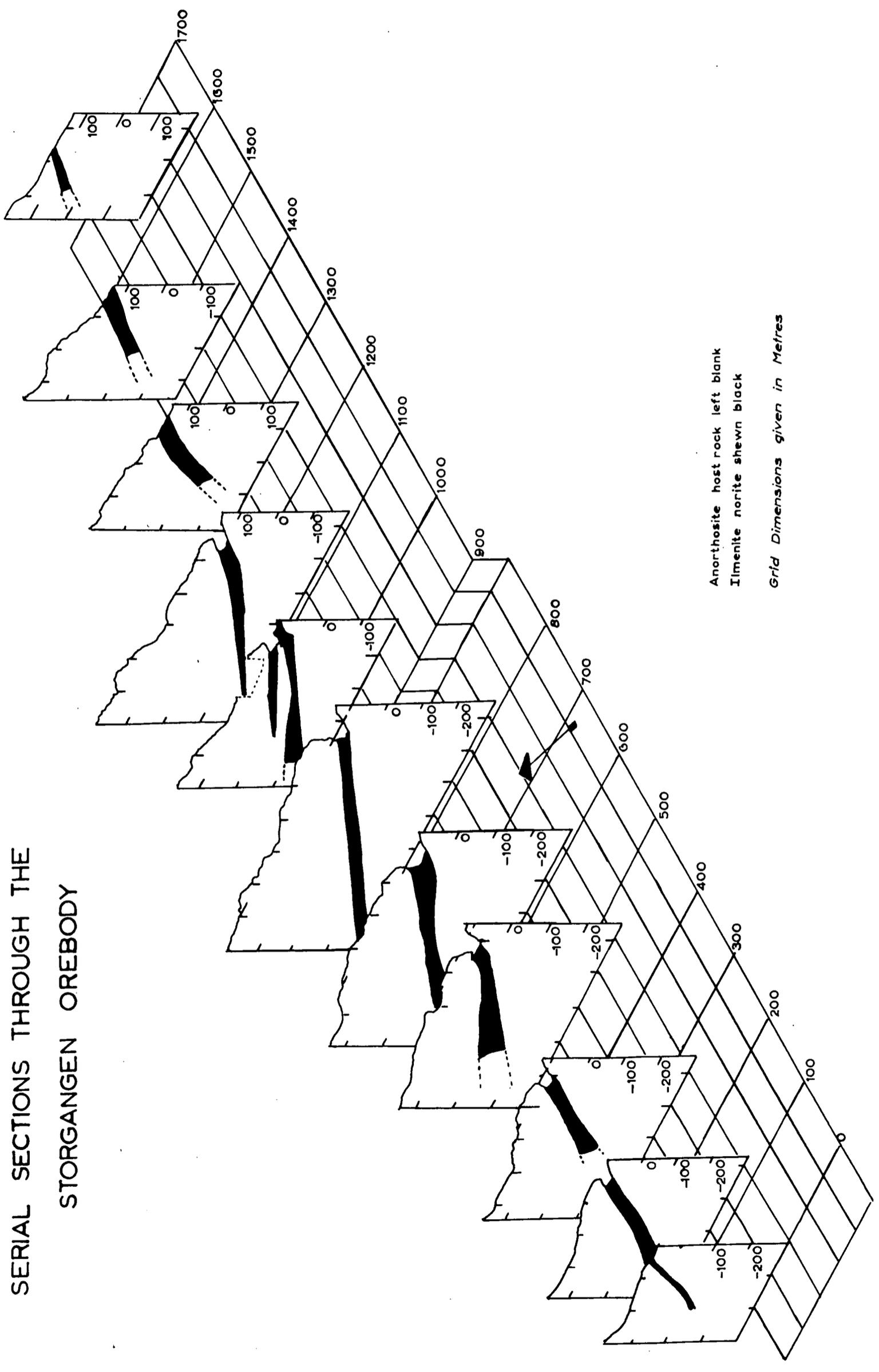
Anorthosite host rock left blank
Ilmenite norite shewn black

Grid Dimensions given in Metres

Plate IV N 3. The hanging-wall contact of the Storgangen orebody.
The darker bands are ilmenite-norite in lighter
anorthosite.   The banded character of this contact
contrasts with the foot-wall contact which is sharp.

Plate IV N 4. Ore from the Storgangen orebody.   The feebly developed
foliation, striking roughly vertical in the photograph,
parallels the walls of the body.   The feldspar is
whiter than usual in this specimen but is of normal
composition.

Plate IV N 5.   Norite with a low overall ilmenite content, but with
                occasional rich dark ilmenitiferous bands, forms the
                depression around Odrevann lake.   The bare hills in the
                background are formed of anorthosite.
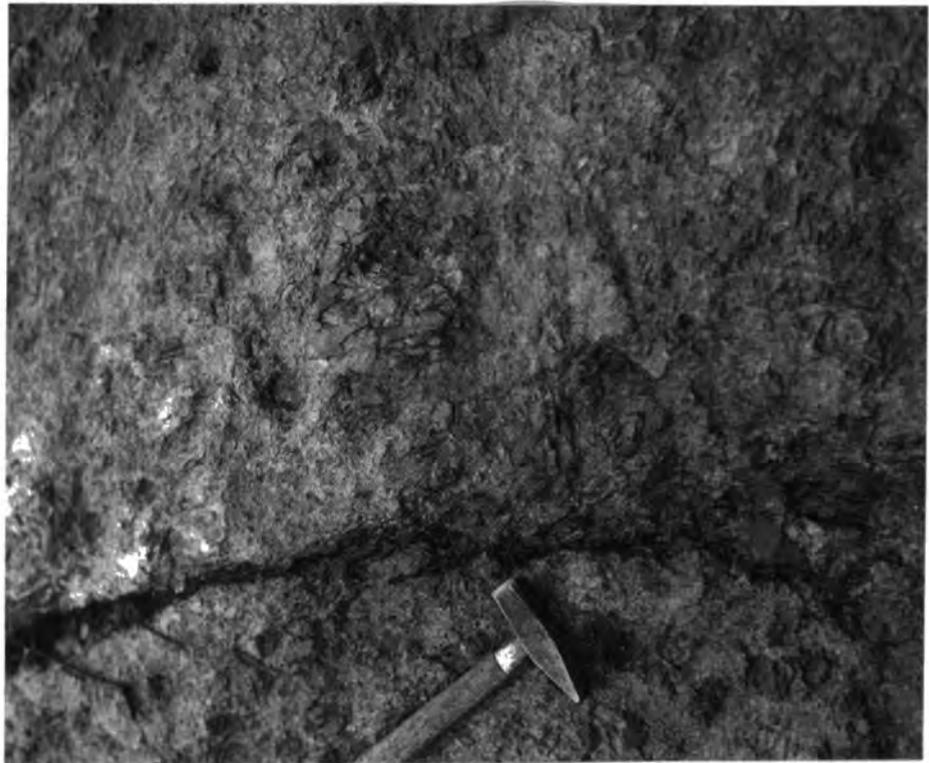
Plate IV N 6.   Typical porphyritic anorthosite of the area near
                Tellnesvann.   The phenocrysts sometimes achieve a
                length of several metres.   In the photograph most are
                only a few centimetres in diameter, but one is nearly
                twenty-five centimetres across.

Plate IV N 7.   Hypersthene-anorthosite verging on leuconorite.
The orthopyroxenes have weathered out to leave
pitted surface.   This type of rock may grade
imperceptible stages to anorthosite or norite,
but see also plate IV 8.
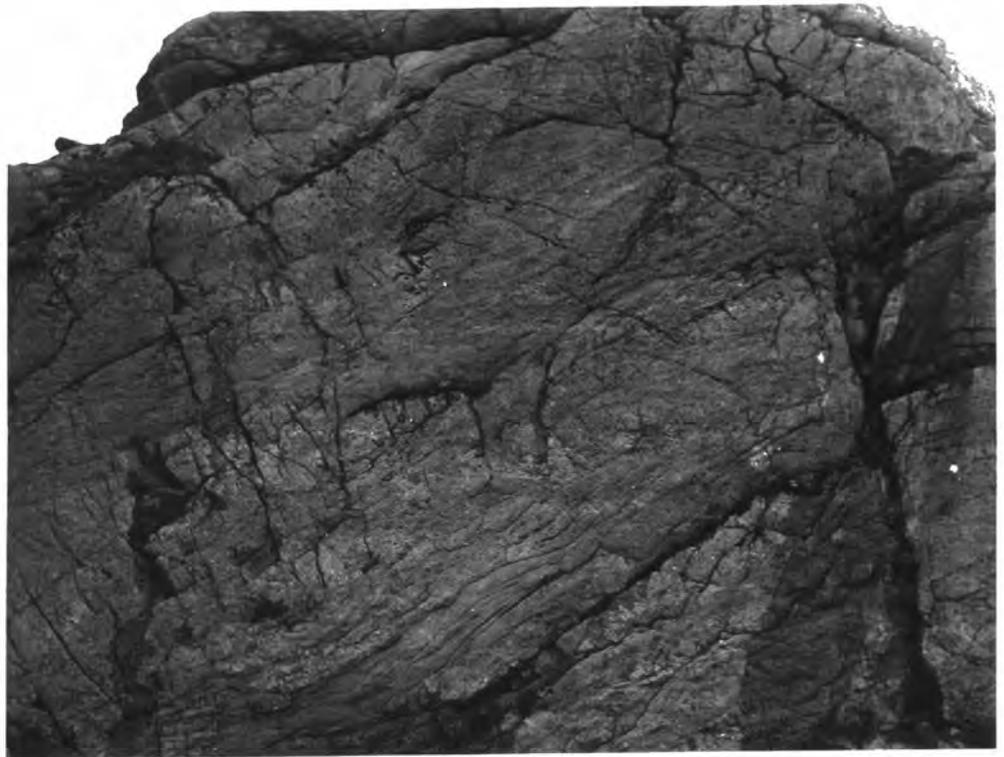
Plate IV N 8.   Large blocks of almost pure anorthosite engulfed
in foliated leuconorite.   The leuconorite must have
been mobile after solidification of the anorthosite
to produce such a structure.   The photograph was
taken a few hundred metres north of Tellnesvann.   The
height of the rock face is fifteen metres.

A panoramic view of the Telluesvaun orebody taken facing south-east. The long axis of the mass runs from the small valley at the head of the lake on the left of the photograph through the point where it was taken. The whole width of the picture between the hills at the left and right consists of ore. The bare surrounding hills and the islands in the lake are anorthosite. The contacts of the orebody figured in Plates IV 10, 11 and 12 outcrop on the promontory which extends into the lake on the righthand side of the photograph.
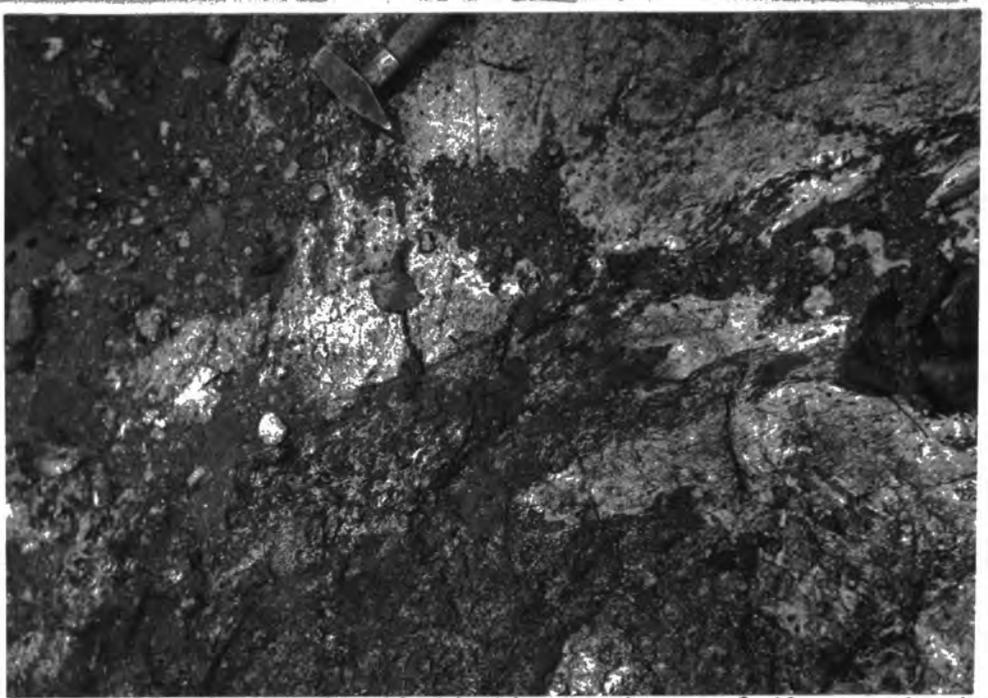
Plate IV N 10.   The irregular interdigitating nature of the contact
of the Tellnessvann ore (dark, left-hand side of
photograph) with anorthosite (light, right-hand side).

Plate IV N 11.   A dyke-like offshoot of ore penetrating anorthosite.
The discordant character of the 'intrusion' shews
clearly.

Plate IV N 12.   The foliated ore has engulfed blocks of anorthosite
                  at the orebody margins. The feldspar in the
                  anorthosite shews no signs of contact metamorphism.
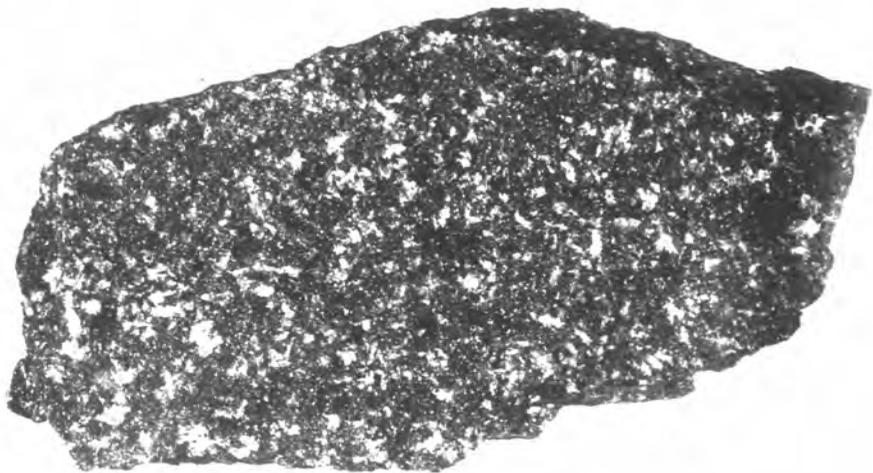
Plate IV N 13.   The Tellnesvann ilmenite-norite ore.   The weak
                  foliation which is sometimes developed does not
                  shew clearly in this photograph.

by cracks which may contain opaque minerals. It was the
first mineral to crystallize and the only one which can be firmly
placed in the paragenetic sequence. Plagioclase was probably
the next to crystallise, in part contemporaneously with hypersthene
which, however, rarely moulds around the feldspar. The ore
minerals mould onto and invade the feldspar crystals and usually
enclose the pyroxenes. Magnetite, in general, preceeded ilmenite
and pyrite, pyrrhotite and chalcopyrite were also earlier
crystallised than ilmenite and, possibly, than magnetite. Biotite
is closely associated with the oxides and is frequently
enclosed by them. Hercynite is an accessory mineral closely associated
with the oxides.

An average analysis of the crude ore as mined, kindly provided
by A/s Titania, is given below together with a modal analysis of
a slightly olivine-rich specimen, computed with a Swift point
counter.

	%		%
TiO_2	18.00	Ilmenite, Magnetite, and	
FeO	23.80	Sulphides	38.7
Fe_2O_3	2.30	Andesine	26.4
V_2O_3	0.12	Bronzite-hypersthene	23.6
Al_2O_3	8.50	Olivine	7.7
MgO	11.00	Biotite	5.3
SiO_2	32.5	Apatite	0.1
CaO)		Hercynite	Tr
Na_2O)	2.3		
K_2O)			

Ilmenite: magnetite: iron sulphides as 30:6:1

The composition of the norite is not constant throughout;
in particular the TiO_2 content, reflecting the distribution of
ilmenite, varies considerably. The accompanying diagram reproduced
from Bugge (1953) illustrates this clearly. The part richest
in TiO_2 is from five to twenty-five metres away from the footwall.

Between the footwall and a point thirty metres into the orebody the TiO_2 content rarely falls below 16%, except towards the eastern end where the distribution is irregular and there is a low TiO_2 zone adjacent to the footwall. The ratio of ilmenite to magnetite is about 5:1 but the ratio of the concentrates obtained tends to be lower than this due to a certain loss of ilmenite to the magnetite fraction during concentration. Olivine is present in most parts of the ore, but may tend to be concentrated near the footwall. The writer has been unable to examine sufficient thin sections to make a confident assertion on this point. Sulphides are slightly enriched at the expense of magnetite at the hanging wall contact.

The ilmenite of the Storgangen ore forms crystals up to 2 mm in diameter and is also apparently exsolved from hypersthene (bronzite) along cleavages parallel with the c-axis. The ilmenite crystals have smooth curvilinear margins against other ilmenite crystals but against silicates are lobate and sometimes serrated on a very fine scale and may be removed by silicate, probably sphene, about 0.01 mm wide. The ilmenite undoubtedly normally encloses the silicates but in some cases the relationship is ambiguous, and the silicates appear to be corroding and embaying the ilmenite. Exsolved discs of hematite are universally present in the ilmenite. Viewed on the 0001 cleavage of the ilmenite they are seen to be very ragged amoeboid bodies rarely as much as 0.2 mm, normally about 0.08 mm, in diameter. They are usually about 0.002 mm thick. These larger discs when seen in a section cut parallel to the c-axis of the ilmenite form layers between which are much smaller discs about 0.01 mm in diameter (length as seen in a c-axis section). Between the areas dusted with the fine discs and the coarser exsolution bodies, there is always a zone free from exsolved hematite. At the contact of adjacent ilmenite

Plate IV N14 x 35   Polished section of Storgangen ore.   Ilmenite
                    (light grey) showing a sub-pokilitic relationship
                    against silicates (grey).   A few small grains of
                    pyrite (white) are also present.

Plate I^V N15 x 35   Thin section of Storgangen ore showing relationships
                    of opaque oxides (black), hypersthene (marked
                    cleavage), olivine (clear grain with high relief)
                    and feldspar (light grey).

grains there is always an abundance of exsolved hematite discs as though Fe_2O_3 has diffused through the crystals to such areas. The hematite discs of the coarse generation do not always lie in line ahead formation along the 0001 cleavage but quite commonly lie 'en echelon' in a very random fashion. The long axes of each individual, however, are always correctly aligned. These zones of coarse exsolution which traverse the crystal are not normally associated with twin planes in the ilmenite, though on occasion such is the case. It is suggested that they may represent zones of strain within the ilmenite, of insufficient strength to cause twinning but sufficiently disrupting to cause exsolution of Fe_2O_3.

All the ilmenite in the Storgangen contains hematite exsolution discs but there does appear to be a rough distribution based on their coarseness. The crystals near the footwall contact contain a higher proportion of very small discs than those adjacent to the hanging wall which contain larger, thicker discs. This might indicate slower cooling of the ore near the hanging wall or, more simply, just a higher content of Fe_2O_3. Owing to the presence of the hematite the TiO_2 content of the ilmenite is never above 46% (see Volume II for a complete analysis).

The ilmenite is pleochroic in shades of brown-grey which for the ordinary ray shows a cream tint. The reflectivity for the ordinary ray is 19.3, a reading which is high on account of the fine hematite lamellae whose effect could not be eliminated.

Near the hanging wall contact of the orebody the ilmenite occasionally shows signs of secondary alteration. This takes the form of replacement along the hematite lamellae by secondary hematite and rutile. The secondary hematite, presumably titanium-free, is
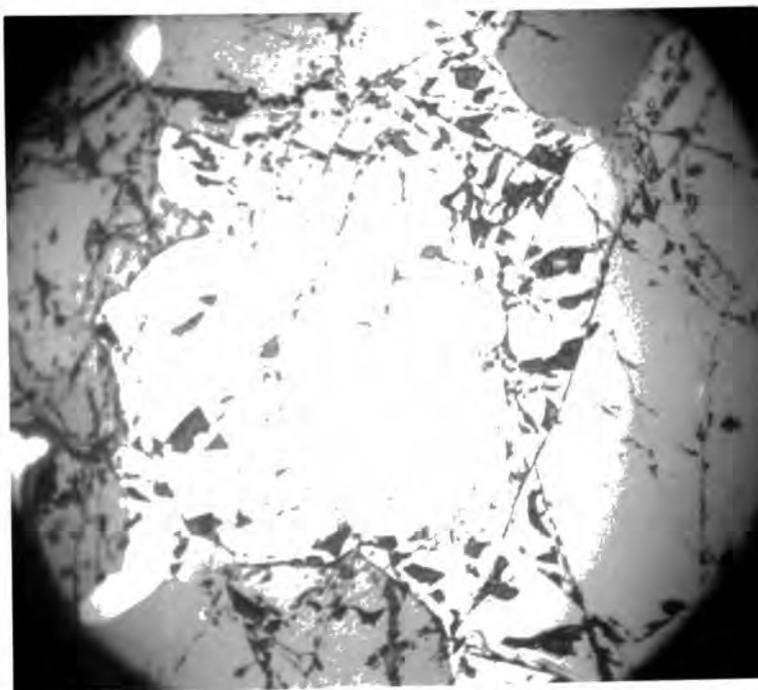
Plate IV N16 x 80   A crystal of ilmenite in the centre of the
photograph of a polished section of Storgangen ore
is almost completely enclosed by magnetite.   The
unusual intergrowth is in the marginal area of the
ilmenite where it is in contact with the magnetite.
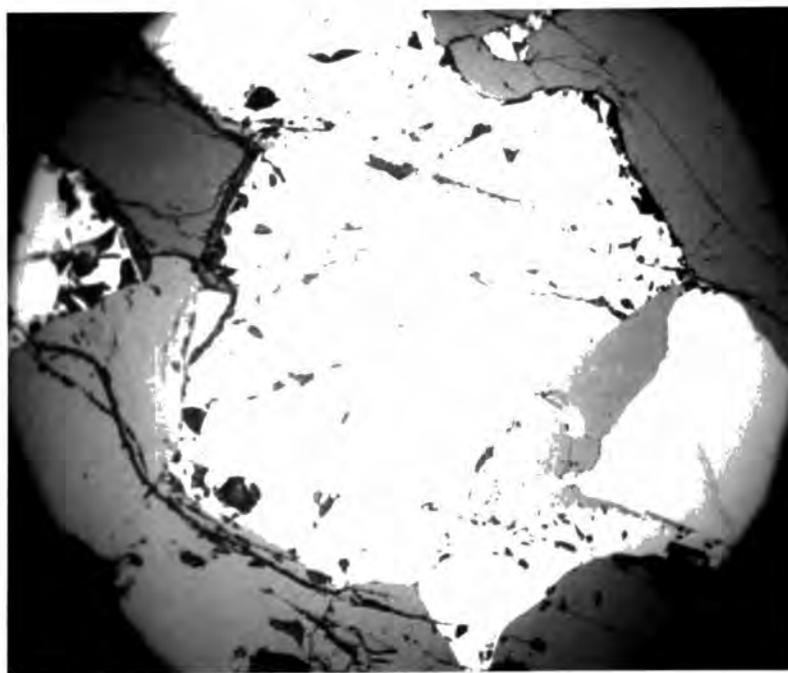
Plate IV N17 x 60   Magnetite (white) containing inclusions of
silicates (black) and lamellae of spinel (very
pale grey) of an unusual type.   Storgangen ore.

always grey against the slightly brownish exsolved titaniferous hematite.

As well as hematite exsolution discs, rare long lamellae of a transparent mineral occur which look like spinel. This is an abnormal feature for ilmenite to display. A further peculiarity of the Storgangen ilmenite is the myrmekitic intergrowth with a transparent mineral which is developed at some contacts against magnetite. Small worm-like intergrowths of the transparent mineral are enclosed in the ilmenite in a narrow border-zone only where it is in contact with magnetite. Apart from these intergrowths only inclusions, as distinct from exsolution bodies, of silicate are seen in the ilmenite.

The magnetite of the orebody is pale rosy brown-grey in colour and isotropic. The crystal outlines are usually ragged in comparison with ilmenite and frequently appear to be corroded by the surrounding silicates. Against ilmenite the outlines are smooth and the magnetite is usually convex against the ilmenite possibly indicating earlier crystallization but the reverse relationship is sufficiently common for it not to be a general rule. The magnetite contains sparse ilmenite and spinel lamellae and abundant inclusions of transparent minerals. It does not take as good a polish as the ilmenite. The ilmenite lamellae, parallel to the 111 direction in the magnetite are long and thin in most crystals, although shorter rod-like lamellae are quite common. The spinel occurs as spindle-shaped bodies parallel to 100. Rare straight broad fragmented lamellae of an unknown, low reflecting transparent mineral occur in the magnetite. They may be spinel but they do not exhibit the normal spindle-shape.

The sulphides of the ore occur as isolated grains and
aggregates disseminated throughout, with a slight concentration
at the hanging wall contact where intergrowths with magnetite
are not uncommon. Pyrite is most widespread, often as small
rounded or spherical grains enclosed in ilmenite. Very commonly
it contains myriad tiny inclusions of silicates and as a result
polishes poorly. Chalcopyrite, pyrrhotite, pentlandite and, in
one instance only, violarite, occur with the pyrite. The chalcopyrite
frequently appears to be suffering replacement by pyrite. The
sulphides often occur in floccular masses consisting of an intimate
mixture of the constituents. These have often suffered corrosion
by the surrounding silicate minerals. Where such globules are in
contact with ilmenite no corrosion has occurred.

One of the features of the Storgangen and also the Tellnes ore-
bodies is the identity in composition of the feldspar with that of
the feldspar of the anorthosite. Despite the 'basic' character
of the ilmenite-norite the feldspar is equally albitic (An_{48}). It
has suffered some replacement by the ore minerals by which it is
rimmed and penetrated, although reaction rims are lacking. In
common with the feldspar of the anorthosite it shows no zoning.

The orthopyroxene in the ore is more magnesian than its equivalent
in the anorthosite, its optical properties showing $nZ = 1.687$,
$nY = 1.685$, $nX = 1.681$. It displays typical pleochroism in
delicate pinks and greens but is abnormal in that many sections
under the microscope show inclined extinction. Statistically a few would
be expected to do this and in some sections the high proportion is
probably due to orientation of the pyroxenes in a foliation which
is developed in the ore. However, whether this is the complete answer

to the problem or whether replacement by clinopyroxene has occurred, the cleavage being merely a relict, is uncertain. The orthopyroxenes contain abundant inclusions of ilmenite and sometimes biotite, together with exsolved clinopyroxene, hence the alternative connotation bronzite. A clinoenstenitic pyroxene is an accessory mineral often enclosed in ilmenite.

Bugge (1953) has advocated gravitative differentiation as the formative process for the Storgangen orebody. He considers that the sharp footwall contact, together with the gradual variation towards the hanging wall indicates that the Storgangen is not a normal intrusive body forced into joints in the older anorthosite. Gravitational differentiation in quiescent conditions of a leuco-norite magma in which feldspar was an early crystallised phase caused an upward accumulation of feldspars leaving a heavy liquid at the bottom of the magma chamber which finally crystallised as an ore-rich norite. Stress exerted before final consolidation caused the liquid ore fraction to be injected as apophyses of the orebody into the anorthosite. The foliated and lineated character of the ore is also presumably to be attributed to late stress. Bugge's hypothesis requires the anorthosites above and below the ore to be of different ages since the lower one must presumably have provided the foundation on which the later magma differentiated. The identical nature of the feldspar in the anorthosites is against this suggestion, as also is the nature of the footwall contact which suggests injection along a fault plane.

If the orebody is to be regarded as introduced, two methods of introduction are available (a) magmatic intrusion; or (b) metasomatic replacement of anorthosite. In both methods an active fault plane

THE TELLNES OREBODY

Diabase

Ilmenite-norite ore ||| Shear zone

Leuconorite ----

Anorthosite ....

Dip of Foliation
▼ 45°

Tellnesvann

SCALE
1:15000
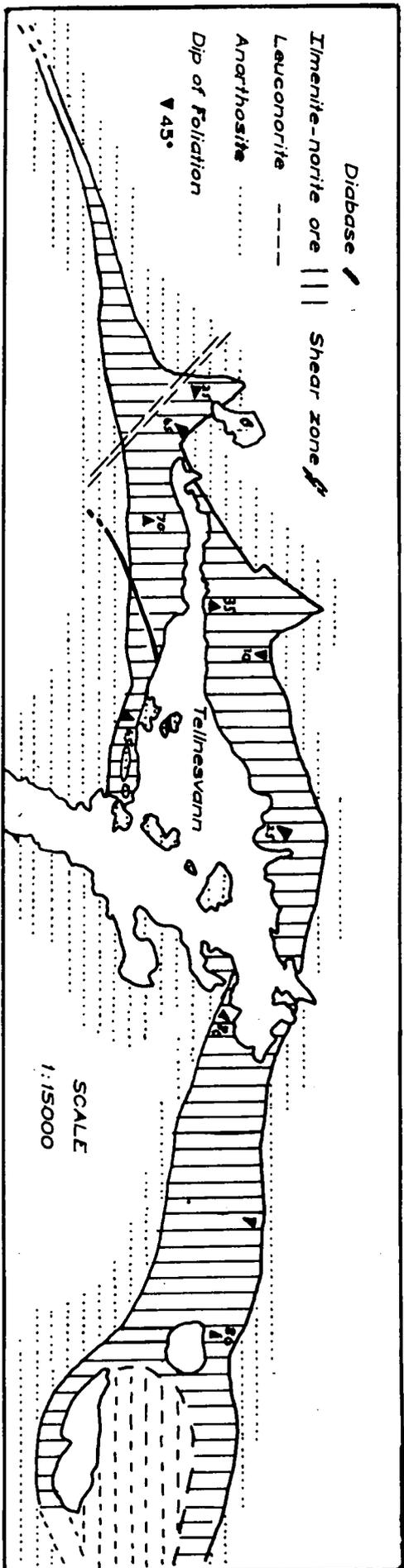
relieving regional stress would have acted as a focus collecting mobile fractions of the regional crystallising magma. It is now an accepted fact that, in certain environments which cannot yet be accurately defined, iron and titanium oxides may crystallise last from a magma. It seems almost certain that the presence of volatile constituents is required to keep the oxides in a mobile condition. However, the Storgangen ore contains only a few percent of biotite and a trace of apatite from which only a meagre volatile contribution to the original magma could have been made. The key to the problem is almost certainly the 'milieu' of the deposit, the deep catazone. The ore-rich magma, originally rich in volatiles has crystallised in granulite facies conditions which, preventing the fixation of the volatiles *in situ* (except for a little water in the biotite), has forced them to be driven to a region of lower pressure. This discussion of the genetic problems posed by the Storgangen orebody will be continued after the evidence provided by the Tellnes and Blaafjell deposits has been evaluated.

The Tellnes orebody (see Plate IV N9) lies six kilometres to the south-west of the Storgangen deposit. It is over a kilometre long by 200 to 300 metres in width, a pod-shaped body narrowing at each end (see diagram). At the south eastern end it passes beneath a cover of anorthosite while the north-western end passes into a narrow dyke of different composition as the floor of the orebody rises towards the surface. In depth it is sack-shaped, the base of the sack lying at a depth of about 300 metres in its central part, at a shallower depth to the north-west and deeper to the south-east.

The ore (see Plate IV N13) is ilmenite-norite, chemically

similar to the Storgangen ore but with certain minor but important
mineralogical differences.   An analysis of average ore from
the central richest part of the orebody is given below together
with a modal analysis of ore of the same type made by the present
writer.

	%		%
SiO_2	30.37	Ore Minerals	37.6
TiO_2	18.40	Andesine	31.3
Al_2O_3	11.70	Hypersthene	12.5
Fe_2O_3	7.25	Olivine	8.6
FeO	17.43	Biotite	4.6
MnO	0.18	Clinopyroxene	0.6
MgO	6.13	Apatite	Tr.
CaO	4.39		
Na_2O	2.40		
K_2O	0.60		
H_2O+	0.15		
H_2O-	0.40		
P_2O_5	0.3		

The orebody is richest in titanium in its upper central parts
where locally the TiO_2 content almost reaches 20%.   Throughout the
axial region the TiO_2 content does not fall below 15%.   Towards
the bottom the content of TiO_2 falls usually to about 10% but in
some areas to as low as 2%.   There is a similar drop in grade
towards the lateral margins of the mass.

In many places at the contact a distinct marginal facies is
developed which is coarser than the average grain size of between
one and two millimetres.   Pyroxene is developed at the expense
of the opaque minerals.   The actual contact of the ore with
anorthosite on the surface is visible only in one small area where
it has a definite intrusive relationship to anorthosite which it
cuts, in dyke offshoots, and encloses bodily (see Plates IV N10,
11 and 12).   The ore has either a sharp contact against anorthosite or

grades rapidly into it over a distance of a few centimetres both
at the surface and in drill cores.

The paragenetic sequence is the same as in the Storgangen ore.
Olivine was the earliest mineral to crystallize and it occurs in
rounded, clear crystals altering to feathery magnetite and chlorite
on their margins.　It is present in amounts varying from 0-9%.
It is optically negative; 2v $\simeq$ 80°. The olivine is frequently
enclosed, or partly enclosed in hypersthene (optically -ve;$\simeq$75°-80°;
$nZ = 1.690$ $nY = 1.686$ nX 1.678) which contains abundant exsolution
rods of ilmenite and clinopyroxene. The hypersthene content varies from
4-12%. Clinopyroxene, probably clinoenstenitic in composition,
is usually present in amounts of up to 3%. It may be intergrown
with orthopyroxene, but in such a way that it is not clear which
of the pyroxenes is developing at the expense of the other. Biotite
in amounts up to 5% is closely associated with the ore minerals
and crystallizes late in the paragenetic sequence with them.

The feldspar of the orebody is andesine of An_{48} composition,
which is identical with that of the surrounding anorthosite and of the
Storgangen orebody. The feldspar is commonly cut and enclosed by the ore
minerals but at the same time often contains a fine dust of
ilmenite crystals.

The ore minerals are ilmenite and magnetite. The ilmenite
is in grains which do not normally exceed a millimetre in diameter.
It is also abundantly exsolved from hypersthene in small quadrilateral
crystals of which the shapes are controlled by the pyroxene cleavages.
The exsolved ilmenite bodies when of a sufficiently large size
contain hematite exsolution discs of a similar character to those in
the free-crystallising ilmenite. Ilmenite crystals always have
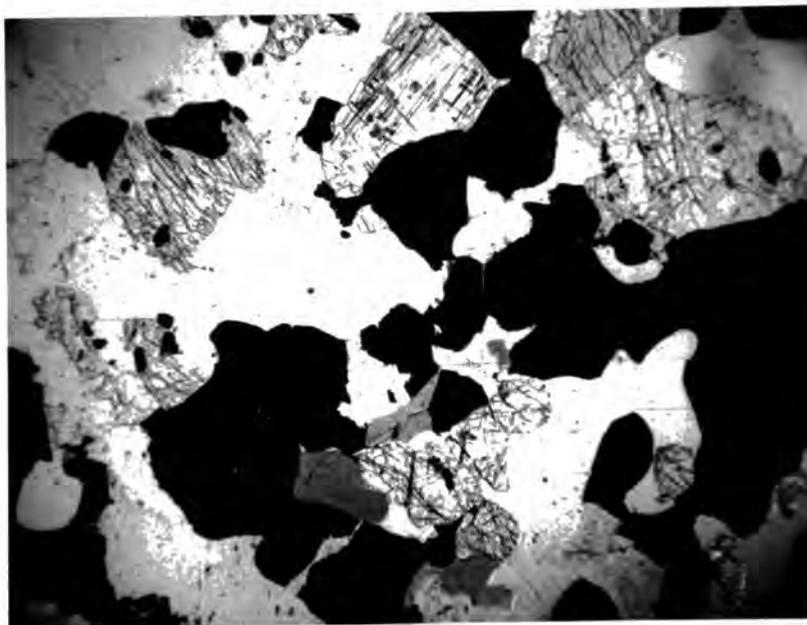
Plate IV N18 x 35   Thin section photograph of Tellnes ore.   Ilmenite
and magnetite are black;   olivine has a high relief,
and occurs in irregularly cracked, rounded crystals
(small crystals in lower half of photograph),
pyroxenes, mostly hypersthene, have lower relief
and show pronounced cleavage;   feldspar forms
the featureless matrix.

Plate IV N19 x 35 xn.   Thin section photograph of Tellnes ore showing
a plagioclase phenocryst set in a matrix of
ilmenite, hypersthene, plagioclase and biotite.
The ilmenite is marginally investing the
feldspar phenocryst.

curving or lobate margins against silicates and straight or curvilinear crystal edges against other oxides. Ilmenite normally encloses magnetite and sulphides. The hematite exsolution discs are precisely comparable with those described in the Storgangen ore except that they are a little smaller in the rich central part of the Tellnes ore. The magnetite is also similar to its Storgangen counterpart in that it contains spinel exsolution lamellae and also lamellae of a different character also tentatively identified as spinel. These lamellae sometimes contain exsolution lamellae of magnetite at right angles to their length.

Pyrrhotite is more common in Tellnes than Storgangen although pyrite is still the most widespread sulphide. Complex sulphide aggregates of pyrrhotite intergrown with pyrite and sometimes pentlandite, and of pyrite replacing chalcopyrite are commonly encountered. Pyrrhotite is sometimes intergrown in a sort of myrmekitic structure with magnetite. The sulphides usually appear to be corroded by silicates but always have smooth, regular margins within ilmenite. One small grain of unusual sulphide has tentatively been identified as vallerite.

Pegamatitic patches and coarse veinlets are quite common in the ore and mineral relationships within these patches differ from the normal. Clinopyroxene predominates over orthopyroxene and is sometimes intergrown with it. The clinopyroxene has a slightly higher refractive index than the orthopyroxene, a higher birefringence (about 0.02) and the angle of 2v is positive and between 25° and 30°. In the intergrowths it is the orthopyroxene cleavage which passes undisturbed through the clinopyroxene, which is therefore presumably the replacive member of the pair. Apatite is enriched in

these patches up to 3.5%. Biotite is present in approximately
normal amount.

The marginal pegmatitic facies varies in composition from
norite to leuconorite. The feldspar, in common with a little of
the feldspar of the normal ore, may contain perthitic streaks
of potash feldspar. The pyroxene content is often as high as
20%, at the expense of the oxide minerals. Clinopyroxene is not
always enriched at the expense of orthopyroxene. The ratio is
usually about 1:3. Biotite is a little more plentiful forming up
to 6% of the rock. Pargasitic hornblende forming up to 1%
of the rock has been noted only from the marginal facies.

Ilmenite in the marginal facies contains the usual type of
hematite exsolution discs, usually on a slightly coarser scale than
in the normal ore. The ilmenite is more frequently altered and
advanced leucoxenisation of some grains is not rare. This evidence
of the presence of oxidising agents together with the slight increase
in hydrous minerals points to the marginal accumulation of volatiles.
On the other hand olivine and the heavy oxides seem to have
accumulated in the centre of the orebody where the latest crystallising
magma fraction might be expected to occur. It is difficult to
envisage any mechanism of differentiation which could bring about a
distribution of this nature and the writer would suggest that the
orebody was formed not by one influx of magma, but by two or more
of slightly different composition. There is slight evidence that
the marginal phase may have been the last to be intruded, if the
pegmatic patches and veins in the ore are directly connected with it.

Sulphide veinlets which traverse the orebody at infrequent
intervals reflect the accessory sulphide content of the ore. Pyrrhotite

is again rather more abundant than in the Storgangen.

At its north-western end the orebody narrows rapidly to pass laterally into a fine-grained variant of the orebody of different composition. The average grain size of this dyke, which is only a few metres thick, is 0.1-0.2 mm. It consists of 44% calcic oligoclase feldspar (nX = 1.542, An_{28}), 43% pyroxene, 8.3% ilmenite and magnetite, 3.6% apatite and 0.7% biotite. Identification of the pyroxenes is difficult owing to the semi-opaque, cracked and altered character of many of them. The rock certainly contains hypersthene with a higher iron content than the orebody (nZ = 1.695), some clinopyroxene and possibly ferrohypersthene of a later generation than the other pyroxenes. It occurs only in small quantity and it has not been possible to isolate it for immersion work. It is optically negative, has a birefringence of approximately 0.02 and nZ is over 1.71. The rock has a distinctive and unusual composition but is not unknown in the Rogaland region as a dyke rock. Its genetic affinities have not previously been so clearly demonstrated, however, as in the case of the Tellnes example. It is interesting to speculate whether other examples of this rock-type indicate orebodies at depth in their vicinity.

The orezone at Blaafjell, about two kilometres east south-east of Storgangen (see map), is comprised of massive veins of opaque minerals together with ferromagnesian silicates within anorthosite. The deposit is part of a discontinuous orezone which stretches southwards from Blaafjell to Bostolj and Odrevann. The ore is discordant and sharply differentiated from the surrounding anorthosite, a description in accord with the views of Bugge (1953) and Kolderup (1896). The ore occurs as an irregular winding zone on a

vertical well-exposed cliff face of anorthosite. The ore itself
is coarse-grained with ilmenite crystals not uncommonly reaching a
diameter of five millimetres. Inspection revealed that the ore is
closely associated spatially with a fault, filled by a dyke which
traverses the cliff in an irregular manner, a fact which has not
been mentioned by earlier workers. Plate IV N 24 figures this
dyke in the mouth of an addit where it is flat-lying. Ilmenite
and pyroxene have replaced anorthosite completely in close proximity
to the fault, and locally the rock is 100% ilmenite and magnetite.
Away from the fault, the mafic content rapidly diminishes to nothing
passing to anorthosite.

The massive ore consists of about 80% ilmenite with accessory
pyroxene, magnetite, biotite, chlorite, hercynite, pyrite,
pyrrhotite and chalcopyrite. The ilmenite has moulded onto the
pyroxenes which contain ilmenite exsolution lamellae and also onto
the magnetite. A thin selvage of biotite or colourless chlorite
usually separates the ilmenite and magnetite and may separate it from
feldspar (An_{44}). The ilmenite contains hematite exsolution discs of two
sizes. They are very strongly developed but against included
grains of magnetite they rapidly diminish in size disappearing in close
proximity to the contact. The ilmenite has suffered two types of altera-
tion and replacement in local patches. Thin veinlets of biotite
and chlorite have penetrated some of the ilmenites grains and on their
margins oxidation has attacked the ilmenite via the 0001 cleavage
planes altering it to hematite and rutile. The secondary hematite
is whiter in colour than the exsolved titanhematite. In other
examples secondary magnetite has invaded the ilmenite via the 0001

cleavage, replacing the exsolved titanohematite which can be seen to disappear into the magnetite. The surrounding ilmenite is also affected and appears to be altering to (?) magnetite. Carstens (1945) gives the following analysis of the Blaafjell ilmenite. The high content of MgO is presumably due to the presence of spinel or may be in solid solution with the ilmenite.

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	V_2O_5	FeO	MnO	MgO	CaO
0.50	44.16	2.00	14.34	0.30	32.69	0.26	5.28	-

The dyke which now occupies the fault plane is separated from the surrounding ore by slickensides along its margin. It is not apparently a direct parent of the ore impregnations but either filled the fault before or after the ore solutions used it. The dyke-rock consists of plagioclase 71.5%, clinopyroxene 15.9%, ilmenite-hematite and magnetite 10.5% and apatite 2.1%. The opaque minerals are predominantly an ilmenite-hematite intergrowth in 1:1 or 3:2 proportions (see Plate IV N 22). These grains are rarely cut by magnetite and there are also disseminated magnetite pyrite and pyrrhotite grains. The ilmenite-hematite intergrowth, exsolved from an originally homogenous ferric-ferrous-titanium oxide crystal has been cut by a veinlet of later magnetite which caused complete disappearance of the hematite for a distance of 0.02 mm on each side of it. The magnetite veinlet is 0.04 mm wide. The broad hematite bands stop quite abruptly and the space between them and the discordant magnetite vein has been filled by ilmenite. The opaque minerals in this rock were once a continuous or semi continuous mass which has been broken up by the silicates; the opaque constituents appear now as inclusions within the silicate matrix. However since this disruption the rock has probably
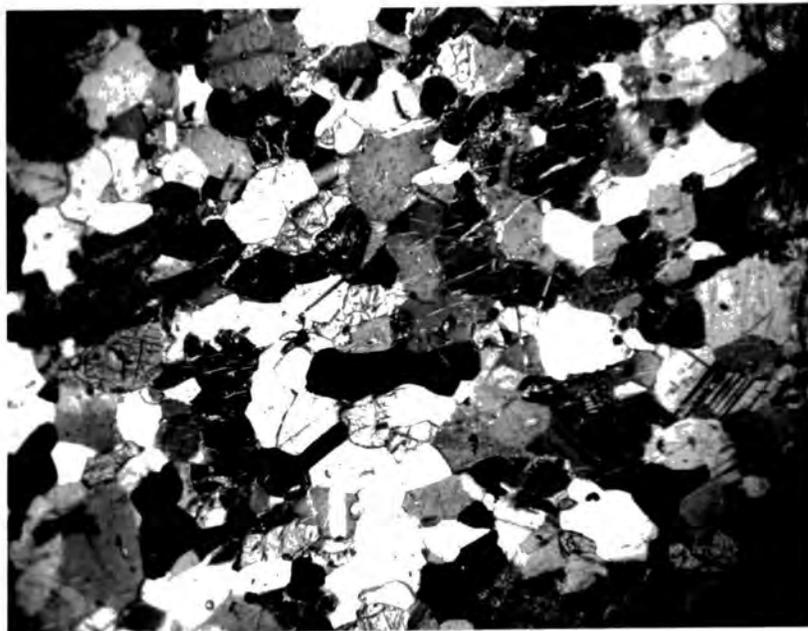
Plate IV N20 x 35 xn   The dyke rock in the fault zone at Blaafjell.
Ilmenite is black; hypersthene-grey with
moderate relief; plagioclase-shades of grey,
sometimes twinned.

Plate IV N21 x 80   A hemato-ilmenite from the dyke rock at Blaafjell.
Hematite is white against the light grey of
ilmenite.
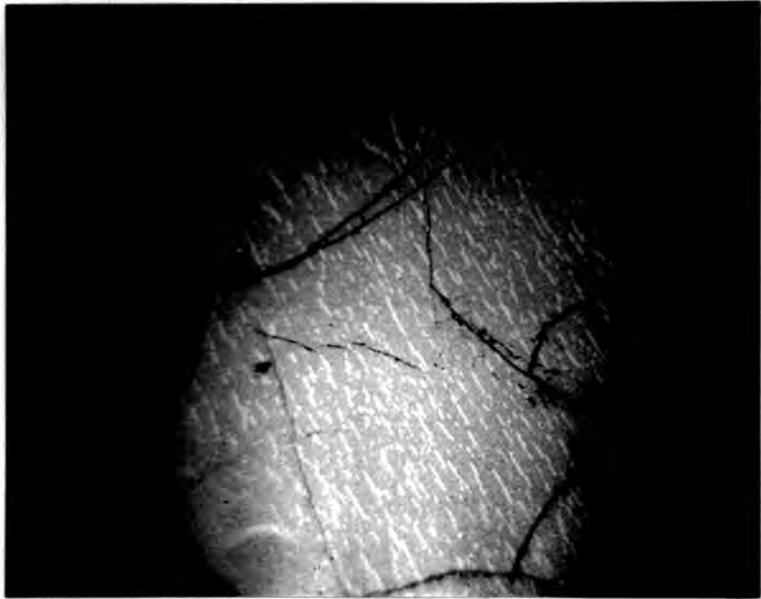
Plate IV ^{N}22 x 80   Hematite discs (here seen in cross-section) in
ilmenite from Blaafjell.   Two sizes of disc
are present, the smaller forming a fine cloud
of white specks between the coarser discs.
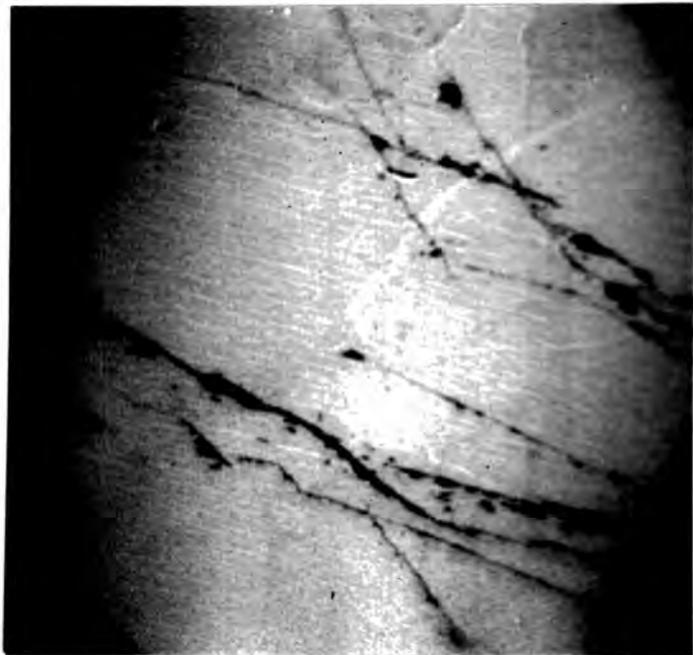
Plate IV N23 x 80   Irregular streaks of coalesced hematite
exsolution discs in ilmenite from Storgangen.   The
streaks cross the 0001 direction at varying angles.

Plate IV N 24   The intrusive dyke at Blaafjell in the adit
                 mouth.   The dyke with slightly sheared margins cuts
                 across the photograph horizontally between ore impreg-
                 nation above and below it.

recrystallised in part, because the relationships between the silicates and opaques are too regular and intimate to represent a simple brecciation.

Before discussing the genesis of the Blaafjell vein ores and the norite ores of Storgangen and Tellnes, a consideration of the ores outcropping near Egersund (see map) will be of value.

The geology and paragenesis of the norite-granite zone in which the ores of Puntervold-Haaland-Kydland-Lien occur has been fully worked out by Michot (1939a; 1955c; 1956b) and a subsequent study of the opaque ore minerals carried out by Hubaux (1956). The account of the geology which is set out below and particularly the petrogenetic theory is based completely on Michot's interpretations. Since he is the only person to have carried out detailed work on these rocks it is necessary to rely upon his account completely, but it must be emphasised that his theories are not a little revolutionary and other workers might give a very different interpretation to the field evidence.

The norite granite series of Puntevold-Haaland-Lien "consists of diverse rocks: anorthosite, norite and leuconorite, noritic gneiss, quartz leuconorite gneiss, monzonitic gneiss, quartz bearing and quartz free mangerite, leucoadamellitic gneiss, leucotoncilitic gneiss and quartzose bands". (Michot 1956b p 189-90 in translation). This complex series of gneisses outcrops over a distance of 15 kilometres but is only a few hundreds of metres wide. It is a narrow selvage between the anorthosite massifs of Egersund-Ogna to the north and Haaland to the south. By comparing the norite rocks of this series with other norite rocks marginal to the anorthosite massifs, the conclusion has been reached that the

norite is of magmatic origin. It is not a normal norite texturally; the hypersthene is poikilitic-interstitial and the accessory opaque minerals have the same textural relations. Exactly similar rocks elsewhere contain opaque mineral constituents but none of them has ore concentrations which are so typical of this zone where the norite is associated with more acid rocks. This has led Michot to connect the development of ore concentrations with the adjacent and intimately associated granite gneisses. The processes of formation which gave rise to the granite gneisses was one of migmatitisation. The ore minerals were driven out of their parent rock, the norite, and concentrated in advance of the migmatitising 'fluids' as a basic front.

The developmental processes, briefly summarised, were as follows.

1. The magmatic intrusion of a norite containing plagioclase (An_{42}), hypersthene, ilmenite and magnetite. The hypersthene and opaque minerals are poikilitic-interstitial to the plagioclase.

2. The rise into the base of the norite of a K, Na, Si metasomatic front, producing a granite migmatite containing relicts of the original norite and causing at a slightly higher level. Anorthositization of the norite.

3. Anorthositization of the norite was caused by the displacement of the mafic constituents, forcing them ahead of the rising granitising front.

4. Basification of the norite above the zone of anorthositisation by the deposition of the elements expelled from the norite at a lower level. The opaque constituents usually are formed into series of narrow parallel veins each a few centimetres wide which some- times coalesce to form a broader ore body. Intercalated with the

opaque minerals veins are norite and pyroxenite horizons where enrichment with Ca and Mg has occurred in contrast to the Ti and Fe enrichment of the ore zones.

5. Anatectic leuconorite formed by homogenisation of the anorthosite-norite zone has been produced in certain areas, presumably as a result of locally higher temperatures above the migmatitisation zone.

6. The whole norite granite zone was later isoclinally folded when the Haaland massif was overthrust from the south.

In all the rocks the opaque minerals were the last to crystallise.

A number of different types of intergrown opaque minerals are present in the various rocks of the zone. According to Hubaux (1956) they are as follows:-

a. Hematite-ilmenite. Ilmenite with exsolution blebs and lamellae of hematite. Normally the hematite content of the ilmenite does not exceed 15% but rarely it rises to 50% and occurs in thick lamellae so that it is not possible to differentiate between host and guest. When it occurs as coarse lamellae the hematite contains ilmenite exsolution bodies; fine lamellae of hematite may be present as well as the coarse which lends support to Ramdohrs (1950) suggestion of two stage unmixing of hematite from ilmenite, which also appears to have occurred in the ores to the south at Storgangen etc.

b. Homogenous ilmenite.

c. Spinel-magnetite. Spinel in irregular very small blebs is exsolved along the 100 cleavages of magnetite.

d. Ilmenite-magnetite. Ilmenite exsolution lamellae in

magnetite occur in two ways. i) Trellis type. Exsolution along the 111 directions inthe magnetite forming a network throughout the mineral. ii)Sandwich type. Coarsely intergrown bodies of ilmenite in magnetite which may reach up to 50% of the composite mineral grain.

e. Spinel. Apart from the intergrown in magnetite it also occurs as

i) Independent grains up to 1.5mm in diameter.

ii) Small grains between ilmenite and magnetite crystals.

iii) Small inclusions in the border zone of ilmenite grains.

The distribution of these intergrowths among the rock types of the zone is interesting. In the original norite, the magmatic rock, only the sandwich type of ilmenite magnetite intergrowth is found. This must indicate slow cooling allowing exsolution to be reasonably complete from an originally homogenous $FeTiO_3-Fe_3O_4$ solid solution.

In the norites of the norite-granite zone, the zone of migmatitisation two types of ore mineral exist a) homogenous ilmenite b) trellis type ilmenite-magnetite intergrowth. Working from the basic assumption that Michot's interpretation of the genesis of these rocks is correct, the following conclusions can be arrived at.

a) During granitization, ilmenite is stable for longer than magnetite. The presence of homogenous ilmenite in this zone suggests that the magnetite of the sandwich intergrowths has been driven off to higher levels before the ilmenite, which must have followed later. (Studies made by the writer on the Carrock Fell gabbro indicate that ilmenite is more stable than magnetite in hydrothermal conditions).

b) Where neither ilmenite nor magnetite were driven out temperatures rose sufficiently to homogenise the opaque minerals and

cooling afterwards was relatively rapid so that only trellis inter-
growths could form.

In the ore mineral concentrations of the basic complex the
remaining types of the intergrowths occur:- hematite-ilmenite,
spinel-magnetite, trellis type ilmenite-magnetite. The lack of
homogenous minerals indicates that after the introduction of the Fe
and Ti oxides, cooling was rapid leaving insufficient time for
exsolution completion. Apatite is relatively concentrated with the
opaque mineral concentrations.

There are certain relationships between the hematite-ilmenite
intergrowths and magnetite which are of great interest.

a) Ilmenite lamellae in magnetite are never seen in the presence
of ilmenite with hematite exsolution bodies. The magnetite in such
an environment may only contain spinel. However Evrard (1944)
has shown that the magnetite in this environment is titaniferous
even though there may be no visible lamellae of ilmenite. He quotes
2.77% TiO_2 in the magnetite. Also when a magnetite grain is in
contact with an hematite-ilmenite intergrowth, the marginal zone of
the ilmenite will be free from hematite inclusions. He finds that
the magnetite in such an environment is short of Fe_2O_3 and he
postulates that a diffusion of Fe_2O_3 occurred from magnetite to
ilmenite when the latter was crystallizing just prior to the magnetite
consolidation and the reverse movement of Fe_2O_3, frozen before
completion, after the magnetite crystallized. Hubaux does not
mention the hematite-free border zones in the ilmenites but actually
figures them in one of his thin section drawings. Although from
a study of crystal shapes it appears that magnetite crystallized
after ilmenite, Hubaux forwards evidence to suggest that they actually

crystallised together and that ilmenite merely has a stronger "force de crystallization". His evidence, however, consists of only one small occurrence.

b) Although Hubaux does not consider that magnetite crystallised after ilmenite it certainly was more mobile and could penetrate the silicate crystals on a very fine scale. His thin section drawings very strongly indicate that magnetite definitely replaced the silicates especially plagioclase. The apparently lower mobility of the ilmenite is most easily explained by assuming that it did in fact commence crystallization at a higher temperature than the magnetite and that the temperature at which the ilmenite was introduced into the rock was not sufficiently high to activate the ilmenite molecule to the extent that it could intimately penetrate the silicate minerals. The question of the greater mobility of magnetite is discussed elsewhere in this thesis, and the reader is especially referred to the section dealing with the Adirondack ilmenite-magnetite deposits.

c) When the volume of hematite exsolution bodies exceeds 15% of the whole ilmenite crystal, magnetite is never found closely associated. This is presumably due to a local high oxidation potential at the time of crystallization which prevented magnetite from forming. This fact again emphasises the preferential and hence earlier crystallization of ilmenite in these ores. It also emphasises that crystallization of an original high temperature solution consisting of TiO_2, FeO, Fe_2O_3 behaves as a ternary system with a eutectic. Given high TiO_2 and Fe_2O_3 concentrations the first mineral phase to separate is a mixed hematite-ilmenite. Apparently this is an example of a system low in FeO where all the available FeO is used up

before the eutectic is reached. It implies that ilmenite very rich in hematite crystallises at a higher temperature than eutectic ilmenite-magnetite.

In conclusion it can be seen that a change in the state of the opaque mineral constituents of a norite takes place when it is anorthositized by granitization processes. Original ilmenite-magnetite coarse intergrowths during their removal in a basic front are oxidised so that the Fe'' ion is replaced by the Fe''' ion. The result of this is the presence of hematite exsolution lamellae in many of the resulting ilmenites with a corresponding decrease in the magnetite content of the rock. In the ore deposits of Koldal, Haaland, Kydland + Liaasen the ratio of ilmenite:magnetite (when present) is usually about 9:1. Spinel lamellae may be present in this magnetite but has not been recorded to occur in the magnetite of the original norite.

Certain features of these 'basic front' ores merit discussion. Hubaux has noted that magnetite never contains exsolution lamellae of ilmenite in the presence of ilmenite containing hematite exsolution lamellae. However true this may be for the ores in question it is certainly untrue of others, Otanmaki for instance where the magnetite does contain ilmenite lamellae. The disappearance of hematite lamellae in proximity to magnetite is a common feature in all ores which the writer has examined where magnetite crystallised later than the ilmenite. Where magnetite crystallised first or contemporaneously with the ilmenite this is not always true, vide Storgangen, Tellnes and Otanmaki.

The order of crystallization of magnetite and ilmenite seems to

vary from one ore to another.   In an oxidising environment such as
this, magnetite is a late crystallising component, as it is in the
dyke at Blaafjell.   Where the oxidation potential was lower, as in
the Storgangen, magnetite crystallised at least in part before
ilmenite.   In Otanmaki, where the issue is more confused owing to
later metamorphism, it crystallised, in general, later but is
not merely an accessory constituent as in the Norwegian ores.
At this stage it must suffice to state that the paragenetic sequence
of the opaque oxide minerals depends probably on two ratios Ti:Fe
and Fe":Fe"'.

Genetic Problems of the Rogaland Ore Deposits.-   In this thesis
the main concern is with the ore deposits but without an understanding
of their regional environment it is impossible to come to any
valid genetic conclusions regarding the ores themselves.   It is
necessary to accept Michot's account of the regional geology as a back-
ground to the discussion.   It is also necessary to assume a genetic
connection between ilmenite ores of the Norwegian type and areas of
anorthosite, but the nature of the connection has to be established.
Facts which must be emphasized are i) the regional P.T.
conditions ii) mthe extraordinary homogenity of the anorthosite
over wide areas iii) the association of opaque minerals with
ferromagnesian silicates iv) their association with small amounts
of hydrous silicates and apatite v) their intrusive character.

It is not the intention here to deal with the problems of the
genesis of anorthosite and the connection of oxide minerals with it;
they are discussed in a later chapter.   The mechanism of emplacement of
the orebodies is of more direct concern in this discussion.   The
views of Michot on the origin of the Puntevold-Haaland-Lien ores have been

carefully expounded.   Can they be extended to the other deposits of the area?   In the case of the massive norite ores the answer is almost certainly that they are unacceptable as they stand.   The Blaafjell deposit on the other hand has many similarities with the Haaland-Koldal ores;   they are of similar composition and texture although their structural environment differs.   The writer is convinced on the field evidence that the Blaafjell ore is not a direct magmatic intrusion but was introduced as a magnesium, iron and titanium rich 'solution' into compact anorthosite which it has replaced.   There is no evidence whether or not it was a basic front, - other than by analogy with the Haaland-Koldal ores - because there is no indication of the presence of granitic rocks at the present level of erosion.

The Tellnes ilmenite-norite is an intrusive mass at the present erosion level, and it was almost certainly a magma, even if a partially crystallised one, at the time of intrusion.   The Storgangen ore also is intrusive but there is less clear evidence whether it was actually magmatic or whether only the mafic constituents were mobile.   Since the norite and the Blaafjell ores all occur near each other in similar structural surroundings a common mode of origin for them can be logically sought after.   The present writer is of the opinion that the identical composition of the feldspar in the orebodies and the surrounding anorthosite is against them being considered to be a direct differentiate of leuconorite magma of which anorthosite is the complementary fraction.   Surely if such were the case the feldspar would be of a different composition, like the dyke extension of the Tellnes ore which is a differentiate of the main orebody.   This leaves two alternatives i)   that the ferromag-

nesian and titanium-rich portions of the ores have been removed
from a hypothetical leuconorite in which the feldspar has remained
crystalline and ii) that the mafic portions of the ore have been
derived from a source external to the anorthosite. The close
proximity of, in particular, the Storgangen orebody to the Hauge norite
of the Bjerkreim-Sogndal 'laccolith' may be significant in this
respect. However, the source of the mafic constituents of the
ores must remain uncertain for lack of conclusive evidence,
but given a mafic fluid it seems possible for it to invest and finally
mobilize an area of anorthosite to form a norite magma which
could itself be intruded. Deposits of the Blaafjell type represent
areas where there has been insufficient mafic fluid to raise the
temperature of the anorthosite to mobilization point. From the
paragenesis of the deposits the process probably commenced with
the introduction of magnesium and iron and was followed by titanium
·and possibly further supplies of iron. The process of
mobilization was aided by small quantities of volatile elements
which have been partially fixed as apatite and hydrous silicates,
but most of the water and halogen content of the rocks has been
lost during subsequent periods of granulite facies pressure-temperature
conditions.

The Anorthosite-gabbros of the Bergen Areas

The anorthosite-gabbros and related mangerites, norites, ecologites,
serpentines, quartz mangerites and berkremites occur in areas centred
on Bergen. The parent magma is assumed to have been richer in iron
and magnesium than the original magma of the Rogaland area.

The larger bodies of anorthosite gabbro consist of andesine-

labradorite anorthosite and some ferromagnesian silicates, and, in smaller part, of pyroxenite, garnet pyroxenite with varying amounts of plagioclase, and small segregations of ilmenite with garnet and pyroxene.   (Kolderup 1933).

Anorthosites and anorthosite gabbros.- These consist of andesine-labradorite feldspar, with pyroxene, garnet and ilmenite as accessory minerals. The pyroxene is diallage surrounded by radiating green hornblende, with a little orthopyroxene.

The garnet is a primary mineral (Kolderup 1903), occurring in euhedral to rounded grains, often associated with scapolite. Garnet-pyroxene-rich parts of these rocks usually occur as lenticular segregations with pyroxene forming the nucleus.

Ilmenite segregations occur with garnet and pyroxene sometimes with the accompaniment of spinel.

The rocks belong to the pyroxene metamorphic facies. Amphibolite facies conditions occur locally - blue green hornblende, epigenetic garnet, where partly saussuritized plagioclase - but the more wide-spread are green schist facies conditions owing to the action of stress throughout the rocks of the region following consolidation.

Eclogites.- Eclogites occur genetically connected with the bodies of anorthosite gabbro (Kolderup 1903; Eskola 1921) in most parts of the igneous bodies and as separate intrusions into the surrounding gneisses. Analyses of anorthosite, (a garnet, pyroxene-rich segregation), and eclogite show chemical continuity. Eskola (1921) found that the garnets in the anorthosites were low in iron content compared with those in the amphibolites and showed "the wide range of solid solutions of the pyrope and almandite compounds (shared) only

with the eclogite garnets". He therefore concluded that since there was no difference in chemical composition between the amphibolites and the pyroxene, garnet, anorthosite the difference in the garnets composition must be a difference of physical conditions leading to the conclusion that the mafic segregations in anorthosite, "the earliest segregations and crystallizations", belonged to the ecologite facies. The significance of the eclogitic garnets found associated with some ilmenite-magnetite segregations is further discussed in connection with the Lake Sanford ores.

The Ore Deposits of the Adirondack Mountains, New York

Within and adjacent to the anorthositic massif of the Adirondack mountains of New York state there are deposits of ilmenite-magnetite ores. They fall into two groups, saturated and undersaturated. The undersaturated group which occurs mainly at the margins of the anorthosite massif contain olivine.

Anorthosite and gabbro-anorthosite rocks of the main Adirondack massif cover an area of about 3,500 sq. kilometres. The massif has been interpreted as an igneous intrusion by all investigators in the field. This synthesis of their views is presented with the intention of emphasizing the similarities, and contrasts of the ores with their Norwegian counterparts. A genetic discussion is presented at the end of the descriptive portion.

The anorthosite massif is comprised of two main facies, the Marcy, typical of the core of the massif, and the Whiteface, which is supposed, according to the 'classical' descriptions, to be confined to the border areas. The name Marcy (Miller 1919) is normally applied to a blue-grey, coarse to very coarse-grained anorthosite with less than 10% of ferromagnesian minerals. The

Whiteface facies (Kemp 1898) is characterised by a medium granular
texture, a milky white colour, a distinct foliation and normally
a higher proportion of ferromagnesian minerals than the Marcy.   It
frequently contains included crystals of blue-grey Marcy-type
feldspar and layers of included Grenville sediments.   A facies
transitional to Marcy has also been recognised.

The massif has been divided into a number of units which are
essentially cores of Marcy anorthosite surrounded by foliated
and granulated Whiteface or transitional facies.   The detailed
structure has not been described but it appears that it may not
be dissimilar to that of the Rogaland region of Norway.   Balk (1930)
has described 'block structure' in the anorthosite.   It consists
of pure anorthosite enclosed in granulated and finer grained,
sometimes more mafic, leucogabbro or anorthosite.   This structure
appears to be very similar to the structure within the Josingfjord
Tellnes anorthosite figured in Plate IV N8.   The foliation and
granulation in the anorthosite has been attributed to late crushing
in an almost consolidated magma, because there has been complete
reworking of fragments broken off phenocrysts, which would not have
occurred during simple cataclastic metamorphism.   However, the large
phenocrysts are unzoned as in the Rogaland anorthosite which suggests
either a metamorphic origin or at least complete reconstitution in
granulite facies conditions.

The following analyses and modes of anorthosite are taken from
Buddington (1939).

	1 %	2 %		1 %	2 %
SiO_2	55.03	53.4	Quartz	–	1.0
Al_2O_3	25.56	23.96	Orthoclase	–	1.6
Fe_2O_3	0.75	0.91	Andesine	93.5	81.2
FeO	1.59	3.02	Augite	2.8	6.8
MgO	1.02	1.88	Hypersthene	2.6	0.3
CaO	9.56	9.85	Magnetite) Ilmenite)	0.5	2.3
Na_2O	4.67	4.17	Apatite	0.2	0.4
K_2O	1.09	0.80	Hornblende	0.2	0.5
TiO_2	0.43	0.62	Garnet	0.2	2.7
P_2O_5	0.09	0.18	Calcite,		
CO_2	0.13	0.42	Chlorite	–	3.1
Cl	0.01	0.01			
MnO	–	–			
H_2O^+	0.28	0.62			
H_2O^-	0.03	0.07			

1. Marcy anorthosite. Plagioclase range in 21 thin sections was An_{40-51} with most in An_{44-48} range.

2. Whiteface anorthosite. Plagioclase range in 21 thin sections was An_{45-50}.

Buddington regards the Marcy anorthosite as a rock consisting essentially of basic andesine with only accessory amounts of femic minerals. There is never a greater variation than An_2 between large phenocrysts and granulated groundmass in any single specimen. The most basic feldspar encountered by him was An_{51} composition, which is in agreement with the findings of Barth (1931). The Whiteface facies is more variable, the groundmass may be up to 8% more albite rich than the ungranulated Marcy type phenocrysts. The rock is also more femic, really a leucogabbro.

Buddington's descriptions apply only to the St. Regis-Westport units of the anorthosite and Stephenson's (1945) descriptions of the rocks enclosing the Lake Sanford area ores are different. The anorthosite is supposed to be "essentially the Marcy anorthosite of Miller" yet he finds that the average composition of the phenocrysts is

An_{55} and of the granulated groundmass An_{45}.   Thus the rock
Stephenson describes as Marcy anorthosite has the characteristics of
the Whiteface facies as described by the earlier workers, except that
the plagioclase is more calcic.   Contradictions of this kind are
unfortunately only too frequent in the Adirondack literature,
making a reviewer's task all the more difficult.

The anorthosite adjacent to the Lake Sanford ores contains the
following minerals in their crystallization sequence:- sodic
labradorite, hypersthene, augite, hornblende, garnet, ilmenite-
magnetite, carbonate, scapolite.   The hypersthene contains 82% of
the En molecule.   The augite is a calcium-magnesium rich variety.
Hornblende is both original and secondary after pyroxene.   In both
cases it is pargasitic.   The garnet, almost always closely
associated with the opaque minerals, consists of 72% grossularite,
18% andradite and 10% almandite.

Buddington, in addition to the conformable and gradational
bands of leucogabbro which lie in or near the border facies of the
anorthosite, mentions "local bands ranging in composition from
gabbroic or noritic anorthosite to mafic gabbro or mafic norite,
which though usually conformable, show sharp boundaries against their
enclosing rocks and may brecciate the older facies".   He noted
also that they contain high proportions of opaque minerals.

The Ore Deposits.-   There are four ore deposits in the vicinity
of Lake Sanford, Sanford Hill, Ore Mountain, Calamity-Mill Pond and
Cheney Pond.   The Sanford Hill orebody is the largest.

The regional anorthosite passes, by an increase in its mafic
mineral content to gabbro which in turn may grade to ore with an
increase in the opaque mineral content.   It is finer in grain

(1-2 mm) than the anorthosite (3-5 mm).   Rare plagioclase

phenocrysts in the gabbro vary in composition from An_{60} to An_{45},

but always have the same constitution as the groundmass

plagioclase.   The mafic minerals of the gabbro are essentially

the same as in the anorthosite but in increased proportions.

Biotite is present in close association with the ore and apatite

may form up to 10% of the rock.   Garnet normally occurs as a

reaction rim to the ore.

The orebodies are of two types:- i) Concordant sill-like

bodies in gabbro formed by an increase in the opaque mineral

content of the gabbro and ii) discordant dyke-like bodies in

anorthosite.   In the gabbro the dominant opaque mineral 58-64% is

euhedral to subhedral ilmenite free from exsolution bodies.

Moulded onto and embaying the ilmenite is magnetite containing 7

to 12% TiO_2 as ilmenite exsolution lamellae and 0.65 to 0.95% of

V_2O_5.   The grain size of the ore varies from 1 to 2 mm.   The richer

orebodies occur in anorthosite and are comprised of between 85 and

88% magnetite containing 12-14% TiO_2 as ilmenite exsolution lamellae

and 0.58 to 0.68% V_2O_5.   The ilmenite is euhedral to subhedral

with no exsolution textures.   (Balsley 1943: Stephenson 1945).

Other workers on these ores have described the microstructure

of the ores differently.   Osborne (1928) mentions hematite

exsolution discs in the ilmenite.   Wheeler (1950) in describing

late crystallized ilmenite from a cavity describes its content

of 4% magnetite as less than any other ilmenite in the mine.

Ramdohr (1956) has briefly recorded the presence of ulvospinel

in the magnetite.

On the structure and location of the ores Stephenson (1945)

drawing on Buddington's (1939) and Balk's (1931) work, has made the following appraisal:- i) The Lake Sanford area is at the apex of the Adirondack anorthosite dome, which is a likely place for late crystallizing liquids to accumulate. ii) Both gabbro and anorthosite show good planar flow structures and sometimes linear structures which are highly irregular in trend. iii) Ore concentrates at the apices of intense bands in the planar flow structure. The ore may grade into gabbro which in turn grades to anorthosite on the flanks of the bends.

The contacts between gabbro and anorthosite are normally gradational although gabbro rarely intrudes anorthosite. Ore grades into gabbro but intrudes anorthosite and at the sharp contact a garnet reaction rim is always developed. Plagioclase relict phenocrysts in the ore are common and a series of reaction rims are developed between the tectosilicate and the oxide in the following order:- i) Plagioclase phenocrysts ii) Clear plagioclase zone with spinel anhedra iii) Garnet myrmekitically intergrown with plagioclase iv) Augite and green hornblende v) Diallage, brown hornblende, hypersthene, and biotite. It is significant that the minerals of the reaction rims are also those of the gabbro. Structures which Stephenson (1945) interprets as flow bands are developed round the included plagioclases.

Haffner quoted by Gillson (1947) describes the Sanford Hill orebody slightly differently and in such a way that a distinct similarity between it and the Storgangen orebody appears. "The ilmenite-magnetite ore occurs as roughly tabular masses, as much as 2,000' long and several hundred feet thick, with dips from 45°-90°.

The ore varies in character from a very massive pure coarse-grained mixture of approximately equal amounts of magnetite and ilmenite, with an average grain size of 5 mm, and a finer-grained disseminated type of ore, which shows gradations from a disseminated gabbroic rock to a nearly pure aggregate of fine-grained magnetite and ilmenite with an average grain size of 1-2 mm. The coarse grained ore occurs as a wide band along the footwall of the ore body, with the finer-grained type of ore lying in bands parallel to it with interspersed bands and lenses of waste rock. At least two major faults are known to cut the ore, offsetting the ore bands two or three hundred feet". Haffner also lists the following minerals found associated with the ore. Pyrhotite, pyrite, chalcopyrite, cobaltite, sphalerite, galena, molybdenite, marcasite, calcite, siderite, ankerite, apatite, tourmaline, scapolite and prehnite, as well as the femic minerals already described. The epizonal character of this assemblage is quite distinct.

Genesis.- Theories concerned with the mode of formation and emplacement of the deposits have mostly considered the gabbro and ore to be late-crystallizing differentiates derived from the parent magma of the anorthosite massif, concentrated by a filter-pressing process and, in part, injected as late liquid segregations into solid but probably still hot anorthosite. The theory of Osborne (1928) considered that filter-pressing of anorthosite yielded a magma consisting of pyroxene, plagioclase and iron ore. This rest magma was then injected into anorthosite to form ore bodies and dyke-like gabbro intrusions. Osborne failed to recognise the gradation from gabbro to ore.

Stephenson (1945) considers the bulk of the plagioclase in the anorthosite to be of intratelluric origin. During injection this mush of crystals would have tended to lag behind the magnesium and iron-rich residuum; constrictions in the channelway of the intruding magma would have acted as focal points for the accumulation of the crystal masses, and in such a restricted environment the granulated texture of the rock could easily have developed. "When the ore rich gabbro encountered the rigid anorthosite masses, ore replaced anorthosite in a very irregular manner and penetrated it along already formed joints. This replacement of anorthosite by ore gave rise to the richest portions of the Sanford Hill and Ore Mountain ore bodies". Stephenson does not consider that replacement is important in any environment other than anorthosite, because he regards the gabbro essentially as an intrusive body in which the ore residuum crystallized as lenses. What little replacement he does envisage was carried out by a tenuous residuum in which, as suggested by Singewald (1957 p 736), "mineralizers participated". The abundance of pyroxene, hornblende and biotite he considers as evidence of the lack of volatile constituents. Stephenson sums up his views by concluding "that the titaniferous iron ores are of two types, magmatic segregations in gabbro and magmatic injections in anorthosite. The magmatic segregations in gabbro would conform to Bateman's (1942) type IIA residual liquid segregations, and ore in anorthosite to type IIB, residual liquid injection".

Buddington (1939) was in general agreement with the concept of late liquid accumulation and in a later paper (1955) sets out to show that the ores were formed at magmatic temperatures. Evrard

(1949) has shown theoretically that the rocks and ores are genetically related to each other though the trend of differention. moves in different directions in rocks and ores. As Fe_2O_3:FeO ratio increases in rocks so TiO_2 decreases, and in ores the reverse takes place. TiO_2 in rocks goes into silicates but in ores into oxides. He finds that in the series Marcy anorthosite $\rightarrow$ Whiteface anorthosite $\rightarrow$ Gabbroic late differentiates $\rightarrow$ Lake Sanford ores the ratio $\dfrac{Fe_2O_3}{Fe_2O_3\ \&\ FeO}$ falls in the rocks and is very high in the ores. He attributes this to the affect of the volatiles CO_2, H_2O, SO_2 etc which are involved in the following reactions which move to the left with lowering temperature

$$FeO.\ Fe_2O_3 + H_2 \rightleftharpoons 3FeO + H_2O$$
$$FeO.\ Fe_2O_3 + CO \rightleftharpoons 3FeO + CO_2.$$
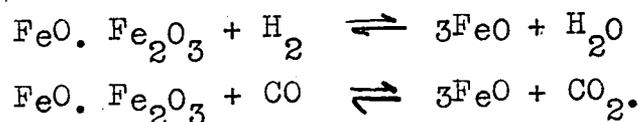
Gillson (1949, 1956) accepts the Marcy anorthosite as a consolidated rock in situ, and considers that the Whiteface anorthosite, the gabbroic minerals, and the ore were formed by replacement and alteration. "The Whiteface facies is not a border facies but simply an andesinised product of the original Marcy type. It certainly is not confined to the border of the mass but occurs in nearly every acre of surface exposed that the author has examined." In the quarries in the ore deposits he finds that strong andesenisation and scapolitization are associated with a fault line which demonstrates that the enrichment in soda is a post consolidation effect. Gillson places great emphasis on the relict feldspar crystals, in all stages of preservation which are common in ore and gabbro. From a consideration of the petrography and intercrystal relationships Gillson deduces the following series of events.

1.   Andesinisation and some scapolitization of consolidated labradorite feldspar, by liquids which probably used faults as their channel way.

2.   Introduction of iron and magnesium and metasomatism of feldspar to yield ferromagnesian minerals. The extent of the metasomatism is controlled to a certain degree by the banded structure of the anorthosite.

3.   Introduction of more iron together with titanium forming ore by replacement of ferromagnesian minerals and reaction with feldspar. The solutions followed gneissic crushed and faulted zones in the wake of the iron and magnesium metasomatism but also invaded other crush zones in anorthosite forming the replacement bodies in anorthosite. The gabbro is finer grained than the anorthosite which would explain the finer grain of gabbro ore. The enrichment of gabbro ore in titanium is not however explained by Gillson, nor is any reason for the higher V_2O_3 content of the magnetite in gabbro offered.

The two contrasted modes of origin which have been suggested merit critical consideration since both have a number of facts which appear to support their respective conclusions.

The magmatic late differentiate theory has the following facts in its favour.

1.   The localization of ore and gabbro at the apex of sharp bends in the foliation suggests that the mafic minerals and the potential ores were present as a magma which tended to accumulate in low stress areas.

2.   There is distinct foliation in the gabbro which is highly suggestive of flow structure.

3. The relationships of gabbro to anorthosite, in particular the gradation between the two, together with occasional injection of the former into the latter are in favour of considering the gabbro as a late accumulate formed from the anorthosite.

4. The geochemical distribution of minerals and elements within the ores can also be accounted for if the ore is considered to be an essential part of a gabbro-ore differentiate. The ilmenite in the ore normally is more euhedral in shape than the magnetite which could be interpreted to indicate that it crystallised first. Accepting the gabbro as a magma nearing consolidation with ilmenite and some magnetite partly crystallized the effect of an application of pressure causing folding might cause the following effects. The gabbroic minerals lubricated by the liquid portions of the melt would tend to move to the apex of folds and at the same time the most mobile portion rich in magnetite would be injected into the surrounding anorthosite where it would solidify more rapidly. The magnetite in anorthosite as a result contains a higher proportion of "frozen in" TiO_2, (12-14%) mostly as ilmenite lamellae, than does the magnetite of the gabbro (7-12% TiO_2), because exsolution processes have less time to come to completion. The magnetite of the gabbro also contains a higher percentage of V_2O_3 .65-95% than that in the anorthosite (.58-.68%) which again would be expected from a consideration of the atomic radii of V^{IV} and Fe^{III} ions which are 0.61 KX and 0.67 KX respectively. Early formed magnetite should always tend to be more vanadiferous, by reason of its capture of the smaller vanadium ion. It is also possible to attribute the coarser grain size of the ore in anorthosite to the presence of volatiles and liquids with a low crystallization temperature which were intruded with the magnetite-rich ore fluid.

There are a number of facts which militate against a purely magmatic origin and are in favour of a replacement origin for the deposit. The most important is the presence of reaction rims between ore and labradorite feldspar, and in particular the presence of garnet which is certainly not a magmatic mineral. It is difficult to understand how a late liquid differentiate could have become out of phase with its surrounding host rock to such an extent that it developed typical skarn minerals at its contact. The texture and inter-mineral and crystal relationships strongly suggest that reaction of ore liquid with, followed by replacement of, labradorite occurred. However, if the opaque minerals did not crystallize from a melt, as pure replacement implies it is difficult to account for the titanium and vanadium distributions between the two types of ore. The difference in grain size presents, of course, no problem.

The presence of garnet reaction rims to the ore in anorthosite provides in itself a problem. Why should they develop at Lake Sanford when in very similar circumstances in many other ilmenite deposits they are absent? The assemblage anorthite-hypersthene-augite-garnet is probably unstable (Turner and Verhoogen) and commonly represents retrogradation to amphibolite facies conditions. In such a circumstance the garnet should be almandine, whereas in this case it is 72% grossular. The garnet has almost certainly formed because the introduction of the ore minerals upset the equilibrium established in the anorthosite, yet the composition of the garnet would not be in agreement with the development of local amphibolite facies conditions. Eskola (1921) has shown that the garnets in anorthosite-gabbros of the Bergen Arcs are calcium-rich pyrope-alman-

dines, very similar to the garnets occurring in eclogites and totally different from garnets developed in amphibolites with the same chemical composition as the anorthosite gabbros. The Adirondack garnets are yet more rich in calcium and resemble closely eclogite garnets. It is, then, not impossible that the ore minerals crystallized in conditions approaching those of the eclogite facies. In this way the inability of the ore to react to form almandine, or even andradite may be explained.

The ore minerals in the Adirondack deposits differ from their Norwegian counterparts in the high proportion of magnetite which they contain. The lack of olivine also distinguishes them, although undersaturated rocks from the region, described below, do contain this mineral. The ores contain more iron and were in a more reduced condition than the Storgangen and Tellnes ores. The absence of an abundance of hematite exsolution lamellae, and the presence of ulvospinel and, locally, graphite (Ramdohr 1956) are evidence of this. Despite this there are distinctly larger quantities of 'flux' minerals− apatite, scapolite, biotite − present than in the Norwegian ores.

Why have the ores reacted with labradorite? Almost certainly some agent present at, or after, the injection of the ores must have caused disequilibrium between the two phases. In most of the other anorthosite massifs of the world they appear to be able to co-exist in equilibrium or, at least, andesine and ilmenite-magnetite can. In a normal gabbro ilmenite and magnetite are frequently in contact with labradorite without a reaction rim developing. For the present the problem must remain unsolved.

<u>Ores Associated with Undersaturated Metagabbros</u>.- In addition to the saturated anorthosite gabbro bodies within the anorthosite massif, independent unsaturated gabbro masses with modal or at least normative olivine occur within and without the eruptive mass. They are usually divided into two groups a) metagabbros of the northwest Adirondacks b) metagabbros of the eastern Adirondacks.

The norwestern group contains no known ore mineral concentrations although the metagabbros are high in TiO_2 content. Unfortunately it is this group which has been most closely studied by Smyth, Cushing, Buddington and others. The eastern Adirondack metagabbros in the Westport-Elizabethtown areas have been described only by Kemp and Ruedemann (1908), Kemp (1899) and (1894) and Osborne (1928).

From a study of the least altered facies Buddington suggested that the metagabbros were originally olivine diabases with ophitic texture. The eastern metagabbros are higher in iron, titanium and phosphorus content, and lower in magnesia than the northwestern metagabbros with consequent larger normative amounts of ilmenite, magnetite and apatite and smaller quantities of calcic feldspar and olivine. Buddington remarks "this is in keeping with the fact that mafic metagabbros and ilmenite-magnetite bodies are almost exclusively associated with the metagabbro masses in close proximity to the main anorthosite massif. It is not apparent what the genetic significance of this relationship is".

The age of the undersaturated gabbro intrusions was considered to be later than the granites and syenites within which they are frequently found, by all workers earlier than Buddington (1939). He regards them all as later intrusions interpreting the marginal facies as zones of recrystallization in contact with the later acid

intrusions rather than as chilled borders.

Mafic metagabbros associated with ilmenite-magnetite ore mineral concentrations occur at Split Rock Mine, north-east of Westport, Kent Mine, Lincoln Pond and at Tunnel Mountain, Elizabethtown Township. Only the Split Rock Mine deposit has been described in any detail (Osborne 1928).

The country rock is described by Osborne as gabbro containing labradorite, olivine, hornblende, augite iron ores, garnet, biotite and various alteration products. The ore contains the same minerals, including olivine, but in different proportions. The plagioclase crystals are granulated and contain multitudinous small inclusions, except the crystal margins which are clear and more sodic in composition. The texture in gabbro and ore is sideronitic.

Reaction rims surround the opaque minerals and olivine. The former are rimmed, from inside outwards by basaltic hornblende, biotite and isotropic, inclusions free, garnet. Olivine is rimmed by colourless augite and plagioclase both inclusion free, garnet on its outer margin graphically intergrown with plagioclase, clear plagioclase and cloudy plagioclase. The various plagioclase zones are usually optically continuous. Augite with inclusions occur other than in reaction rims. The ore minerals are magnetite with inter-grown ilmenite and spinel. No other details are given by Osborne, but from one illustration it appears that ilmenite probably crystallised before magnetite.

The ore bodies take the form of four subparallel zones of variable dip. They are probably one continuous ore zone which has been folded. The ore bodies are banded parallel to their contacts

Analyses of Undersaturated Metagabbros.

	68 L	71 L	72 L
SiO_2	44.77	17.90	13.35
Al_2O_3	12.46	10.23	8.75
Fe_2O_3	4.63	15.85	20.35
FeO	12.99	27.94	28.82
MgO	5.34	6.04	6.63
CaO	10.20	2.86	2.15
Na_2O	2.47	-	-
K_2O	.95		
H_2O^+	.48	1.33	1.68
H_2O^-	.12		
CO_2	.37	0.1	0.17
TiO_2	5.26	15.66	16.45
P_2O_5	.28	.04	.02
MnO	.17	-	-
S	.26	.14	.09
V_2O_5	-	.55	.61
Cr_2O_3	-	.51	.55
	100.75	99.15	99.62

Norm.

	68 L	71 L	72 L
Orthoclase	5.56		
Albite	20.96		
Anorthite	19.46	14.18	10.84
Corundum	-	5.00	4.79
Diopside	24.02		
Hypersthene	6.07	17.79	5.91
Olivine	5.31	5.84	14.26
Magnetite	6.73	22.97	29.46
Ilmenite	9.73	29.79	30.55
Apatite	.67		
Chromite	-	.67	.90

68 L   Wall Rock of Ti-Magnetite Lincoln Pond Elizabethtown
Green Augite, hypersthene brown hb, plagioclase and
magnetite.   Microperthite less common.   Garnet
absent to rich.   (Kemp 1899).

71 L   Ore, Split Rock Mine.   (Kemp 1910).

72 L   Ore Tunnel Mt. Mine. (Kemp 1910).   Magnetite,
ilmenite, brown hornblende, olivine, garnet,
plagioclase.   Corundum of norm appears as spinel.

with the gabbro which are sharp.   Osborne considers that the ore
was injected into the gabbro as a dyke but that some iron ore
constituents were introduced for short distances across the contacts.

The ore cannot have originated by crystal sinking.   Olivine
and all the silicates crystallized before the ore minerals which
therefore cannot have accumulated gravitationly as crystals.
Differential refusion of oxide minerals only after gravitative
accumulation does not appear possible owing to the high melting
temperatures of the oxides under investigated conditions.   Refusion
of early formed crystals as proposed by J.H.L. Vogt cannot apply
in this case.   Immiscibility of the iron-titanium oxides and spinel
and their retention in the liquid state until after the crystallization
of the silicates would satisfy the petrographic requirements, but
appears unlikely from experimental evidence and field evidence
elsewhere.

Osborne cannot suggest a mode of origin for these orebodies
because the presence of olivine destroys any rest-magma hypothesis.
He does not consider a replacement origin.

Deposits in the Morin Anorthosite of Quebec

The Morin anorthosite mass, 900 square miles in area, lies
to the north west of Montreal just within the Canadian Shield.
It is surrounded by older granite gneisses except on its southern
boundary where Grenville sediments and younger genetically related
marginal granitic facies border the anorthosite.   In some
places these granites with quite high proportions of potash feldspar
and quartz grade into the anorthosite, but they may also be
reinjected into the parent rock.   (Adams 1895).

The anorthosite consists of large plagioclase crystals varying from basic andesine to labradorite in composition (Adams 1895) or labradorite of An_{50-60} composition (Osborne 1928). The plagioclase is clouded with minute non-opaque inclusions. In general it is antiperthitic in character. Accessory minerals in the anorthosite forming up to 10% of the rock are hypersthene, augite, biotite, ilmenite, apatite, orthoclase and quartz.

Two types of ore deposit are found within the massif, ilmenite ores with exsolved hematite inclusions, and ilmenite-ilmeno-magnetite ores.

The Ivry deposit is an example of the first type. It consists of ilmenite with hematite exsolved along the 0001 crystallographic direction and accessory pyrrhotite, chalcopyrite, pyrite and marcasite, which occur as scattered grains in the main part of the orebody but form crosscutting veins in the marginal portions. The marcasite is an alteration product of the pyrrhotite. Scapolite in small quantity also accompanies the ore.

The orebody has invaded the plagioclase-rich rock and has enclosed and penetrated the feldspar crystals in a manner reminiscent of replacement (Osborne 1928). The contacts of the orebody are normally sharp but locally gradational contacts have been observed. In all cases the ore minerals are interstitial to the feldspars. There are no reaction rims developed about the ore minerals; garnet and hornblende are absent and biotite is of rare occurrence. Osborne (1928; 1935) considers that the ore is a late crystallizing differentiate of the anorthosite, which has been reinjected into its parent rock when it was still hot. Although he mentions that replacement has occurred on the margins of the orebody he does not

consider it to be the prime method of emplacement.

The Desgrosbois deposit has not been adequately described but it appears to be a more disseminated ore body occurring in a gabbroic variant of the anorthosite. The ore minerals are ilmenite, and magnetite with ilmenite exsolution lamellae. The gabbro is regarded to be genetically connected with the anorthosite (Dulieux 1913; Osborne 1935) so that two different ore types appear to have been generated within the same anorthosite massif.

The Ore Deposits of the Lower Romaine river Anorthosite massif, Quebec

The Allard Lake or Lower Romaine river anorthosite massif lies along the south-east margin of the Pre Cambrian shield close to the contact between Pre Cambrian intrusive and metamorphic rocks and Palaeozoic sediments unconformably overlying the Pre Cambrian. The anorthosite is part of the Morin series. The anorthosite is oval in shape with the long axis 90 miles in length directed east-west. It is between twenty and thirty miles wide.

Several facies are present within the massif. The most common is anorthosite with less than 5% of the femic minerals, hypersthene, augite and ilmenite. The plagioclase forming 95% of the rock has a composition ranging from $An_{40}-An_{56}$, and crystals of it commonly show granulation along their borders indicating pre- or post-consolidation movement. (Hammond 1952). A facies of anorthosite carrying varying proportions of disseminated ilmenite appears to be approaching an ilmenite gabbro-norite in composition. It contains a slightly more, basic feldspar (An_{50-60}), and more ilmenite (5-20%), pyroxene, biotite, pyrite and magnetite than the normal anorthosite.

Anorthosite-norite occurs on the north-eastern and eastern margins

of the massif.   It is foliated, coarse grained and contains
feldspar, hypersthene, ilmenite, magnetite, biotite and a little
quartz.

The contact relationships of the massif have received little
study.   On the eastern margin the increase in mafic minerals is
accompanied by accentuated foliation and the appearance of granite
pegmatite dykes.   The contact itself is usually a hybrid zone up
to 1,000' in width.

Bourret (1949) (quoted by Hammond 1952) considers that the
anorthosites of the Morin series have been forced into older Grenville
gneisses as concordant tabular sheets, or sill-like masses of
large areal extent.   There is some supporting evidence for this
hypothesis in the pseudo stratification seen in some disseminated ilmenite
deposits within the Allard massif.

There are no descriptions available of any structural phenomena
developed within the anorthosite massif and superficially the ore
deposits appear to be randomly distributed within the north-eastern
corner of the massif, between two and fifteen miles from the contact.
Morphologically there are three types of deposit a) flat lying
tabular bodies of large areal extent b) steeply dipping dyke like
bodies   c) lenticular irregular masses.   Details of the shape of
the orebodies are included in the economic section of this report.

The ore is coarse-grained hematite-ilmenite.   Hematite, exsolved
as blades of small size within the ilmenite along the 0001 cleavage
directions, forms up to 20% of the ore.   The coarse blades of
hematite contain lamellae of ilmenite which in turn contain smaller
hematite discs.   Typical high grade ore contains 75% ilmenite, 20%
hematite as exsolution bodies and 5% pyroxene, feldspar, pyrite pyrrho-

tite, and chalcopyrite.

The relationships of ore to anorthosite are the same in all the three types of deposit. "The contacts between ilmenite and anorthosite are sharp. Ilmenite is coarse grained at the contacts indicating that the anorthosite was still hot when the ore was emplaced, but had cooled enough to become fractured. Inclusions and irregular blocks of anorthosite within the orebodies show little if any alteration. Tiny dikelets of coarse granular ilmenite commonly cut the anorthosite at the contacts with the orebodies. A little pyrite and pyrrhotite are present, all of which occur interstitially. Biotite is found in a few places along the contacts, but there is no aureole of alteration in the wall rocks...... On the basis of the above direct field evidence, the writer prefers to class the Allard Lake ores as being late magmatic. A process of late gravitative liquid accumulation with injection of the oxides into fractures within the present anorthosite presents the most satisfactory explanation of such field observations." (Hammond 1952).

Hammond concedes that a late magmatic origin need not necessarily apply to all ilmenite or magnetite deposits in anorthosite but is quite definite in his opinions with regard to the Allard occurrences. In this case, where there has been ample opportunity for studying drill cores and evidence is not restricted to surface outcrop, there can be little doubt that there is no evidence of hydrothermal or pneumatolytic activity. In a number of other instances, in particular. St. Urbain and Lake Sanford, conflicting evidence has been presented and the impression is given that the late magmatic theorists have based their conclusions on incomplete evidence; certainly such is the

conclusion if one judges from the evidence submitted by Gillson (1932; 1949; 1956) in support of the pneumatolytic-hydrothermal theory. The Allard Lake deposits however would seem to give scant support to the latter school of thought.

The Ore Deposits of Sept-Iles Bay Area, Quebec

The deposits in the Seven Islands Bay area on the north shore of the St. Lawrence are associated with an anorthosite body covering about 60 square miles. The anorthosite is part of the Morin or Buckingham series of which the Morin anorthosite, described elsewhere, is the largest basic massif.

The Sept Iles anorthosite is surrounded by granites and granite gneisses some of which are younger than the anorthosite and are considered to be congenetic with it (Faessler and Schwartz 1941). The ore deposits are situated near the southern margin of the anorthosite mass in an area where bands of anorthosite and gabbro alternate with later granitic bands which have shattered the basic rocks. Elsewhere there is gradation between acid and basic facies.

Most of the anorthosites are dark coarse-grained rocks containing labradorite-bytownite feldspar of An_{60-80} composition. This is notably more basic than the plagioclase of the other Quebec anorthosites and of the Adirondack and Egersund-Sogndal massifs. It is much closer in composition to the anorthosites of the layered gabbro-norite complexes and the banded nature of rocks in this area suggests that it may in fact be a layered complex which has been intruded by later granites. The literature available for study does not contain sufficiently detailed descriptions of the area to form

any definite opinion and the massif is poorly exposed, but the possibility should not be excluded.

With an increase in femic minerals, usually hypersthene with a little biotite and hornblende, the anorthosite grades into gabbro which in turn grades into ilmenite-magnetite gabbro and finally ore lenses. The dark anorthosites and the gabbros contain included masses of white anorthosite, largely converted to carbonate, clinozoisite, epidote and sericite, which apparently have been torn from some hidden anorthosite layer through which the banded rocks have been intruded. The dark anorthosites do not exhibit a granulated texture which is again an unusual feature for anorthosite massifs.

The ore deposits occur disseminated in gabbro which by increase in opaque-mineral content becomes massive ore, and by decrease in mafic minerals grades into leuconorite or anorthosite. The minerals comprising the ore lenses are ilmenite and magnetite frequently in about equal quantities, but either may be in excess of the other. The ilmenite usually contains exsolution lamellae of magnetite arranged parallel to the (0001) cleavage direction in a normal manner. The magnetite contains irregular inclusions of ilmenite and some spinel and only occasionally regular ilmenite lamellae arranged along (111) cleavages. The ilmenite shows variation "from a rather diagrammatic en echelon type to almost complete irregularity. By far the most common arrangement is a series of blades forming en echelon zones across the magnetite. Less commonly the ilmenite forms somewhat curved stringers. These may be composed in part of en echelon lamellae or irregular stringers." (Faessler and Schwartz 1941).

"In some specimens that show the en echelon and irregular
inclusions of ilmenite, segregation to grain boundaries of the
magnetite was observed.   In many cases stringers cut across the
grains and some of these show a narrow zone of lattice work of ilmenite
on each side.   The grains in the stringers usually show a random
orientation but the ilmenite lamellae of the lattice work are
arranged along octahedral planes and could reasonably be interpreted
as of later origin than the abundant en echelons and irregular
inclusions."   These facts suggest quite strongly that normal (111)
lamellae may have been formed by replacement from the veinlets rather
than by the usual exsolution method.   In a few specimens both normal
and abnormal intergrowths occurred together but always in sharply
differentiated areas.   In the disseminated deposits in the gabbros
only normal intergrowth textures were observed.

Faessler and Schwartz could find no evidence that the unusual
arrangement of lamellae was caused by minor shearing of the crystals
after exsolution.   "Available facts suggest that the distortion
of the planes along which the ilmenite segregated had taken
place between the time of crystallization of the magnetite and the
time of exsolution of the ilmenite.   The concentration of the
lamellae mainly in one series of parallel planes suggests that some
stress was active during exsolution."   Their conception of the
course of events during cooling is as follows:-   "As the temperature
fell and ilmenite began to exsolve, it took up positions along
planes that had been subject to extensive closely spaced slipping or
translation.   Crystallographic planes at an angle to the plane
of translation would be offset and thus perhaps account for the en
echelon arrangement of the ilmenite inclusions.   Where the deformation

was more complicated curved and irregular arrangement of the

inclusions resulted."

The Sept Iles deposits appear then to contain a somewhat

unique type of ilmenite-magnetite intergrowth.   A more detailed

study of the geology of the deposits in relation to their host rocks and

the inter-relations of the constituent members of the latter would appear

to be necessary before any conclusions can be drawn regarding the

ultimate cause of such unusual phenomena.

The Anorthosite Massif and Associated Ore Deposits of the Laramie Range Wyoming

"The anorthosite massif outcrops in a belt roughly thirty-six

miles long and twelve miles wide, elongated in a north-south

direction, making up the bulk of the central mass of pre-Cambrian

crystalline rocks in the eroded arch of the Laramie Mountains, north-

east of Laramie. There are many outliers of the anorthosite in the

surrounding rocks near the contacts of the main body."

"Associated with the anorthosite are gabbroic masses distributed

in small patches within the anorthosite itself or in scattered outcrops

along the contact.   The largest mass of gabbro occurs in an indentation

of the anorthosite in the central western part.   "The smaller outcrops

of gabbro are located within the anorthosite but no more than two

miles away from its border." (Fowler 1930).

The lenselike masses of titaniferous magnetite at Iron Mountain,

the Shanton and Taylor all occur in the anorthosite within about

two miles of the eastern contact but smaller dyke-like bodies

are known to occur throughout the massif (Diemer 1941).

"The Sherman granite batholith, which is the largest intrusive

igneous mass in this part of the Rocky Mountains, almost completely

surrounds the anorthosite body and penetrates it in the form of dykes and knobs. "The Sherman granite carries xenolithic fragments and roof pendants of the early pre-Cambrian complex crystalline schists..." "Occasional zenoliths of schist also occur in the anorthosite." (Fowler 1930).

The anorthosite is made up largely of labradorite feldspar with accessory diopside, magnetite, apatite and probably minute rutile needles. The feldspar in the massive anorthosite away from the contacts has undergone protoclastic granulation with development of light rims around the feldspar crystals. Diopside is altered to uralite, chlorite, actinolite and finally biotite by end-stage alteration. Quartz, sericite and zoisite are locally found. The presence of carbonate and quartz-feldspar veins is taken to indicate the action of mineralizing solutions from the surrounding granite (Fowler 1930). Titaniferous magnetite and apatite crystallized last and they cut, and fill interstices between, labradorite crystals.

Cataclastic structures and abundant evidence of the action of granitic solutions are visible along the contact zones particularly in the east. In the north-west where the deepest part of the massif is seen, protoclastic and cataclastic structures are highly developed.

The gabbros are lens-like leucocratic to masotype bodies containing 50-70% labradorite, diallage and rarely diopside and augite. Olivine is an accessory and magnetite crystallized late and may form 25% of the rock. There is abundant evidence of deuteric alteration probably mainly due to the action of granitic solutions.

The surrounding granite consists of 50% microcline, 20% orthoclase, 20% quartz and 10% of biotite, uralite and other accessories. There is a syenitic phase also developed. Its origin is uncertain.   (Fowler 1930).

Analyses of the Rock types (Fowler 1930)

	Anorthosite	Gabbro	Granite
SiO_2	53.02	45.50	73.75
Al_2O_3	28.04	15.46	14.5
Fe_2O_3	0.46	4.04	0.73
FeO	0.87	11.01	0.49
MgO	0.33	4.95	0.32
CaO	10.94	10.40	1.35
Na_2O	4.19	2.50	3.80
K_2O	0.81	0.68	4.19
TiO_2	0.40	3.48	0.30
P_2O_5	0.16	1.09	-
MnO	-	0.22	-
H_2O^-	0.10	0.30	0.25
H_2O^+	0.84	0.44	0.35

The granite appears to be a normal batholithic granite similar to Daly's plutonic granite. From chemical evidence there does not seem to be any reason to assume that the anorthosite has separated as a basic fraction of the granite as suggested by Fowler (1930). The similarity in constituents of anorthosite and gabbro and their mutual lack of, for instance Cobalt and Zinc, is used by Fowler as evidence of consanguineity.

Structure.-   Fowler (1930) infers that the anorthosite is a cone-shaped igneous mass much thicker in the centre than at the margins. The evidence for this inference is the lack of zenoliths and schistosity in the centre of the mass and the presence of both in a relatively narrow zone near the margins.

The gabbros occur as lense-shaped bodies which grade into anorthosite.   They were late-crystallizing differentiates of the

anorthosite and show foliation structures not present in the latter, attributed to its solid state while the gabbros crystallized under stress. The location of the gabbros near the margins of the mass agrees with Osborne's (1928) conception of their genesis as late crystallizing differentiates which have been filter-pressed away from the centre of the anorthosite but have been trapped by the intense zone of shearing at the margins of the body where they crystallized. The locations of some of the gabbro bodies in the Laramie anorthosite have been controlled by a rotational injection of the anorthosite which caused local variations in stress.

The ore deposits occur as dyke or lense-like bodies which according to Fowler (1930) narrow in depth. The margins of the bodies may be clear cut or gradational and show "no evidence of having moved other than with the anorthosite magma." Diemer (1941) found different evidence. "That the magnetite-ilmenite moved through the anorthosite is well-substantiated by evidence in the form of slickensided gouge and breccia at the contacts (and) zenoliths of anorthosite. Banding within the dyke indicates that differentiation was still in progress during intrusion."

Genesis.- From the field evidence it appears to be fairly clear that the anorthosite was intruded as a partly or almost completely crystallized magma with mobile gabbroic and iron-titanium oxide rich differentiates included in it. All workers in the field are this far in agreement.

Regarding the iron-titanium ores Fowler (1930) thinks that they are last stage, in situ, differentiates. Her views can be regarded with some scepticism in the light of Diemer's (1941) work, but it must be borne in mind that slickensiding could be caused after

solidification of the ore however it came into place, so that
such evidence need not be absolutely conclusive of an intrusive
origin.

More recently Newhouse and Hagner (U.S.G.S. open file rept.)
have studied the ore deposits and their summarised views are given
by Lawthers (U.S.G.S. open file rept.).   They find complete correlation
of ore location with structural features in the anorthosite and they
believe that a replacement origin for the ore is "supported by the
marked change in mineralogy along strike, dip and plunge of the
orebody and of individual layers".   Unfortunately this work has not
been available for closer study.

The petrography of the ore minerals does not appear to give direct
evidence for either genesis.   The ore when containing over 95% of ore
minerals consists of apparently homogenous ilmenite and magnetite.   When
the silicate content rises above 5% the magnetite contains abundant
exsolution lamellae of ilmenite of all sizes.   A photograph of a
polished section of the ore in Warren (1918), shows what is almost
certainly an intergrowth of ulvospinel in the magnetite, together
with ilmenite and spinel.   Without a more detailed mineragraphic
account it is impossible to adequately discuss the problems of ore
genesis.

Anorthosites in South-Eastern Ontario

Massive bodies of anorthosite have intruded Grenville sediments
and older gneissic granites in the Hinchinbroke area of south-east
Ontario. (Harrison 1944).

The anorthosite and associated gabbroic masses are concordant
with the structures of the enclosing rocks.   They are coarse grained in

the central portions and fine grained near the margins, where

they show gneissic structures.

The anorthosites are composed of plagioclase in the andesine-labradorite range (An_{45-53}) with accessory hypersthene, augite, titaniferous-magnetite and apatite. Towards the borders of the mass a gradation to gabbro occurs by reason of an increase in the mafic mineral content. The gabbro, and sometimes anorthosite directly, grade into syenite by an increase in the potash feldspar content and the incoming of oligoclase in place of andesine-labradorite.

Gabbroic anorthosite composes most of the intrusives apart from the pure anorthosite described above. The Tichborne anorthosite is unusual in that the feldspar within it varies from labradorite to oligoclase fairly regularly from west to east and from the centre to the margins. Orthoclase gradually becomes an important constituent as the plagioclase becomes more sodic but this is probably mainly due to a later intrusion of alaskite granite which surrounds much of this anorthosite body.

The accessory minerals are chiefly hypersthene and augite which are usually uralitized. Amphibole occurs as blue green actinolite replacing pyroxene and arranged in stringers between grains of feldspar and as, probably original, basaltic hornblende. Biotite is an alteration product of pyroxene, amphibole and titaniferous magnetite.

Magnetite occurs as small early crystallizing grains and as blades in pyroxene released during uralitization.

Ilmenite-magnetite intergrowths occur as late crystallizing veins and stringers often crosscutting silicate minerals. Apatite and pyrite are often associated with the titaniferous magnetite. Scapolite is

a common accessory which replaces feldspar.   There is

a strong suggestion that it is formed by assimilation of limestone.

Sphene is common in the sodic part of the mass coating titaniferous

magnetite.

These anorthosites do not contain any known mineable concentrates

of ilmenite but they are of some interest in that they have many

features in common with the anorthosites which do contain important

ore concentrations.   The gneissic, more mafic marginal areas are

well developed and are comparable with the Whiteface facies of the

Adirondacks.   The Tichborne anorthosite is of especial interest

in that it provides a link between the more common andesine-

labradorite type and the rarer more sodic masses of the Virginian

type with their abnormal ore deposits.   The connection which Harrison

(1944) suggests to exist between increasing soda content and the

proximity of alaskite granite may have a direct bearing on the

genesis of anorthosites of the Virginian type.   The implication is

that the more sodic facies of anorthosite are formed by a soda ±

potash metasomatism or 'granodioritization' of labradorite-andesine.

The appearance of sphene at the expense of the ilmenite and

titaniferous magnetite in the sodic portions of the massif is of some

interest.   Sphene is normally the most common titaniferous mineral in

acid and especially peralkaline rocks.   It is commonly associated

with the Adirondack magnetite ores (not the ilmenite-magnetite ore

of lake Sanford) which are briefly discussed in a later section

of this work.   It is also a typical of the granulite facies

and is hence to be considered secondary in connection with

anorthosite massifs.

Anorthosites and Ore Deposits in Virginia

Anorthosites, nelsonites and associated titaniferous ore minerals occur in Nelson and Amherst Counties Virginia. The anorthosite mass is 13 miles long x $2\frac{1}{2}$ miles wide and has a surface area of 22 square miles. It has been emplaced in a quartz-biotite monzonite gneiss, a metamorphosed igneous rock of Pre-Cambrian age. The anorthosite is also probably of Pre-Cambrian age. Within the anorthosite and just without it in the gneiss, nelsonite bodies of dyke or pod-like form contain ilmenite and rutile. Ferromagnesian lenses and quartz veins also intrude the anorthosite. (Ross 1941; Watson and Taber 1913).

The anorthosite is a strongly granulated rock containing only very small ungranulated areas, rarely larger than 20 cm diameter. The ungranulated rock is 75% blue grey andesine $An_{31.5}$, and 25% microcline occurring as small included lenses and antiperthite streaks within the soda feldspar. The granulated anorthosite is predominantly andesine (An_{36-30}) with some oligoclase and albete probably of secondary origin. There is a little primary quartz. Oligoclase anorthosite (An_{20}) locally borders masses of andesinite. It is probably secondary in origin and might be analogous with the Whiteface facies of the Adirondacks.

Injection anorthosite in the gneiss at the borders of the main massif varies from stringers to large lenses. The order of crystallization is antiperthite oligoclase (An_{20}), perthite free of oligoclase, reaction rims of microcline, clinohypersthene, quartz, apatite, rutile, ilmenite with hornblende, sericite, biotite and clinozoisite disseminated through the rock. The gneiss has

recrystallized and has secondary minerals disseminated in it.

The Nelsonites are veinlike, dykelike, and lensoid in habit. Rutile nelsonites occur only within the anorthosite; ilmenite nelsonite is commonest within the anorthosite but also occurs in the gneiss. Magnetite nelsonite is found only in the surrounding gneiss. The nelsonite bodies usually have sharp contacts, but in certain of the rutiliferous bodies they are gradational.

The mineral content of the ilmenite nelsonites varies rapidly within a body. Andesine, present as inclusions from the anorthosite is always either replaced by biotite or hornblende or recrystallized to quartz, albite and hornblende. Ilmenite and apatite frequently in augenlike masses are set in a matrix of biotite, actinolite and/or hornblende. Pyroxene, almost completely replaced by hornblende, is sometimes present. Magnetite sometimes occurs in cracks in the ilmenite. A typical rich nelsonite contains ilmenite 64%, apatite 27%, biotite 5% and actinolite 4%.

Ross (1941) describes all the minerals of ilmenite nelsonites as secondary except for the antiperthitic andesine, and pyroxene where present in the ferromagnesian facies. This statement is supported by the textures visible in the many thin section and polished rock surface photographs reproduced in his paper. The ilmenite clearly invades, rims and replaces feldspar and is found in the cleavage planes of clinohypersthene. The texture of the nelsonites is sideronitic although much affected by shearing. Davidson, Grout and Schwartz (1946) examining the Piney River deposit seriously questioned Ross's evidence, for they found in unaltered nelsonite (something of a rarity), that primary ilmenite and apatite were

oriented by magmatic flow and enclosed in primary pyroxene. They figure two photographs, one not very convincing, to substantiate their findings.

Only one rutile nelsonite has been studied (Ross 1941). It consists of rutile, apatite, a little ilmenite cutting the rutile, clinozoisite and pyrite. The rutile is "leucoxenized" to sphene.

Ferromagnesian lenses, containing andesine from anorthosite, clinohypersthene and accessory quartz, apatite, ilmenite, rutile, amphiboles, sulphides and micas in that approximate order of crystallization, have been described by Ross (1941). They seem to have relationships to the anorthosite similar to the nelsonites.

Rutile occurs generally disseminated throughout much of the anorthosite and is locally concentrated to 30% in disconnected stringers. It is associated with feldspar, quartz, secondary hornblende and, rarely, ilmenite. (Watson and Taber 1913).

Mineralogy.- Feldspar, when ungranulated is antiperthitic andesine of the following composition:- Orthoclase 25.1%, Albite 51.0%, Anorthite 23.4%, and Celsian 0.5%. It is frequently more sodic when granulated (Ross 1941). Clinozoisite is a common inclusion in andesine.

Quartz occurs as irregular masses associated with ferromagnesian lenses and in veins.

Clinohypersthene, an essential mineral of the ferromagnesian lenses, occurs also in low grade nelsonites. Composition:- Clinoenstatite 42.0%, Clinoferrosilite 40.5%, Diopside 7.5%. It is optically negative; $Z \wedge C = 44°$; $2v = 62°$; $n\alpha = 1.694$, $n\beta = 1.710$, $n\gamma = 1.715$.

Amphiboles occur in three ways. 1. Actinolite or hornblende replaces pyroxenes in anorthosite and ferromagnesian lenses. 2. Actinolite replaces feldspar in anorthosite, nelsonite and ferromagnesian lenses. 3. Tremolite and hornblende form within feldspar grains in anorthosite away from nelsonites and ferromagnesian lenses.

Biotite high in TiO_2 content and low in Fe" and Fe"' is common in nelsonites where it formed later than ilmenite and replaces apatite and ferromagnesian minerals.

Rutile occurs in two varieties. 1. As red brown grains in anorthosite. 2. Steel black grains close to ferromagnesian lenses. Analyses of each type (Ross 1941) are as follows.

	FeO	Cr_2O_3	V_2O_5	TiO_2	SpG
1	0.40	0.04	0.28	99.28	4.304
2	0.62	0.06	0.28	99.04	4.280

It is sometimes slightly altered to leucoxene.

Ross (1941) gives no mineralogical details concerning ilmenite. Davidson, Grout and Schwartz (1946) figure ilmenite from nelsonite. It contains abundant magnetite "rods and plates" which are presumably parallel to the 0001 crystallographic direction.

Sphene occurs especially in the quartz monzonite gneiss near the anorthosite. The "leucoxene" derived from the alteration of the titaniferous oxide minerals is finely comminuted sphene(Ross 1941).

Apatite, in rounded granular crystals, is an essential constituent of the nelsonites. It contains 1.43% F and 0.1 Cl. $nO = 1.630$ $nE = 1.634$.

Magnetite occurs in magnetite nelsonite outside the anorthosite area and magnetite also veins ilmenite in the ilmenite nelsonites.

Pyrite replacing ilmenite is figured by Davidson, Grout and Schwartz. Pyrrotite also occurs (Ross 1941).

Genesis.- Watson and Taber (1909, 1910, 1913) regard the anorthosite as a rock intrusive into regional gneisses. The nelsonites were regarded as liquid magmatic bodies which had segregated from the anorthosite, but whether they originated by in situ segregation, or segregation at depth with later intrusion into the anorthosite crystal mush, is not clear.

Davidson, Grout and Schwartz (1946) on the basis of a study of one of the ilmenite nelsonite deposits (Piney River) consider nelsonites to be liquid magmatic injections of dyke-like form. They found evidence of crystal orientation attributed to magmatic flow, and the orebody was considered to be conformable with the dip of the foliation in the surrounding anorthosite. The paragenetic, sequence is given as apatite, ilmenite, pyroxene, plagioclase but in some of the text figures of their paper this does not appear to be correct, although the quality of the reproductions does not permit a reliable conclusion to be drawn. It does seem clear, however, that at least locally ilmenite occurs in unsheared mafic rocks, and that ilmenite has suffered a) shearing b) at least local replacement by pyrite. The shearing is not always in accord with the platy orientation of the minerals. The authors attack much of Ross's (1941) evidence and interpretations but to some extent confuse his descriptions of nelsonite with disseminated deposits and ferromagnesian lenses. The disseminated deposits they admit

to be of replacement origin.   Ross (1947) replying to
these statements shows. that their evidence compared with his own is
restricted and very local;   he also questions their methods of
abstracting quotations from his work out of context.   However,
he does not fully answer their case and it certainly seems that
some of the ilmenite may occur in a normal magmatic gabbroic rock.
Davidson, Grout and Schwartz did not deny secondary replacement
effects but considered that they introduced only water and sulphur
resulting in hydration of the ferromagnesian minerals and a lowering
of the ore grade of the deposit.   The nelsonites are considered
to be genetically related to the anorthosite.

Ross (1932, 1934, 1936, 1941, 1942) has studied the titanium
deposits more widely than any other person within recent years and
deals at considerable length (1941) with the origin of, and the
physicochemical processes causing the development of, the deposits.

The anorthosite he describes as an intrusion, metamorphosing
the surrounding gneiss, altering plagioclase to clinozoisite and
sericite and introducing sphene to the new mineral assemblage.
Crushing and granulation on a large scale occurred during and after
intrusion.   Most of the mafic minerals are not badly crushed,
quartz shows only strain shadows and ilmenite has only minor
cataclastic structures.   These minerals are considered to have been
introduced after granulation of the feldspar.

The disseminated minerals in the anorthosite, ilmenite and
rutile, are arranged zonally, ilmenite occurring in close association
with crushed zones in anorthosite and injection gneisses and
in proximity to ferromagnesian lenses, while rutile is more generally
disseminated but only in the anorthosite.   Ilmenite replaces rutile.

The ferromagnesian lenses are associated with shear zones; the original pyroxenes are altered to amphiboles and biotite. The sequence of events during the formation of the rocks he regards to be. **1.** Introduction of iron and magnesium forming clinohypersthene by replacement of feldspar. **ii.** Introduction of quartz, apatite, ilmenite, rutile, amphiboles, sulphides and micas in that general order with much overlapping of each stage.

Replacement processes were also the controlling factor in nelsonite formation. The paragenetic sequence is the same as in the ferromagnesian lenses. There is no evidence of any metamorphic effects at the margins of the nelsonite bodies which are sericitized, a typical result of hydrothermal action. Later shearing might produce a similar effect but Ross states that the shearing preceeded the emplacement of the ore and associated minerals. Rutile nelsonite occurs only in anorthosite; ilmenite nelsonite within and without the feldspar mass, and magnetite nelsonite only in the gneisses. Thus ilmenite has formed only where local iron was available e.g. in the gneisses and in the ferromagnesian lenses. However, the occurrence of magnetite veining the ilmenite demonstrates that iron was also introduced. It seems that titanium and iron were introduced along shear zones but that there was a deficiency of the latter so that it did not reach far out into the anorthosite away from the channels by which it was introduced.

Summary of the evidence for a replacement origin.

a) Titaniferous and associated minerals are absent in primary ungranulated feldspar.

b) Ilmenite has replaced pyroxenes which replaced feldspar.

c) Secondary minerals are abundant near features capable

of acting as feeders.

d)   The titaniferous minerals are ungranulated.

c)   The mineral association is typical of hydrothermal suites.

f)   Sphene is formed in quartz monzonite gneiss a mile away from the anorthosite contact.

Ross considers two other magmatic modes of origin which he discards as unlikely, they are

(1) The nelsonites are intrusive and thus are later than anorthosite, but if the disseminated deposits are magmatic they must be of the same age as the anorthosite, hence titanium mineralization is of two ages which is improbable.

(2) If the two types of deposit are of the same age then two different processes were active at the same time for the formation of the same minerals.

The paragenesis, in summary form, as conceived by Ross is stated below.   Some of his conclusions regarding the methods of introduction of the new elements are discussed in a later chapter.

1. P_2O_5, F, and a little Cl were distilled off from a hidden ferromagnesian source at high temperature and pressure.   They were deposited from vapour or liquid condensed from it en route.   Calcium was abstracted from local feldspar to form apatite.

2. TiF_4 vapour followed and was fixed as rutile.

3.   Fe and Mg were next introduced either as halogens or bicarbonates in solution forming ilmenite and ferromagnesian minerals. Ca was not introduced; it was presumably fixed by alteration of orthopyroxenes to amphiboles at depth.

4. SiO_2 was introduced at all stages but probably most of it was derived from the anorthosite.

The principal weakness of this postulated sequence of events is their disagreement with the paragenetic mineral sequence observed in the ferromagnesian lenses where rutile and ilmenite have formed later than the ferromagnesian minerals.

Moore (1940) has evolved a completely different theory concerning the origin of the anorthosite and nelsonites. He recognises the following different rock types in the region. a) The Lovingston quartz-biotite monzonite. b) Hypersthene granodiorite greatly affected by hydrothermal action but identified as a facies of the granodiorite mass forming the Blue Ridge some miles away. c) Nelsonite dykes occurring in both gneiss and anorthosite but more common in the former than the latter. d) anorthosite. Moore regards the basic structure of the region to be a batholith of hypersthene granodiorite thinly covered by a roof pendant of Lovingstone gneiss locally hydrothermally altered. The anorthosite is regarded as a pegmatitic differentiate of the granodiorite, Watson and Taber (1913) and Ross in his earliest work (1933), also considered the anorthosite to be pegmatitic. Moore maintains that the anorthosite in one area passes laterally into an anorthosite-gneiss injection zone, then into a hydrothermally altered gneiss which in turn passes into granodiorite. The nelsonite dykes are similarly regarded to be later differentiates of the granodiorite. The nelsonite dykes are regarded to be definitely magmatic in origin be-cause of the following observed facts. 1) Their even granular texture 2) sharp walls to the intrusions 3) simultaneous crystallization of apatite and ilmenite for which the evidence is of inclusions of one within the other 4) The hydrothermal minerals are later than the ilmenite and apatite and replace them 5) The nelsonite dykes are the foci of

hydrothermal action of the gneisses, but titaniferous minerals are no more common in altered gneiss than in the normal facies which should not be the case had the Ti been introduced hydrothermally. 6) Marginal jointing can be recognised on dyke margins. Thus according to Moore the association of anorthosite and nelsonite is purely chance: both are the products of a granodiorite magma.

A report by Hickman (1947) on the economic possibilities of a nelsonite in Roanoke County. Virginia may lend support to Moore's hypothesis. A dyke of nelsonite is described as "a dark bluish-grey rock fine grained to porphyritic in texture. Ilmenite apatite and magnetite are the principal minerals and feldspar, quartz,epidote and biotite are accessory minerals. The apatite occurs as well developed phenocrysts". The dyke has intruded syenite and greenstone at the contact between the two. There is no mention of anorthosite in the area. This nelsonite occurrence is in a continuation of the same belt of Pre-Cambrian intrusive and metamorphic rocks as that in which the anorthosite of Nelson and Amherst Counties is situated, but some seventy miles separate the two localities. To base any conclusions on the scanty evidence presented by Hickman (1947) would be unwise but even with such slight support, Moore's hypothesis must not be discarded out of hand.

The anorthosite of Nelson and Amherst Counties is distinctly more sodic and potassic in composition than the large anorthosite massifs of the world and it would be incorrect to preclude completely the possibility that it might be genetically connected with sub acid to intermediate igneous rocks.

Poor exposure and a deep zone of weathering in all areas where nelsonite bodies occur has been the greatest factor causing

the confused and contradictory geological accounts in the
literature.   Unfortunately the differences of opinion expressed
by workers in the area are not confined to matters of interpretation
but include contradictory accounts of the petrography and
petrology of the rock masses.   In such circumstances any
evaluation of the evidence is hazardous but, provisionally, the
account and opinions of Ross should be allowed greatest weight
since he is the only worker to have made a completely thorough
survey of the whole anorthosite area.

The Ore Deposits of St. Urbain, Charlevoix County, Quebec

The St. Urbain ore deposits lie within an anorthosite massif
at a distance of about one mile from its southern margin.   The
anorthosite is an elliptical-shaped mass with dimensions of twenty
miles from north to south and nine from east to west.   It is
surrounded by granites, syenites and diorites.   No intrusive
relationships between anorthosite and the granite-diorite rocks
has been observed although two small detached masses of
anorthosite occur in the granites near the contact.   It has been
concluded (Mawdsley 1927) "that the granite-diorite series and the
anorthosites were developed in stratiform fashion with the granite-
diorite rocks overlying the anorthosite, and that the stratiform
arrangement was,in part, obliterated by movements of the two
rock groups while still at least only partly crystallized."   To
the south of the anorthosite the granite-diorite rocks are followed
by an assemblage of schists and gneisses of sedimentary origin
(the Grenville series) and intrusive granite gneisses.   The
former are definitely older than the granite-diorites.

The anorthosite massif contains two different facies one essentially composed of antiperthitic andesine (An_{30-35}) the other composed of labradorite (An_{56-65}). The more common sodic variety outcrops towards the margin of the massif and cuts the central calcic variant. The division into calcic and sodic facies is somewhat arbitrary because there is complete gradation between the facies in many places. A constant feature of the anorthosite is the presence of large plagioclase crystals which have been fractured and invaded by a finer grained fedlspar groundmass (Gillson 1932). In the vicinity of the ore deposits this varies in composition from An_{36} to An_{45}.

Accessory minerals in the anorthosite are hypersthene, hornblende,, biotite, ilmenite and apatite forming about 4% of the rock. In more acid phases up to 8% orthoclase is present. (Mawdsley 1927; Osborne 1928). Hypersthene, hornblende and orthoclase were not seen by Gillson (1932) but hypersthene is figured by Karpoff (1953). The paragenetic sequence according to Mawdsley is "plagioclase starting first and continuing over a long interval, then hypersthene and iron ore, the iron ore ceasing before the hypersthene and the latter before plagioclase; hornblende and biotite commenced after hypersthene and finished with the plagioclase." Osborne (1928) describes the order of completion of crystallizations as plagioclase, hypersthene, iron ore.

There is little information available regarding the overall structure of the anorthosite other than the zonal arrangement of the sodic type. In the vicinity of the orebodies a distinct gneissic structure is apparent and a texture which is probably protoclastic but which could be cataclastic is developed (Osborne 1928).

The earlier workers, in particular Mawdsley, thought that
the ores "do not seem to be along any definite zone nor to be
structurally related to one another", but Gillson (1932) has
definitely shown that the ores occur along distinct zones.   The main
ore zone containing the Coulomb and Glen deposits lies along the
foliation but judging from a diagram in Karpoff (1953), the ore
zone dips to the south-west while the foliation dips north-east (Gillson
1932).   Other cross-zones run from north-east to south-west
approximately at right angles to the main zone, and according to
Gillson the best ore occurs where these zones intersect.   The
detailed distribution of the ore deposits is given in volume two
of this thesis.

The massive ore is a crystalline aggregate in which the grains
average $\frac{1}{4}$"-$\frac{1}{8}$" in diameter.   The ore mineral is ilmenite with
hematite exsolution lamellae;   in the General Electric deposit in
particular there is a considerable amount of associated rutile.
Magnetite is very rarely found in the General Electric mine.
Pyrite, chalcopyrite and pyrrhotite accompany the ore in small
quantity.   The gangue minerals of the ore are andesine
(An_{45} composition), hypersthene (75% $MgSiO_3$) and apatite (Osborne
1928).   A later generation of oxides, silicates and carbonates also
accompanies the ores (Gillson 1932).   Horses of barren anorthosite
are common to all the deposits and show considerable evidence of
hydrothermal action (Gillson), although Mawdsley (1927) says that
there is no hydrothermal alteration of the 'horses'.   According
to Osborne only anorthosite in the General Electric deposit shows
much evidence of hydrothermal action.

Mineralogy.- The texture of the ore is xenomorphic.   Hematite

lamellae form about 20% of the average ore grain, enclosed in apparently homogenous ilmenite. The lamellae form substantially parallel series. Along their length minor fluctuations of width occur and they taper abruptly at each end. Between the larger lamellae a series of small lamellae occur but a zone comparatively free from them exists on each side of the large lamellae. Small faults indicating post consolidation readjustment of the mass displace the lamellae occasionally. (Warren 1918).

Associated with the ore are oligoclase, apatite, phlogopite, rutile, sapphirine, chlorite and carbonates, minerals which apart from oligoclase and a little apatite are absent from the anorthosite (Gillson). Hypersthene and hornblende are also present according to Osborne (1928) and Mawdsley (1927).

The oligoclase occurs as rims replacing earlier basic andesine, Phlogopite, zeolites and carbonate also replace basic andesine. Spinel, sapphirine and rutile occur as rounded grains. Ilmenite is found definitely replacing phlogopite and is itself rimmed by chlorite, and more rarely by sapphirine. The paragenesis of the more important minerals is oligoclase-phlogopite; rutile, apatite, sapphirine, spinel, ilmenite, sulphides, chlorite, carbonate and zeolites. (Gillson 1932). Green and pink feldspar, some of the latter of which may be the 'orthoclase' of earlier writers, Gillson found to be respectively andesine veined by chlorite and andesine veined by zeolites.

Gillson's descriptive mineralogy is based mainly on material from the General Electric deposit, but he does not make that fact very clear. On the other hand Osborne who does not find that

pneumatolytic-hydrothermal minerals are common associates of the
hematite-ilmenite ore, bases his conclusions on the other orebodies
and makes an exception of the General Electric deposit.   Both
authors agree, however, that the ore minerals are of a later
crystallization period than the primary feldspar.

Genesis.- Two conflicting views on the manner of emplacement
of the orebodies have been put forward: those of Osborne (1928),
Robinson (1922), Mawdsley (1927) and Schneiderhohn (1933) on the
one hand, and Gillson's (1932) on the other.   The former view is
summarised by Osborne as follows. "The ore is essentially intrusive
in character.   It has injected the anorthosite, broken through it,
and engulfed blocks of it.   It is difficult to convey an idea
of the irregularity of outline of the deposit.   The walls are not
sharply marked, fissures as they are in many dykes.   The ore is,
essentially, a concentration of the last crystallizing constituents
derived from one part of the anorthosite and injected into another
part...   The silicates (in the ore) show a well defined fluxional
arrangement...   The absence of chilled margins of the ore against the
rock may be explained if one assumes that the ore was injected into
hot anorthosite."   Filter pressing, to squeeze out from the
anorthosite the late crystallising ore fraction, is the
concentrating method invoked.

Gillson has the advantage of having made a more thorough
study of the deposits and, with the aid of geophysical methods, to
have gained a more complete picture of the distribution and
relationships of the individual deposits.   He also had opportunities
to examine borehole material.   He "concludes that the ores were
formed by replacement in the already solid anorthosite, and were

deposited from solutions, either gaseous or liquid, which soaked through the rock".

The Gillson and Osborne schools of thought are in agreement inasmuch as they accept that a) the orebodies originate from the same magma reservoir as that from which the anorthosite formed b) the anorthosite was still hot when the ores were injected. Gillson does not agree that the ores are pyrogenetic or orthotectic but considers a pneumatolytic-hydrothermal origin is proved because of the following reasons (summarised).

1.   The ores are related to definite structural lines that developed after the almost complete solidification of the anorthosite.

2.   The richer and larger ore bodies are found at the intersections of major structural features.

3.   The ore in many places is in narrow veinlets and stringers and in many places has followed cracks and cleavages in other minerals.   Larger masses of older rock contain disseminated deposits.   Such features could only have been produced by a very tenuous 'magma'.

4.   A definite paragenesis of minerals can be observed, demonstrating a sequence from high to low temperature periods and indicating a long period of deposition.

5.   The ores are associated with various pneumatolytic and hydrothermal minerals which are not subordinate in amount but are decidedly abundant.

To reach any fair conclusion from the conflicting evidence available is difficult.   Gillson (1932) apparently "saw pneumatolytic and hydrothermal replacement in every specimen examined", there may

also be truth in his assertion that "Osborne and Mawdsley get away from the evidence of the associated minerals by attaching no importance to the few that they saw". However, even allowing for the fact that Osborne's conclusions are, in general, based on deposits where there are apparently few pneumatolytic-hydrothermal minerals to be seen, in face of Gillson's more exhaustive study one must accept his findings.

CHAPTER IV

PRIMARY TITANIUM ORES

DEPOSITS IN GABBROS AND OTHER IGNEOUS COMPLEXES

This chapter is concerned with concentrations of titaniferous minerals which occur in rocks other than those directly associated with the batholithic anorthosites. These concentrations are, with a few exceptions, not of commercial value at the present time, due to the comparatively low titanium content of the ore minerals and the fact that it is usually so intimately associated with magnetite as to be inseparable by normal concentration techniques.

The opaque mineral concentrations in the gabbroic rocks consist, almost exclusively, of titaniferous magnetite with or without ilmenite usually in subordinate quantity. The magnetite always contains exsolved lamellae of ilmenite and frequently also of ulvospinel. The latter iron-titanium oxide is probably more abundant than has been reported, on account of the difficulty in seeing it due to the small size of the exsolved lamellae. The ilmenite often is free from exsolution structures but may, not uncommonly, contain exsolved magnetite and, more rarely, hematite. Rutile and discrete grains of hematite are probably always of a secondary nature. In more siliceous rock the mineralogy becomes more varied. It is discussed in the relevant parts of this chapter.

For description and discussion in this chapter the host complexes to the titaniferous 'ore' deposits have been grouped approximately as in the classification outlined in Chapter I. The large gabbro-norite layered complexes are discussed first since, owing to their great size, very fundamental processes of differentiation must have

operated during their formation. They provide, therefore, a basis for comparison. Alkaline basic layered complexes and other titaniferous alkaline intrusions are then discussed. The remainder of the chapter deals with titaniferous mineral accumulations in gabbros and rocks which can with some certainty be considered to be reasonably direct magmatic differentiates of these. The Carrock Fell complex in Northern England is given a special treatment. Finally the ilmenite-magnetite ore deposit at Otanmaki, Finland is described in detail, and certain abnormal occurrences of titanium are discussed.

Layered Gabbro-Norite Complexes

The large basic rock complexes of the world in which layering is strongly developed all contain horizons at which there are concentrations of iron-titanium oxide minerals and very often chromite rich horizons as well. Some of these complexes contain sufficiently large concentrations of oxides to be considered potential ores of iron and titanium but as yet none of them have been actively exploited. Titanium oxide is not as abundant in these ores as in the concentrations in the large anorthosites; it usually comprises between 2 and 20% of the whole ore. Ilmenite is frequently not present as discrete grains, appearing only as exsolution lamellae in titaniferous magnetite. As a result of the complex intergrowths always exhibited by the magnetite it cannot be used as an iron ore at the present. The successful operation of the Sorel smelter does, however, offer some hope that the abundant reserves of these ores may become of value in the future.

The Bushveld Complex.- The Bushveld Basic Complex is 280 miles long,

150 miles wide and its visible thickness is $3\frac{1}{2}$ miles.   It is
overlain by acid rocks which may be genetically connected with the
basic complex.   The complex is divided into five main zones (Hall
1932) which together with their average thicknesses are given below.

Upper Zone 9,000'	Gabbro, with interstitial granophyre, with andesine anorthosite and diallagite bands.
Main Zone 15,000'	Norite, labradorite anorthosite and diallagite bands. Three titaniferous magnetite-ilmenite rich horizons occur near the top.
Critical Zone 3,000'	Norite, diallagite norite, bronzitite, harzburgite and bytownite anorthosite bands. Chromite and platinum band near top and three chromite horizons lower down.
Transition Zone Variable Thickness	Basic norite, bronzitite, bytownite anorthosite with minor chromite bands.
Chill Zone Variable Thickness	Basic norite, bronzitite and bytownite anorthosite.

It is generally accepted among students of petrology that the
complex has differentiated by a process of crystal precipitation and
sinking of the heavier minerals, but it is not certain whether the
whole complex was crystallizing at one time as in the case of the
Skaergaard intrusion.   On the whole it is considered more probable
that the magma roughly differentiated elsewhere and was intruded
to its present position in separate pulses of different composition
which completed their crystallisation in situ.

The iron-titanium oxide bands are associated exclusively with
norite and anorthosite, the feldspar being of An_{58} composition.
Individual bands and lenses of oxides are continuous over considerable
distances reaching, in one case, ten miles.   Individual bands have
sharp lower contacts but tend to grade upwards mixing with greater

and greater proportions of silicates. "In the feldspar-magnetite rock at the top of the main layer in the lower set of iron ore bands near Magnet Heights, the magnetite, which makes up about half the rock, wraps round idiomorphic labradorites and shows inclusions of the latter, while in places the iron ore has a kind of reaction rim of rhombic pyroxene, or deep-brown biotite, with now and then a peculiar light greyish zone closely resembling very fine grey granophyre" (Hall 1932).

Much has been written about the opaque minerals in the ore bands of the Bushveld, most of it of a thoroughly confused and contradictory nature (Frankel and Grainger 1941; Schwellnus and Willemse 1943; Strauss 1947). The confusion has arisen over the difficulty involved in getting different observers to agree about the characteristics and identity of the minerals in the ore due to slight variations in colour and shade. The problem has been complicated by the failure to recognise ulvospinel in the magnetite; a failure due to inadequate optical equipment no doubt. Ramdohr (1953) has described ulvospinel in the Bushveld magnetite but has not mentioned or denied the existence of various vanadiferous and non-vanadiferous varieties of magnetite and maghemite and the presence of coulsonite. In the light of Ramdohr's work the ore would appear to have consisted originally of magnetite containing exsolved ulvospinel, ilmenite and spinel (pleonaste) together with some discrete ilmenite grains in the more titaniferous portions. As a result of alteration due to atmospheric weathering maghemite has developed secondarily. This does not agree with the descriptions of some of the earlier workers who regarded the maghemite as magmatic, but it is difficult to conceive how ulvospinel and maghemite could have crystallised from the same magma contemporaneously. Some goethite accompanies the maghemite.

The Bushveld ores were originally (^{H}all; Wagner 1928) conceived to be formed by gravitative settling of early crystallizates but Hall (1932) later showed that the magnetite crystallized late and concluded as follows:- "one can conceive a gradual sinking and concentration of fluid magnetite to a level determined by a given anorthosite band; the upper part of such a band is now overlain by a heavy magma fraction and its feldspar crystals can be expected to have risen upwards through the future magnetite layer." This implies a reversal of the established position of iron oxides as early forming crystals in a gabbroic magma. One method of surmounting this is to invoke remelting of the oxides (Vogt and Lindgren) which has been opposed by Bowen on the grounds that the silicates should also melt. There are then two magmatic alternatives (a) immiscibility of the oxides for which there is no experimental evidence (b) residual magma accumulation the presence of !volatiles and fluxes! maintaining the oxides in a liquid condition well below their normal freezing point. The other line of approach is to regard the ores as introduced matter for which there is no evidence in this case. Bateman (1942) has discussed the problem and accepts the theory of depressed freezing pint. He invokes tectonic forces to produce different physical types of deposit-disseminated, massif, injection veins etc. In the case of the Bushveld he considers that the liquid oxides drained down through a crystal mush to rest on an anorthosite layer. Loose crystals from this layer tended to rise through the magnetite melt with the result that some became 'frozen in' as the temperature dropped to crystallization point. Bateman is aware that late liquid differentiates are normally siliceous but points out that Fenner has shown that the system $Na_2SiO_3-Fe_2O_3-SiO_2$ can in one case

yield iron oxide in its final product. [I]t does, however, seem to
be extrapolating rather far such a special case to apply to it
to such a common phenomenon as late oxide ores.

Wilson (1953) has emphasised the relationship which exists
between the composition of oxide ores in basic differentiated complexes
and the composition of the immediate host rocks.   This has been
discussed in its essentials in Chapter I.   Principally with reference
to chromite in layered intrusions he has shown that the oxide minerals
in similar rocks in widely separated intrusions have very similar
compositions.   He cites as one instance the chromite at the Merensky
horizon in the Bushveld and the Bird River chromites of Manitoba which
occur in serpentinised peridotites sixty feet below gabbro.   In the
Bushveld the titanium content of oxide mineral aggregates increases
upwards as chromium decreases and in the highest band averages
18.2% in a norite-anorthosite carrying plagioclase of An_{60} composition.

On this basis one would expect oxide minerals associated with
more acid rocks to contain higher percentages of titanium.   Such
is, in many instances the case.   The Allard Lake batholithic
anorthosite (see Chapter III) contains ilmenite orebodies, which
contain 38% TiO_2, enclosed in calcic andesine feldspar.   In south-west
Norway the ilmenite of most of the ores contains about 43% TiO_2,
but if one takes into account the associated titaniferous magnetite
the average TiO_2 content of the ores falls to about 36%.   The
associated feldspar is of An_{48} composition, a calcic andesine.
The Lake Sanford ore in the Adirondack Mountains of New York State
is more difficult to evaluate because it occurs in two modifications,
and it is not certain what their relative proportions are.
Assuming them to be 1:1 the average TiO_2 content is 29% in a

rock containing an average plagioclase of An_{51} composition.
(figures calculated from Balsley 1943; plagioclase composition from
Stephenson 1945). The layered norite-anorthosite Colony complex
of Sierra Leone (see below, Volume II p 143 and Junner 1929)
contains ilmenite, and titaniferous magnetite segregations which, on
average, seem to contain about 15.5% TiO_2. Higher figures than
this probably occur locally where ilmenite is abundant, a feature
in common with the Bushveld. The composition of the associated
feldspar is An_{60}. The comparison with the Bushveld is striking.

At St. Urbain in andesine anorthosite the Coulomb ore, which contains
some rutile, runs 40% TiO_2. In Virginia, as with the Lake Sanford
ores, it is difficult to arrive at an overall figure on account of
the existence of more than one ore type and three oxides, rutile,
ilmenite and magnetite. However, the ilmenite contains 51% TiO_2
and probably the rutile and magnetite would cancel each other out
with a bias in favour of rutile. The feldspar is a basic oliogoclase.
If one attempts to extrapolate farther in the acid direction the
method breaks down because ilmenite enters silicates to an increasing
degree and non-titaniferous magnetite becomes commonplace.

The above figures show that there is considerable support for
assuming a direct genetic connection between the titanium-bearing ores
and the rocks in which they occur, a connection which was assumed,
on other grounds, in the discussion in Chapter III. However, accepting
the connection, it does not necessarily imply, as has been tacitly assumed
by many authors, that the ores and their host rocks have originated by
gravitational differentiation, with reinjection where necessary, of
a gabbroic magma. The very fact that there is a difference between

the various host rocks implies that different sets of conditions were extant during their formation.   The conclusion that the titaniferous content of the oxide phase of any 'basic' intrusive is predictable from the composition of the plagioclase is of some economic significance. It implies that certain rock-types, the olivine gabbros with basic labradorite and rocks more basic than this can be disregarded as hosts for titanium ores.   In fact any rock which contains average plagioclase more calcic than An_{55} is probably of little interest in this connection.   However, when applying this hypothesis it must be borne in mind that later metamorphism may greatly alter this concept owing to the change in the mineralogy of the oxide minerals which it may bring about.   The outstanding example here is the Otanmaki ore of Finland, which is discussed elsewhere in this chapter.

The Colony Complex of Sierra Leone.-   The Colony Complex is, in the context of the present work, very similar to the Bushveld Complex and it will not be described in detail.

The complex is 25 miles long, 8 miles wide and 3.5 miles thick in its exposed portion.   Its true width is more likely to be 25 to 30 miles and its true thickness 7 miles, according to recent geophysical work (M.W.P. Bott, private communication).   The visible complex consists of four zones each of which is essentially similar in character, representing four separate magma pulses.   Each pulse of magma after injection differentiated in situ in a similar fashion.   A typical section follows (Wells and Baker 1956):-

Peridotite layers

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Iron ore veins;  pegmatitic
Leucogabbro or anorthosite
Olivine gabbro
Troctolitic gabbro
Banded Troctolite
Peridotite layers
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The rock-types occuring in greatest bulk are the anorthosites, leucogabbros and olivine gabbros and troctolites. The composition of the plagioclase is An_{59-64} except in the banded troctolites of one zone where it rises to An_{68}. Opaque minerals are concentrated primarily in the upper pegmatites but do occur elsewhere, mainly in the anorthosites.

The opaque minerals are magnetite containing exsolved ilmenite, ulvospinel and spinel and ilmenite containing some exsolved spinel. The magnetite is altering in places to maghemite. The composition of the ilmenite is as follows (Junner 1930):-

Fe_2O_3	FeO	TiO_2	V_2O_5	Cr_2O_3
25.06	28.02	42.34	0.38	0.00

The composition of the ore as a whole has already been given.

Basic Alkaline and other Alkaline Plutonic Complexes

The Kola Peninsula in the Soviet Union provides a wealth of examples of alkaline plutonic rocks some of which contain accumulations of titaniferous minerals, often on a grand scale. The complex at Gremyakha-Vyrmes on the Tuloma river is of great importance as a link between complexes of the Bushveld type and the exotic masses of the Khibine and Lovozersky tundress, also in the Kola area. As a layer-differentiated complex it is anomalous in that the oxide ores accumulate in olivine enriched rocks and not with anorthositic types; in this respect it shows similarities with the Skaergaard intrusion and, further, may provide a link with the titaniferous magnetite olivinites. In geological literature in the English language it has largely been ignored and on account of this is described here in some detail, the description being almost entirely

based on the description of Polkanov (1944).

The Gremyakha-Vyrmes Pluton.- The Gremyakha-Vyrmes Pluton is formed by three intrusive rock series

a) An hortonolite-gabbro-akerite-pulaskite double complex.

b) A nepheline syenite complex.

c) An alkaline basic granite and syenite complex.

Titaniferous ore minerals are associated with the alkaline gabbro complex.

There are two intrusion subphases distinguishable in the gabbro complex which occupies an area of 50 sq. km. During the first subphase the intrusion and crystallization differentiation of gabbroic magma resulted in the formation of a series of rock types:- hortonolitite, hortonolite-pyroxenite, melanocratic hortonolite gabbro, hortonolite gabbro, leucogabbro, hortonolite anorthosite, anorthosite, associated in a layered structure. During the second sub-phase of intrusion the magma consisted of oligoclase gabbro -akerite and, as the result of an analogous differentiation a second rock series was formed:- hortonolitite, hortonolite -pyroxenite, melanocratic hortonolite-oligoclase-gabbro, akerite, pulaskite, laurvikite, also associated in a layered structure.

Structural analysis of the primary tectonic features of the complex has shown (Polkanov 1941, 1944) that the complex dips to the south-west. The rocks of the second intrusive sub phase are situated in proximity to the hanging wall of the intrusion while those of the first subphase lie against the foot-wall.

The ore minerals are associated with the basic and ultrabasic rocks of each series i.e. with the peridotites, pyroxenites and melanocratic

gabbros.   These rocks occur principally near the margins of the complex, particularly on the hanging wall side.   In the centre of the complex the leucocratic members of the series are more widely developed, at the expense of the melanocratic ore mineral bearing types.

The rocks of each series are associated in layered structures. Some of the peridotite layers are layered lensoids and it is suggested that many of the layered bands of all the rock types may have this shape.   The thickness of the basic and ultrabasic layers varies from 10 cms to 10 metres.   The thick lenses do not have a uniform composition but exhibit banding on a very fine scale, the composition of each band varying from hortonolitite to pyroxenite and melanocratic gabbro.

The relationship between melanocratic and relatively leucocratic bands takes two forms.   In general the lower surface of a melanocratic band will have a sharp junction against the underlying leucocratic horizon.   In an upward direction the melanocratic bands normally pass gradually into the overlying leucocratic rocks.

On a regional scale there is a similar distribution of rock types, in general melanocratic facies predominate towards the foot-wall side of the intrusion.   Two illustrative successions are as follows.

Gabbro	Aekerite
Hortonolitic mela-gabbro	Hortonolitic aekerite
Hortonolitic mela gabbro	Feldspathic peridotite
Peridotite	Hortonolitic aekerite
Plagioclase peridotite	Peridotite
Anorthosite	Leuco-aekerite
Hortonolitic leucogabbro	Mela-aekerite
Hortonolitic mela gabbro	Peridotite
Hortonolitite	Aekerite
-----	Mela-aekerite
	Hortonolitite
	Peridotite

The layered structure of the complex is interpreted to be due to gravitational stratification. The summarised evidence for this conclusion (Polkanov 1944) is:

1) The preponderance of heavier mineral constituent in the lower and earlier of the two rock series.

2) The large scale distribution of predominantly melanocratic layers within each series.

3) The small scale distribution of the melanocratic bands within individual layers.

4) The asymmetric structure of the individual layers.

The petrographic characteristics of the peridotite-gabbro-anorthosite series can be summarised as follows. The rock texture is hypidiomorphic-granular for polymineralic compositions and panidiomorphic for monomineralic compositions. Both types pass to sideronitic texture with higher ore mineral contents. Rock structures are directional and layered.

The chief minerals are andesine An 40-50%, titan-augite and augite with a high content of the hedenbergite molecule, hortolitite with 46-58% fayalite, titanomagnetite and apatite. Secondary amphibole, biotite, potash feldspar carbonates and scapolite may be present.

The structural and textural characteristics of the peridotite-goligoclase gabbro-aekerite series are essentially similar. The chief minerals are oligoclase, antiperthitic oligoclase, microperthite, microcline, (albite and nepheline), titan-augite diopside with an acgirine molecule content, hypersthene, hortonolite 59-74% Fa, titanomagnetite and apatite. Secondary albite, biotite and amphibole may also be present.

Percentage Modal Analyses

(Polkanov 1944)

I   The peridotite-gabbro-anorthosite series.

	187b	170g	155n	155+	187+	97
Titanomagnetite	58.3	26.02	26.40	5.3	2.5	-
Apatite	3.6	7.40	8.6	2.1	1.8	-
Hortonolite	37.8	0.33	26.22	-	4.7	-
Titan-augite		57.57	15.1	5.5		-
Hypersthene		-	12.0		5.1	-
Amphibole	0.3	6.03		14.4[2]		-
Biotite		1.53	1.2		-	0.9
Plagioclase		1.12	10.5	72.7	85.9	86.4
Scapolite	-					12.0
Calcite	-					0.7

2   Together with hortonolite

187b Hortonolitite	179g Pyroxenite
155n Melanocratic gabbro	155+ Leucocratic gabbro
187+ and 97 Anorthosites.	

II   The peridotite-oligoclase gabbro-aekerite-pulaskite series.

	126c	126b	125u	125c	52b	90g
Titanomagnetite	19.5	21.3	15.0	27.83	31.96	17.04
Apatite		2.6	6.6	5.80	2.12	0.80
Hortonolite	78.5	46.6	0.2	23.55	17.59	6.09
Titan-augite		29.5	19.3[1]	42.0	39.75[2]	25.39
Hypersthene			24.6			
Amphibole	2.0		27.3			8.85
Biotite			6.5	0.82		
Plagioclase			0.5		8.58	41.83

c

	155u	137	125p	126b	52a
Titanomagnetite	10.04	5.04	33.4	10.2	-
Apatite	0.79	1.68	6.3	1.4	-
Hortonolite	-	9.68	-	3.0	-
Titan-augite	-	14.65	34.4[1]	4.7[1]	5.1[2]
Hypersthene	-	-	7.2	-	-
Amphibole	8.04	3.4	2.4	)3.2	-
Biotite			3.4	)	7.6[4]
Plagioclase	81.13	6550	12.9	77.5[3]	83.0[4]

1	Diopside	2	Aegirine-diopside
3	Antiperthite	4	Microcline.

126c Hortonolitite   126b Peridotite
125.u Pyroxenite   125c and 52b Olivine pyroxenite
90g Melanocratic oligoclase gabbro   155u and 137 Leucocratic
oligoclase gabbro-aekerite   125p Melanocratic aekerite
126b Leucocratic aekerite   52a Pulaskite

Both rock series are interpreted as developing in situ from two separate intrusion sub phases of which the peridotite-gabbro-anorthosite series was the earlier.

Diagrams of the parageneses of gabbro oligoclase gabbro and aekerite compiled from thin and polished section studies (Polkanov 1944) show that the crystallization of the magma led in each case to the formation of a residual liquid containing potential hortonolite, apatite and ore material. This liquid is assumed to have separated from the rising magma stream containing the already crystallized minerals.

There exist three types of ore each with a different genesis.

The ore minerals occur as small rounded inclusions in pyroxene and hortonolite together with chalcopyrite. Secondly they are found as small laminae in pyroxene developed by exsolution from the silicate host. This is either ilmenite or titanomagnetite. Both these types of ore mineral occurrence are rare. The bulk of the ore mineral occurs in the ultrabasic and melanocratic rocks

of both series producing when present in quantity a typical
sideronitic texture. This third type of ore separated towards
the closing stages of solidification of the constituent rocks of
the gabbro-peridotite complex.

The silicate-ore mineral relationships in the rocks indicates
simultaneous crystallization of pyroxene, hortonolite and ore
in most cases. Some pyroxene though was definitely of an earlier
crystallizing stage together with some hortonolite because many
crystals show corroded outlines against ore minerals indicating
a reaction relationship between the two mineral phases. Apatite
on the other hand is consistently idiomorphic. Locally protoclastic
deformation has broken the crystals of the silicate minerals and the
cracks have been infilled by ore mineral, but there is in such cases,
a complete lack of any indication of a reaction relationship.

The opaque ore minerals are a mixture of ilmenite, and magnetite
containing ilmenite exsolution lamellae according to polished section
analysis (V.P. Popov in Polkanov 1944) although of three chemical
analyses only one definitely indicates the presence of ilmenite as a
separate mineral phase according to Polkanov. However, of the
chemical analyses quoted all contain a great excess of FeO.
Polkanov attributes this to the presence of FeO leached out from
insoluble silicate during analysis. It seems unlikely that this is
the sole cause of the excess and the presence of ulvospinel must be
suspected.

According to Popov modal analysis of an ore bearing specimen
gave the following result:

Non-ore minerals   73.21%
Ilmenite   15.20%
Ilmenite-magnetite   11.59%

                       100.00%

The magnetite contained 20–30% by volume of ilmenite as exsolved lamellae.

The contact of the ore minerals against feldspar are usually defined by a reaction border of brown amphibole, actinolite or biotite. Biotite rims ore where it was intruded into a crack in the rock. This appears to indicate that slight tectonic disturbance may have accompanied the ore crystallization period.

This empirical data shows that the final melt contained apart from ore, also MgO (biotite and amphibole) K_2O (biotite) OH (amphibole and biotite), Cl or F and P (apatite) assuming that all the Na_2O, CaO, Al_2O_3 and SiO_2 were obtained from already crystallized feldspar by reaction of ore and plagioclase.

It is unfortunate that the available information on the chemical composition of the individual layers within the complex is meagre. It would be of the utmost interest to be able to compare TiO_2 contents of the opaque minerals at different levels in the intrusion as is possible with the Bushveld. However, recalculating roughly from Popov's modal analyses and making assumptions for the TiO_2 contents of the opaque minerals it would appear that the actual 'ore' contains 28–30% TiO_2. This is in association with a calcic andesine, if Polkanov's generalised data can be applied to the opaque mineral rich hortonolitic differentiate, which does not seem to agree with the figures suggested by studies on other basic complexes discussed in the preceeding section on the Bushveld. The TiO_2 content is here too

low for the feldspar.   However, without more reliable data further
discussion of this point is purposeless.

Polkanov (1944) considers the genesis of the ore-minerals
in the theoretical cases of ore formation suggested by Zavaritskii e.g.

a)   Ore-containing melt corresponds to the eutectic point
situated close to the composition of the ore component.

b)   Ore-containing melt is a final stage of solidification of
the ore-bearing silicate magma with limited solubility of the ore
and silicate melts in the liquid state.

c)   Ore minerals were deposited in the interstices between the
silicate crystals from a gaseous ore rich solution impregnating almost
completely solidified rock.

The evidence of simultaneous crystallization of hortonolite and
are mineral admits the possibility of the existence of a eutectic
relationship between these minerals.   The accumulation of ore in
hortonolites, peridotites, melanocratic gabbros and aekerites is in
agreement with the observed parageneses.   The fact that a small
amount of ore is found in leucogabbro and anorthosite does not
contradict the paragenesis scheme since this small quantity
of ore is only part of the main mass which accumulated in the residual
melt with hortonolite and migrated then into the melanocratic rocks.

However the observed substantial accumulation of ore in
pyroxenites cannot be reconciled with the parageneses since
pyroxene crystallized early and ore late unless a separate ore
bearing pyroxenite magma existed which is unlikely.   Hence, the
accumulation of ore could only have occurred during the migration
of the ore-bearing magma and solid pyroxene during the crystallization
gravitational differentiation of the gabbroic magma.

If a eutectic relationship existed between hortonolite and ore
their quantitative relationship should be constant.   In the
hortonolitites and peridotites there is a great variation in the ore
mineral: hortonolite ratio.

Hortonolitite 187b   60.68% ore mineral   39.32% Hortonolite
              126c   19.9% "   "   80.1%   "

According to Polkanov the observed parageneses for the ore bearing
rocks are not explainable in terms of a eutectic unless it lies very
close to the composition of the ore on the phase diagram and the
existence of ore in cracks in protoclastically deformed silicates,
with complete absence of simultaneously crystallized silicate minerals
other than reaction minerals confirms that at least for the very latest
stages of crystallization, a eutectic was not operating.

Gaseous deposition of ore can be discarded in this case since
the evidence is for settling of ore minerals in a heavy liquid form
rather than rising as a gas.

Polkanov considers that the possibility of the existence of
the ore minerals as an immiscible liquid phase can neither be confirmed
nor abandoned on the evidence.   The evidence can be interpreted with
equal facility as either eutectic crystallization with the eutectic
point close to the ore mineral composition or as liquation of ore and
silicate.   The two possibilities although theoretically very
different are in practical effect so similar as to be indistinguishable.

Fersman (1937, 1939) has suggested that ore deposits of this
type are formed by agpaitic crystallization connected with the ability
of the ore material to form complex ions.   Polkanov points out that
again the features observable in the rocks do not enable this theory
to be confirmed or rejected so that it too must be retained as a
possible mode of origin.

Whatever may have been the mode of segregation of the ore mineral

to form a late crystallizing liquid, the existence of such a liquid
Polkanov considers to be a demonstrable fact. Mobilization of
geological conditions in this case caused by gravitational
differentiation of a sloping magma stream during motion, led to
the formation of an ore deposit.

The Lovozersky Complex, Kola.- The Lovozersky tundra is formed of
an alkaline intrusive complex pluton comprised of four separate but
genetically connected complexes (see Volume II p. 45). The two
largest of these are primary stratified foyaite, urtite, malignite,
lujavrite and primary stratified eudialyte lujavrite complexes.
Both are sheet-like in form the former being 500-800 metres thick
and the latter 300-600 metres thick and both exhibit banding due to
magma flow. They have originated by the differentiation of a nepheline
syenite parent magma in place (Eliseev Zelenkov et al 1938).

Geochemically the complexes are remarkable for the accumulation
of tantalum, niobium and titanium (the loparite complex) together with
zirconium (the eudialyte-lujavrite). The loparite, which contains
38.5% TiO_2, 34% rare-earth oxides and 10-12% niobium and tantalum
oxides, is accumulated as the top of the loparitic complex despite
the minerals high specific gravity (4.8). This has been explained by a
process of gas transfer of early formed crystals (Vorobieva 1938 and others)
a process apparently generally accepted by Russian writers, except Fersman
who has advocated complex anion formation delaying crystallization.
Vorobieva stresses the importance of the abundant presence of
volatiles H_2O, Cl, F and P as carrying agents.

In the abundance of zirconium in the eudialyte lujavrite there
is a geochemical association of zirconium and titanium which is not
seen in any other primary rocks but is commonly encountered in a

sedimentary environment.

The Khibine Complex, Kola.- The Khibine complex pluton is not dissimilar in structure to the Kovozersky pluton. It consists of nepheline syenites, urtites, foyaites and ijolites (see Volume II p. 44). Titanium is here accumulated with fluorapatite in sheets between the ijolite-urtites and nepheline syenites. The association of titanium with volatile elements is again emphasised. The titaniferous mineralsin this case are titaniferous magnetite, ilmenite and sphene.

The Africanda Complex, Kola.- The complex at Africanda consists of basic and ultrabasic rocks and is not dissimilar in some respects from the Gremyakha-Vyrmes pluton. Titanium is here concentrated in knopite and titaniferous magnetite instead of ilmenite and titaniferous magnetite. The ore bearing horizon is known as africandite and consists of 55% diopsidic augite, 22% titanomagnetite, 18% knopite and some nepheline. However, a titaniferous magnetite-hortonolite pridotite is found in veins so that the Gremyakha-Vyrmes ore bearing rock is represented.

Mariupol Complex.- In the Mariupol complex, in contrast to the Kola area, ilmenite is the most abundant titaniferous mineral. It concentrates in alkaline pegmatites associated with alkaline syenites but is only sparsely represented in associated nepheline syenites. The ilmenite, which is associated with titaniferous magnetite contains between 48 and 54% TiO_2, up to 2.9% MnO and 0.4% $(Nb, Ta)_2O_5$ (Panteleev 1938).

Okorusu, S.W. Africa.- An unusual paragenesis for titanium is seen in the fluorite deposit at Okorusu which is associated with alkaline intrusions. A poorly (7.3% TiO_2) titaniferous magnetite

replaces limestone at the contact of a sheet of fluorite.

Alkaline Volcanic Complexes

<u>Magnet Cove, Arkansas</u>.-   The most well known and closely studied alkaline volcanic complex with which titanium is associated is the Magnet Cove occurrence in the United States.   Study of the complex has been made more difficult by the intense late hydrothermal alteration, helped by sub-aerial weathering, which has obliterated the relationships of many of the constituent rock-types.   It is only since the work of Fryklund and Holbrook (1950) and Fryklund, Harner and Kasser (1954) that a clear picture of the geology of the area has emerged.   Borehole records have confirmed their deductions and conclusions.

Earlier workers in the field have considered the complex to be a volcanic agglomerate composed of aegirine phonolite porphyry metasomatised with the introduction of the ore minerals' rutile (brookite in one area), magnetite, perovskite apatite and sphene (Ross 1940; Kinney 1949; see Volume II p. 103-104).   However it now seems that the minerals have been introduced in veins of which six types have been defined.

    (a) Coarse-grained biotite-calcite veins, no rutile.

    (b) Albite-dolomite veins, up to 5% rutile.

    (c) Microcline-calcite veins, 1-2% rutile.

    (d) Albite-ankerite veins, abundant rutile.

    (e) Albite perthite-carbonate veins, little rutile.

    (f) Calcite-rutile veins, abundant disseminated rutile.

The abundance of carbonate is such that the complex is virtually an intrusion of carbonatite, a rock type which is increasingly being recognised to be intimately associated with alkaline rocks.   Niobium,

and to a lesser extent yttrium and lanthanum are concentrated in the veins, the niobium closely following titanium. Vanadium also is tied to titanium but it is not clear whether it replaces it in rutile or replaces ferric iron as it does in the ilmenite of gabbros and anorthosites. Yttrium and lanthanum concentrate in the associated apatite.

Bukusu, Mbale district, Uganda.- An increasing number of eroded volcanoes of this type are gradually being discovered and described in the African shield areas and Bukusu is selected merely as an example of these.

The intrusive complex, a circular mass of syenite, ijolite and pyroxene enclosing a magnetite-apatite-phlogopite-vermiculite ring with a carbonatite core is described in some detail in ^{V}olume II, pages 138-140; it is intended that only certain mineralogical-geo-chemical features should be indicated here. The ore minerals vary from non-titaniferous magnetite in one part of the complex to a mixture of titaniferous magnetite, ilmenite, leucoxene and knopite. The leucoxene is microcrystalline anatase. The titaniferous magnetite contains a high proportion of magnesium and a high vanadium content where the titanium content is low (contrast Magnet Cove). ^{A}patite is generally abundant.

Carrock Fell - A Gabbro Complex rich in Ilmenite

In the County of Westmoreland in northern England there is a gabbro-diabase-granophyre plutonic rock complex which forms the hill known as Carrock Fell. Descriptions of the complex are few in number, the most important being Harker's (1894) and Hollingworth's excursion guide (1938); analyses of some of the rocks have been carried out by B.E. ^{D}ixon of H.M. Geological Survey. The complex

The east face of Carrock Fell. The rock types indexed in ink on the photograph are:- M Microgranite; IG Ilmenite-rich gabbro; IGH The hybrid zone between the gabbro and the granophyre

has been resurveyed by officers of the Geological Survey but their results have never been published. The following account concerns only the petrology of the oxide-rich portions of the gabbro with emphasis on the opaque constituents as potential ore minerals, and is not intended to be an authoritative account of the geology of any other parts of the complex.

The Carrock complex is elongated in a roughly east to west direction and is about four miles long by one mile wide. The northern half of the complex consists of granophyre, and diabase in subordinate amount, and the southern half of a separate banded mass of gabbro. The eastern end of the complex is the only portion which is at all well exposed and here granophyre is adjacent to gabbro, though a hybrid basic granophyre has been formed by intermixing at the actual contact. Diabase is present on the northern flanks of the summit of the fell, which is formed of granophyre. The age of the complex is unknown,

The southern half of at least the eastern end of the complex is comprised of a series of vertical or near-vertical sheets of gabbro of varying composition which parallel the general strike of the whole complex. Further west the structure is not certainly known owing to poor exposure. The east-facing scarp of the fell (see large Plate) therefore displays a cross-section of the constituent sheets. The two marginal sheets to north and south, are composed of ilmenite-rich melanocratic gabbro and between them are various gabbroic variants including coarse quartz-gabbro, a medium grained 'normal' gabbro, banded and fluxion gabbros. On the east face of the fell, medium and coarse quartz gabbro are the most widely exposed varieties. The contacts between the various sheets appear to be gradational over

a short distance and no chilling phenomena were observed. The
southern belt of ilmenite-gabbro contains abundant included masses
of the country rocks Skiddaw slates and Borrowdale lavas,
into which the gabbros have been intruded. In places zenoliths may
predominate over gabbro which becomes little more than a cement
in a coarse breccia. Since a rock of such inconstant composition
would be valueless as an ore, attention in this work has been
centred exclusively on the northern sheet of ilmenite-gabbro
which contains only a few included blocks.

The northern marginal gabbro sheet outcrops on the east face
of the fell in the gully formed by Further Gill Syke (see large
Plate and Plate IV C2. The ilmenite-rich facies does not occur
as a sharply differentiated sheet, but grades gradually and irregularly
from a normal even textured medium-grained gabbro banded in part and
containing drawn-out schlieren of incorporated material, to a
melanocratic rock, containing a higher proportion of opaque minerals,
which is very variable both in colour and texture. Patches of coarse
hornblendic and/or feldspathic pegmatite are common especially
along the northern margin of the sheet in close proximity to the
hybrid zone which is transitional to granophyre.

The gabbro throughout the melanocratic belt has suffered widespread
alteration and it is quite difficult to find an unaltered specimen
which clearly shows the original minerals and textures of the rock.
Gabbro in an early stage of alteration is shown in Plates IV C18
and 19. It is unusual that the deuteric effects do not have a
consistent effect on the rock: in some places the pyroxene is
uralitised while the feldspar remains fresh and in others the
feldspar is completely replaced by saussurite while the pyroxene shows
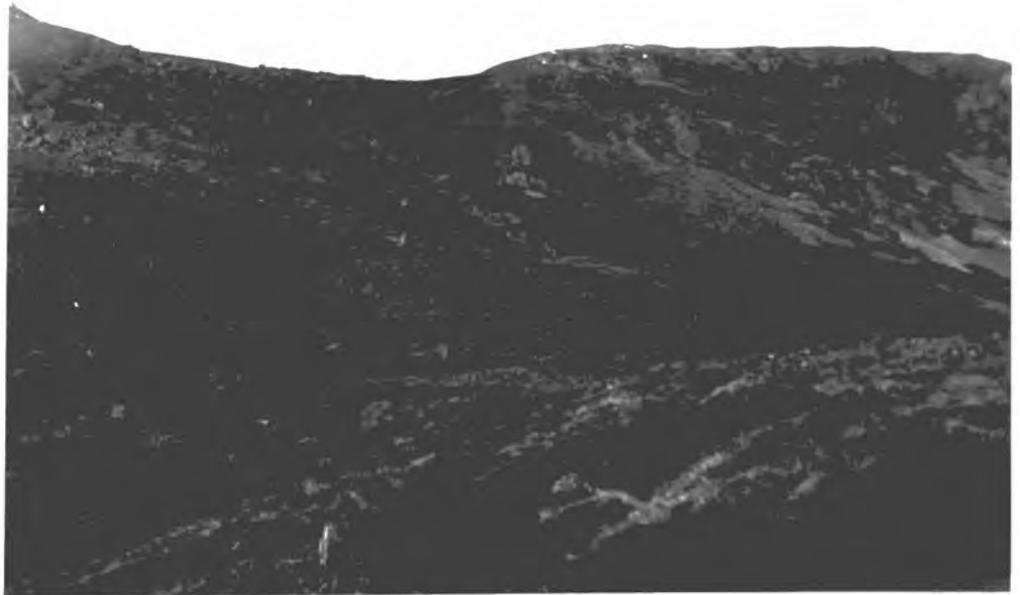
Plate IV C2   Further Gill Syke, east face of Carrock Fell.
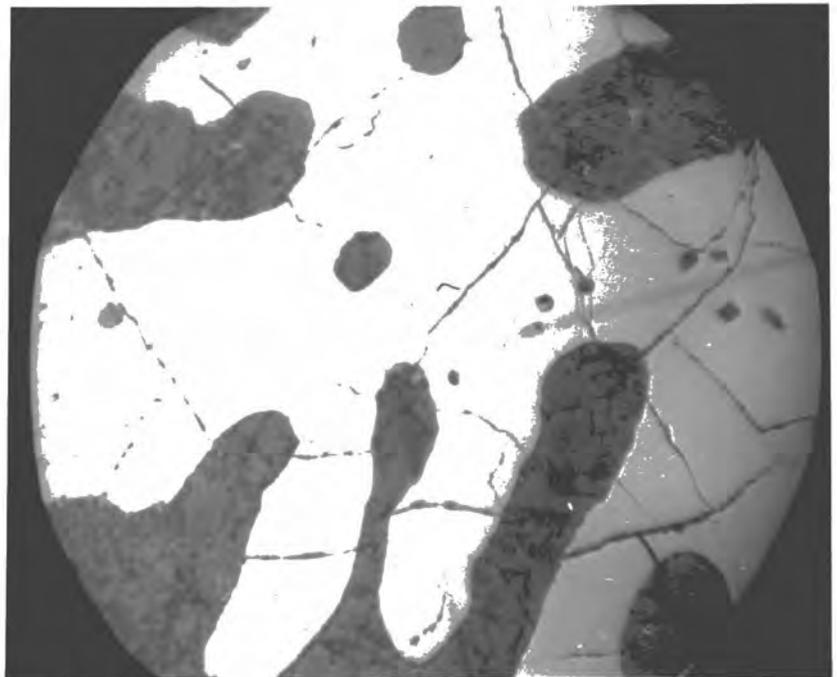
Plate IV C3 x 30   Lobate and fingering ilmenite.   This photograph
is of a single crystal.

only incipient uralitization.

The original melanocratic gabbro appears to have been a subhedral-granular rock consisting of labradorite, augitic pyroxene, ilmenite, magnetite, biotite, apatite and pyrite. The texture is variable, but is commonly sub-poikilitic, the pyroxene ($nY = 1.699$) partially rimming both labradorite and the opaque constituents, but against the latter the relationship may be reversed. The position of apatite in the paragenesis is uncertain because although occurring in the unaltered gabbro it is most common in the thoroughly serpentinised and chloritized material where relationships are obscure. Probably it is mainly of primary origin with a small proportion of secondary crystals. The relationships of the opaque minerals are not entirely unambiguous either. The bulk of them (excluding pyrite) almost certainly crystallized early and were then partly resorbed by the magma giving rise to the rounded and lobate crystal outlines of, in particular, the ilmenite which is the commoner oxide. The lack of observable corroded remnants of ilmenite indicates that the resorptive stage must have been pre-complete crystallization. It is significant that ilmenite crystals have rounded, and sometimes quite extraordinarily lobate and 'fingered' outlines whether in comparatively fresh gabbro or secondary chlorite-serpentine (see Plates IV C3, 4, 5, 6, 18, 19, 20, 21 and 24).

Magnetite contrasts strongly with ilmenite regarding its stability in changing environments. It is both an early crystallising primary magmatic and a late secondary mineral. The early magmatic magnetite is frequently associated closely with ilmenite in medium-sized crystals which usually have a ragged appearance when compared with the smoothly lobate ilmenite. Sometimes the
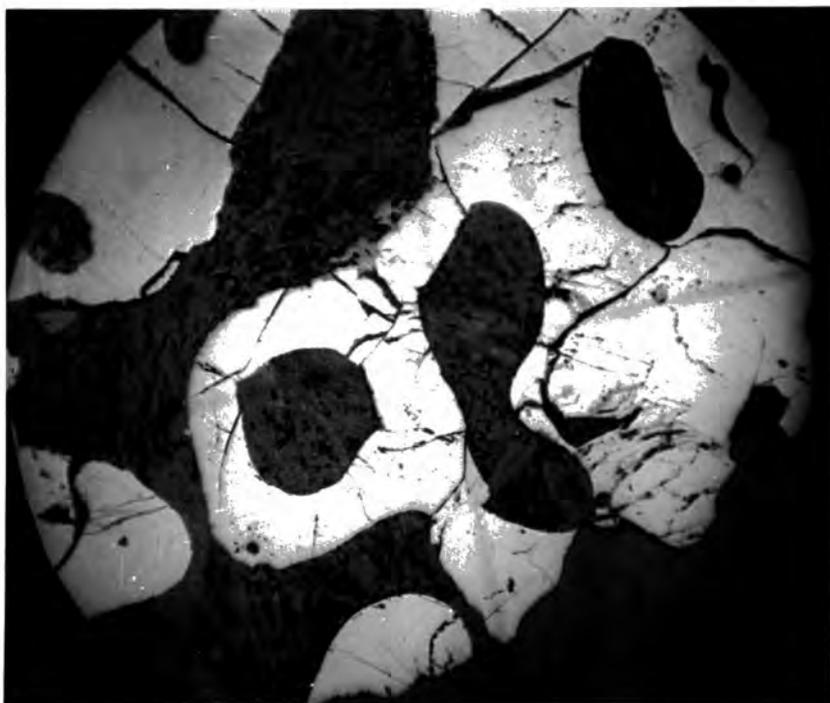
Plate IV C4 x 30   Ilmenite enclosing silicate.   The photograph
is of a single crystal.
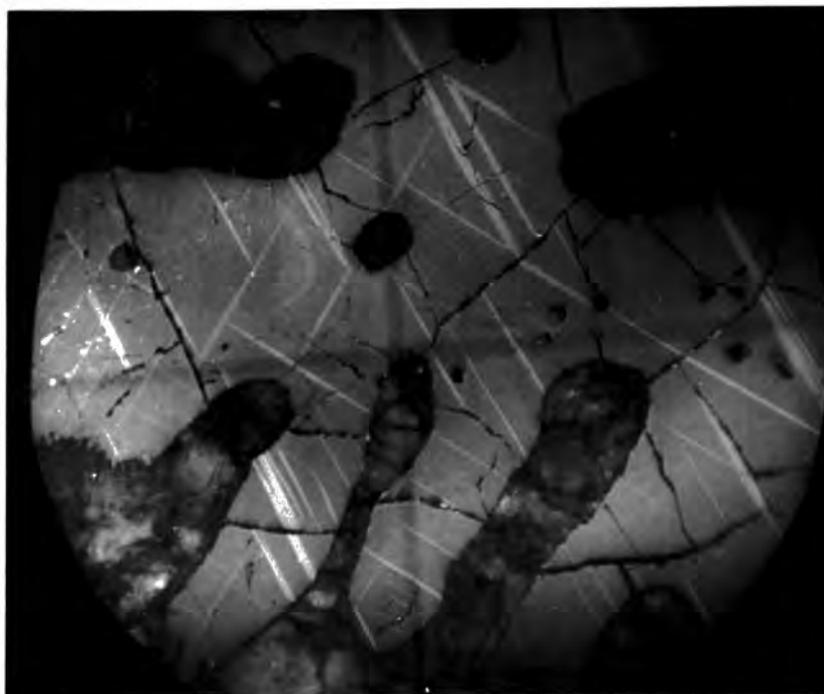
Plate IV C5 x 30   The ilmenite of plate IV C3 in crossed polarised
light.   The twin lamellae appear to have been
continuous across the areas which are now
silicate.   Is the ore of early or late
crystallisation?
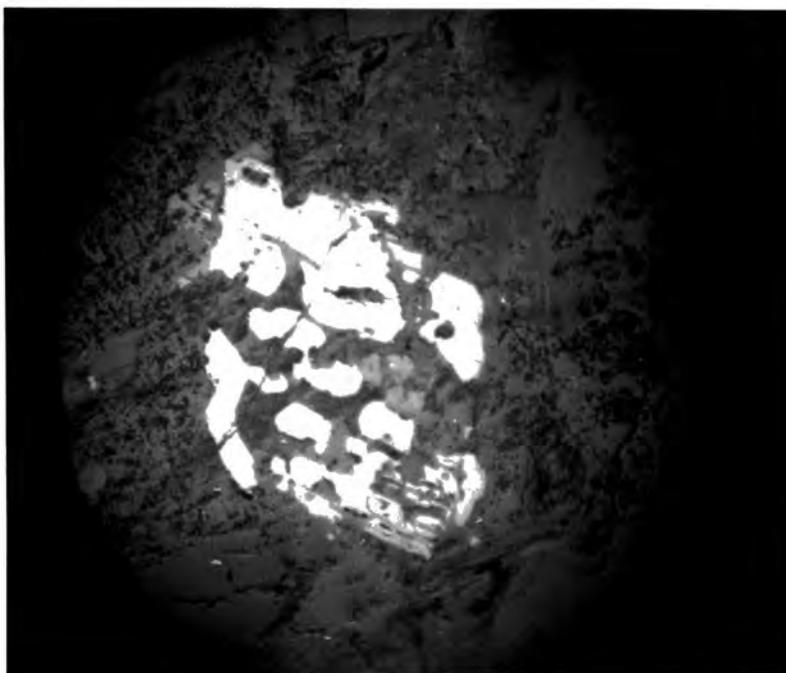
Plate IV C6 x 50   A corroded crystal of early crystallised ilmenite. All the fragments are optically continuous.
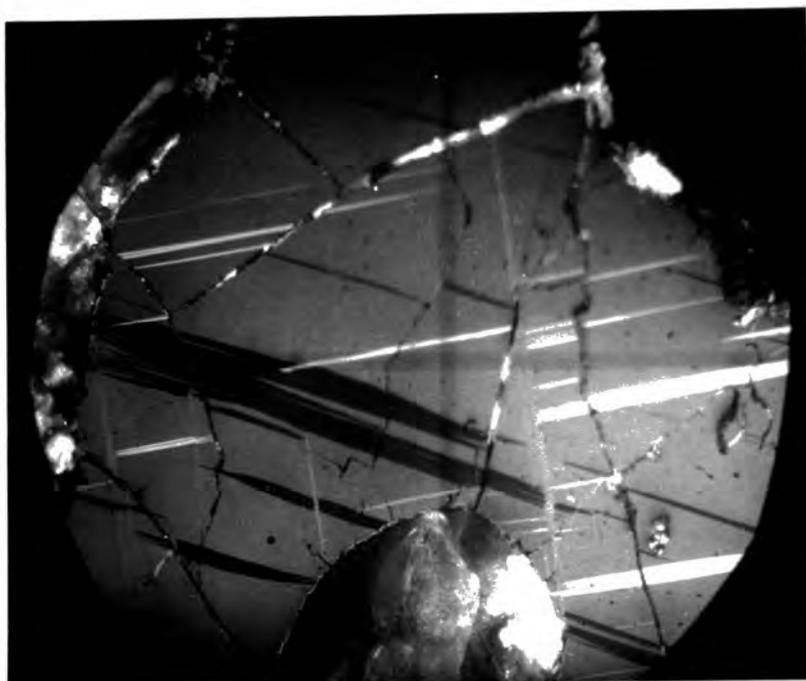
Plate IV C7 xn x 100   Twinning in ilmenite.

magnetite crystals have crystallised after ilmenite which is mantled by it (Plate IV C14), but the reverse relationship also occurs (Plates IV C13 and 17) where ilmenite is apparently of later crystallization but still of 'magmatic' age. The magmatic magnetite contains exsolution structures which are described later. Magnetite in unaltered gabbro is normally fresh except for slightly ragged crystal edges but with the appearance of uralite or chlorite-serpentine aggregates the magnetite shows advanced alteration to martite (and sometimes maghemite) followed by replacement by silicates. These are sometimes identifiable as chlorite but are usually a fine-grained serpentinous aggregate. The magnetite, on replacement, leaves behind a skeletal pattern of remnant ilmenite exsolution lamellae which have sometimes been altered to rutile and sometimes to sphene (see Plates I^V C8, 9 and 14). While titaniferous magnetite is so clearly unstable in hydrothermal metamorphosing conditions, titanium-free magnetite is widely disseminated as a late-crystallizing mineral. Small crystals of magnetite frequently accompany late pyrite which ramifies through the hydrous secondary silicates (see Plates IV C10, 23 and 25). Much of this magnetite is probably introduced but there are indications locally, where the magnetite seems to be restricted to certain ghost crystals of pyroxene (?), that it may be part of the iron of the magmatic silicate recrystallised in situ.

The hybrid mela-granophyre which outcrops at the contact of granophyre and mela-gabbro contains small crystals of both ilmenite and magnetite set in a matrix of plagioclase (variable composition, mostly andesine-oligoclase), hedenbergitic pyroxene and perthitic and myrmekitic feldspar (see Plate IV C22). Ilmenite forms individual crystals with smooth outlines showing slight evidence of corrosion,

Plate C8 x 180   Relict lamellae of ilmenite in a completely replaced crystal of magnetite. The replacive material is mostly chlorite.

Plate IV C9 x 100   Replaced magnetite crystal with relict ilmenite lamellae enclosed in ilmenite.
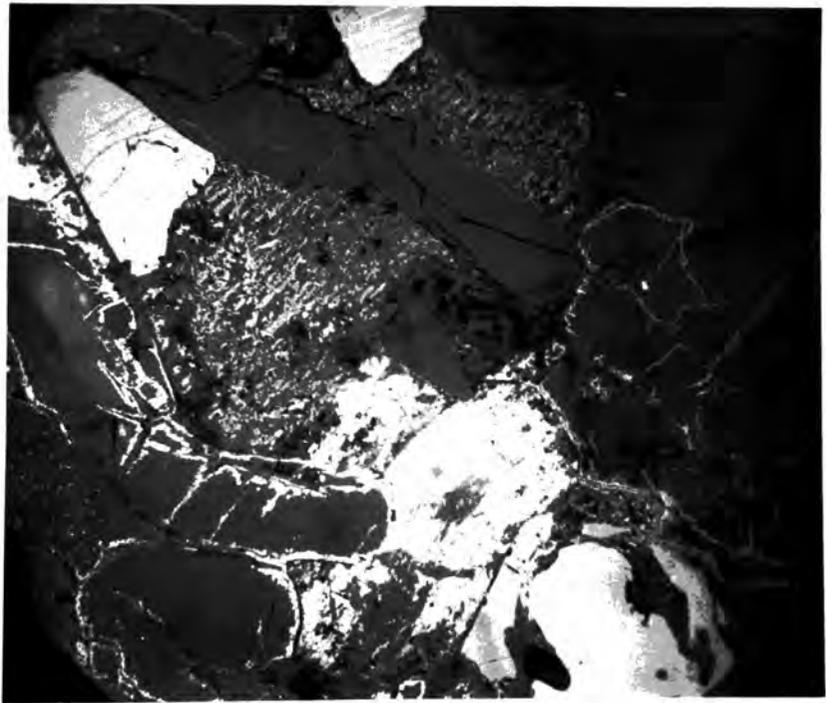
Plate IV C10 x 50   Late pyrite (white) rimming and replacing silicates. The homogenous grey areas are ilmenite and the disseminated grey areas are a late generation of magnetite, probably exsolved from a silicate host.
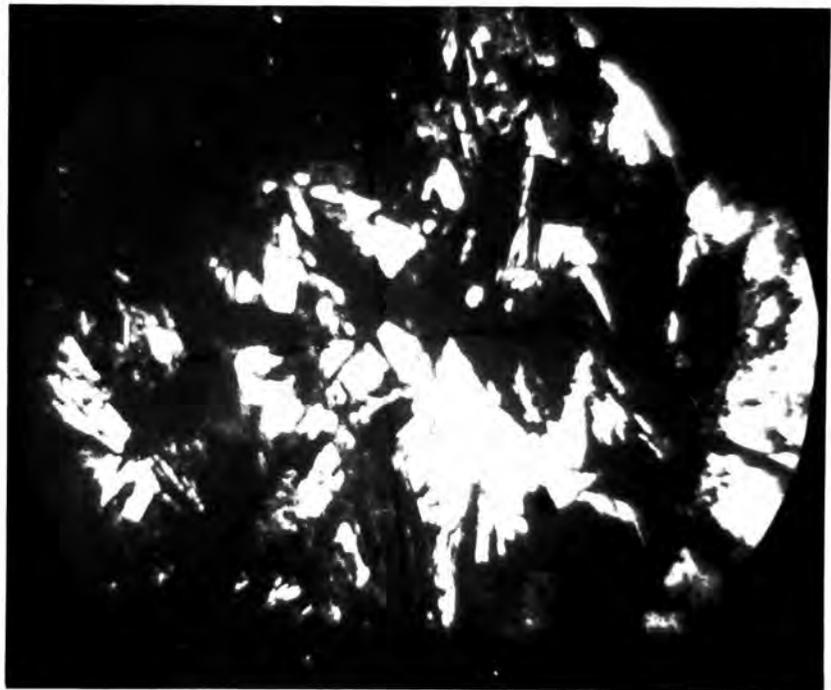

Plate IV C11 x 180   Late "feathery" pyrite in a dark chloritic matrix.

Plate C12 x 180   Magnetite (medium grey) rimmed by martite (white) in
                   a matrix of silicates (dark grey).   The totally
                   grey grain is ilmenite: from a polished section
                   of the hybrid granophyre zone.
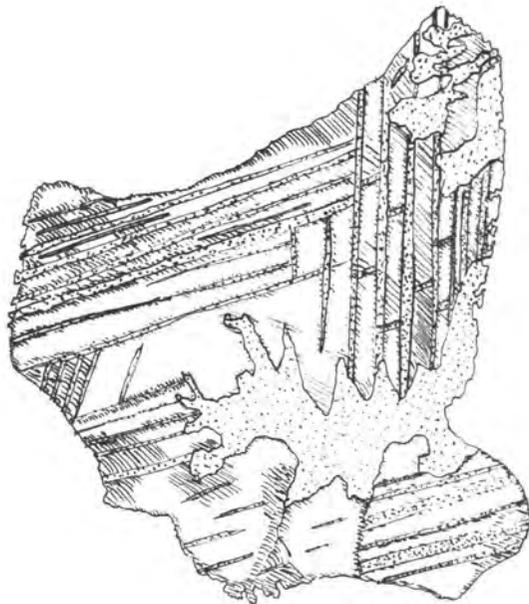
Plate IV C13 x 850   Replacement of magnetite (white by martite (striped)
                      and ilmenite (stippled). Martitization has
                      proceeded along cracks and along the edges of
                      ilmenite lamellae. An indian ink drawing of part
                      of the polished specimen figured in plate C12
                      above.
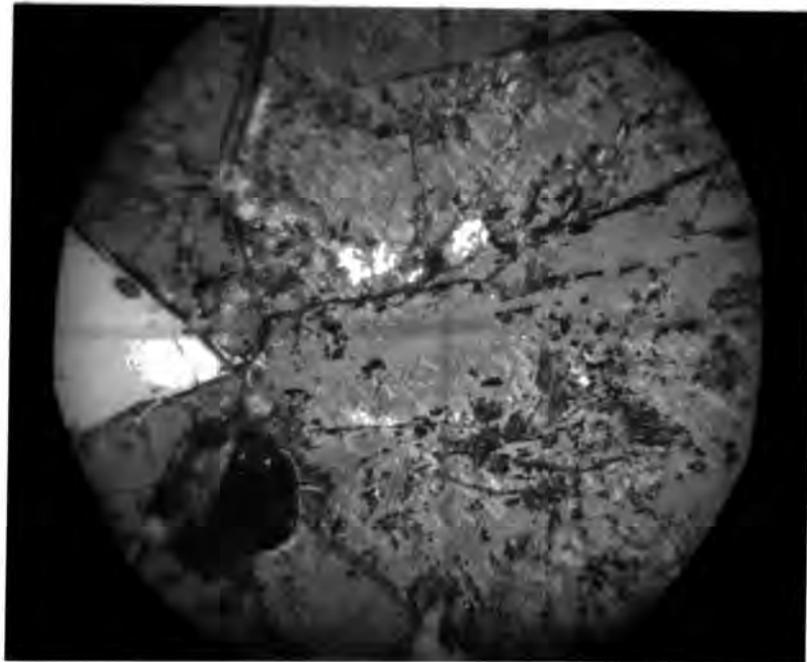
Plate IV C14 x 150 (Nicols at 75°) Polished section of part of a crystal
of magnetite in an early stage of replacement by martite, goethite and
silicate.   The silicate is a very dark grey shade throughout most of
the section, but is white where bright internal reflections occur.
Martite is present as a few small light grey patches.   The wedge
shaped light grey crystal is ilmenite and light grey and dark grey
ilmenite exsolution lamellae are visible in the magnetite.   Their
shade depends on their orientation.

Plate IV C15 x 950   Indian ink camera lucida drawing illustrating the
manner in which silicate (black) replaces magnetite (white) along the
edges of ilmenite exsolution lamellae (stippled).   Martite is
striped.   Note how the ilmenite lamellae remain as projections into
the silicate at the margins of the magnetite grain.
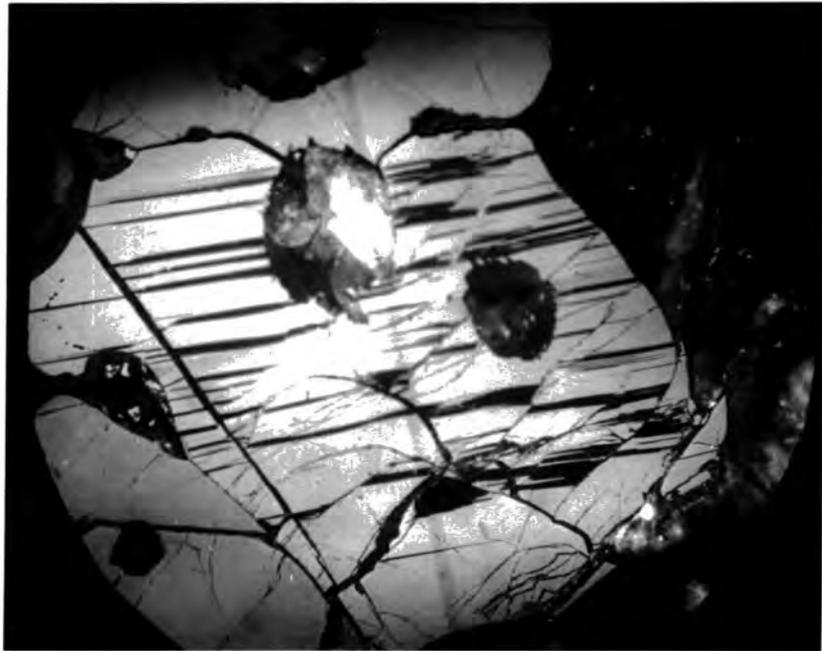
Plate IV C16 x 80 (Nicols at 87°).   A twinned crystal of ilmenite
         showing translation of the twin planes along small
         sheer planes which traverse the crystal, indicating
         that post-crystallization stress has been operative.
         The round inclusions are silicates.
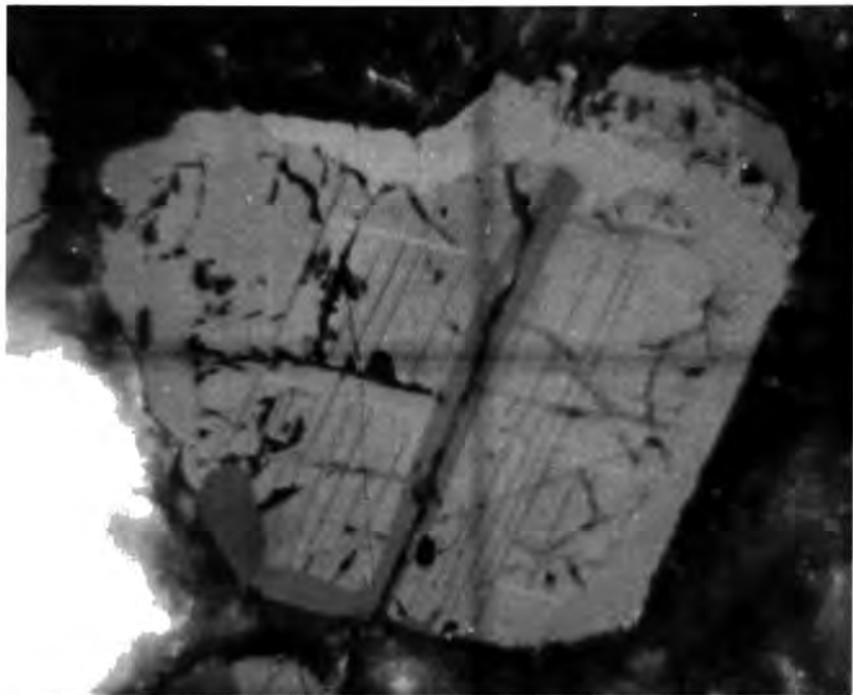
Plate IV C17 x 100   (Nicols at 80°) Ilmenite (light, even grey and dark
         grey) rimming and cutting an earlier magnetite
         crystal, traversed by cleavage and irregular
         cracks filled with silicate (black).

while magnetite is in ragged crystals which have well-developed rims of martite.   The oxide minerals may be regarded as primary magmatic constituents of the granophyre.   It is interesting that magnetite was apparently just becoming unstable in the environment at the temperature of solidification.

The following analyses of the mela-gabbros have been published. The mode has been determined in the course of the present work.

	A	B		C
SiO_2	41.38	32.53	Plagioclase (An_{60})	35
Al_2O_3	14.04		Pyroxene	15
Fe_2O_3	3.14	8.44	Hornblende)	
FeO	15.90	17.10	Chlorite)	30
MgO	5.63	7.92	Biotite)	
CaO	9.73		Ilmenite with	
Na_2O	1.56		Magnetite and	16
K_2O	0.72		Pyrite	
H_2O+	1.88		Apatite	2
H_2O-	0.18		Quartz	2
TiO_2	5.05	5.30		
P_2O_5	0.14			
MnO	0.37			
$Fe S_2$	0.22			
Cr_2O_3	-			
	99.94			

A.   Ilmenite gabbro (southern marginal facies) chemical
        analysis by Dixon (1933).
B.   Ilmenite gabbro (northern marginal facies) chemical
        analysis by Harker (1894).
C.   Ilmenite gabbro (northern marginal facies).   Average
        of three modal analyses.

The Opaque Minerals in Polished Section.- Ilmenite is the most common opaque constituent of the marginal gabbro.   It occurs in rounded and lobate crystals up to several millimetres in diameter with smooth edges but against magnetite it shows straight crystal boundaries.   The edges are sometimes serrated on a very fine scale and there may rarely be a very narrow rim of what is probably sphene developed.   More rarely still a broader, but still narrow, rim

of biotite has been formed. The relationships of the ilmenite to
the magmatic silicates is ambiguous, but it probably crystallised later
than plagioclase and contemporaneously with pyroxene because each in
different specimens mantles the other. Apatite is enclosed in
ilmenite.

The ilmenite is pale cream or brown grey in colour. It
is slightly pleochroic and anisotropic. It takes a good even polish.
The reflectivity (ordinary ray) is 18.54 at a wavelength of 581 $\overset{o}{A}$ (Ilford
filter spectrum yellow), as measured with a Cooke, Troughton and
Sims microphotometer. The anisotropy colour is usually a
slightly brownish or greenish grey. The maximum angle, measured
at right angles to the basal plane, of rotation of the plane of
polarisation was 2.4° (white light). The ilmenite in every specimen
examined was quite free from exsolution bodies of any kind which
considering the close association with magnetite, would appear to
indicate a moderate to low temperature of crystallisation. In many
specimens the ilmenite shows well developed twinning which, together
with the presence of dislocation planes which displace the twin
lamellae, indicate that post-crystallization stress was operative
(see Plates IV C5, 7 and 16).

The magnetite in the gabbro varies in appearance depending
on the silicate minerals associated with it, as has already been
discussed. In its least altered aspect magnetite is a pale brown
grey colour with a slightly higher reflectivity than the maximum
for ilmenite. It is isotropic. It does not polish well,
containing a number of pits, many of which are caused by the presence
of small silicate inclusions. Cracks are usually present in the
mineral and where they traverse an adjacent ilmenite crystal it is
noticable that they are always more pronounced in the magnetite.

With increasing chloritization and uralitization of the gabbro magnetite becomes heavily altered and replaced, and is often absent from the most affected areas of the gabbro. The process of alteration usually commences with martitization at grain boundaries extending into the crystal along cracks and by the side of ilmenite lamellae (Plates IV C13 and 15). This is followed by replacement by silicate and goethite, the latter finally disappearing with, finally, complete replacement by silicates (probably a chlorite in most cases).

The original magnetite contains exsolution lamellae of ilmenite in the normal pattern. They seem to vary in size from about 0.01 mm thick down to the limits of resolution (0.0001) (Plates IV C8 and 9). The secondary magnetite is free from these lamellae and is usually less brown in colour, being nearer a steel grey. Small inclusions of pyrite and chalcopyrite occur sparsely in the magnetite.

The sulphides in the gabbro are pyrite and chalcopyrite of which only the former occurs in significant quantity. It is of two generations, magmatic and hydrothermal. The former is present in small rounded or euhedral crystals enclosed in both silicates and oxides. The latter occurs as a feathery overgrowth on, and replacement of, the silicate minerals (see Plates IV C10, 11, 25).

Discussion.- The ilmenite melagabbro of Carrock Fell occurs as the marginal facies of a complex gabbro intrusion. There are two sheets of oxide-rich facies, a southern and a northern. The former contains large included masses of metamorphosed country rocks and generally carries less ilmenite than the latter. The northern sheet has suffered hydrothermal alteration probably caused by the intrusion of the Carrock Fell granophyre. There is a

Plate IV C 18xn   Subhedral plagioclase and rounded crystals of ilmenite partially enveloped by uralitized pyroxene. The gabbro is, in this specimen taken at a distance of several hundred feet from the microgranite, in its least altered condition.
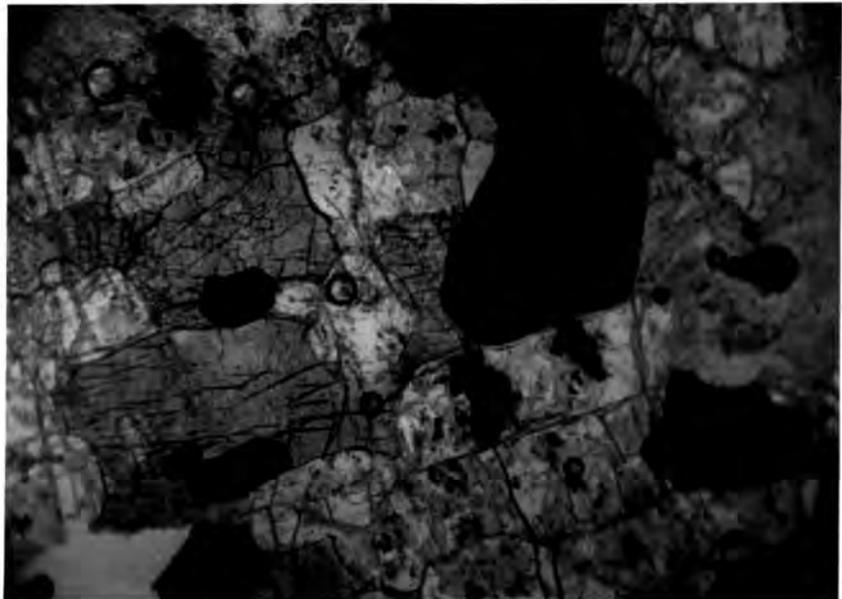

Plate IV C19 x 35   Ilmenite-gabbro in its least altered state. Rounded and embayed ilmenite crystals (black) and altered plagioclase occur together with sub-poikilitic pyroxene which is slightly uralitized.
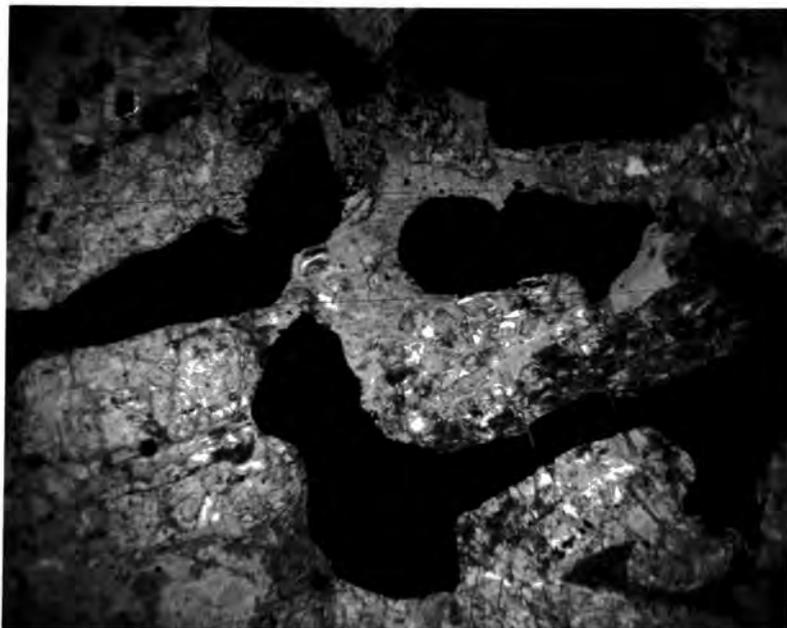
Plate IV C20 x 35   Characteristically lobate ilmenite in a groundmass
of saussurite and serpentinite in ilmenite gabbro
south of Further Gill Syke.

Plate IV C21 x 20   Rounded crystals of ilmenite in a matrix of
thoroughly uralitized pyroxene.
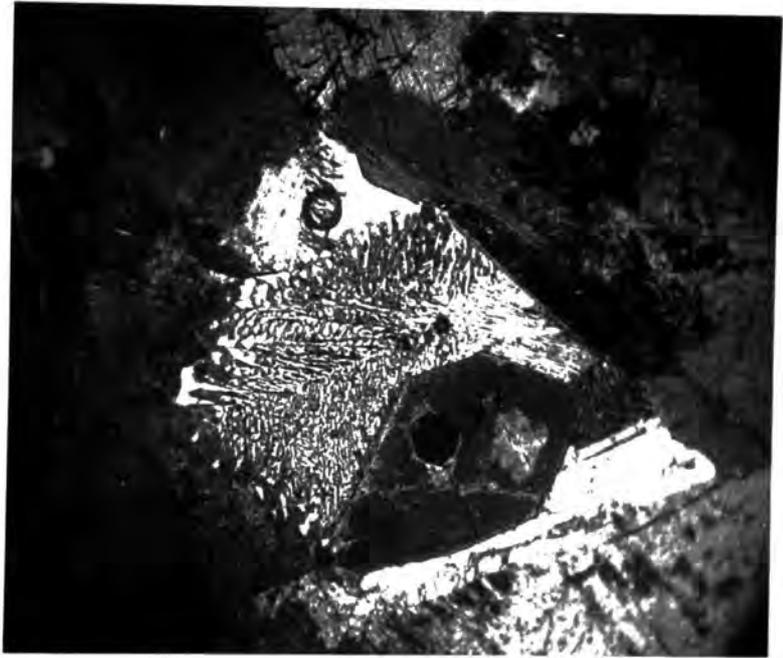
Plate IV C22 x 35   A crystal of pyroxene enclosed by myrmekitic feldspar.
Myrmekite of this type is restricted to the more
acid rocks of the hybrid granophyre (this
illustration) and the microgranite.
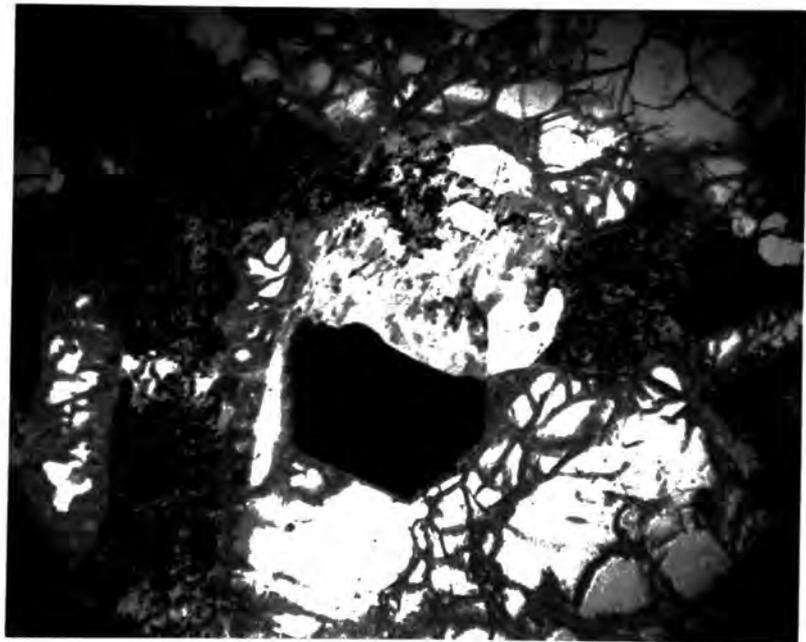
Plate IV C23 x 35   Shattered plagioclase (white) and ilmenite (black)
in a matrix of serpentine (grey) and disseminated
secondary magnetite and pyrite; from ilmenite
gabbro within 100' of the hybrid granophyre.
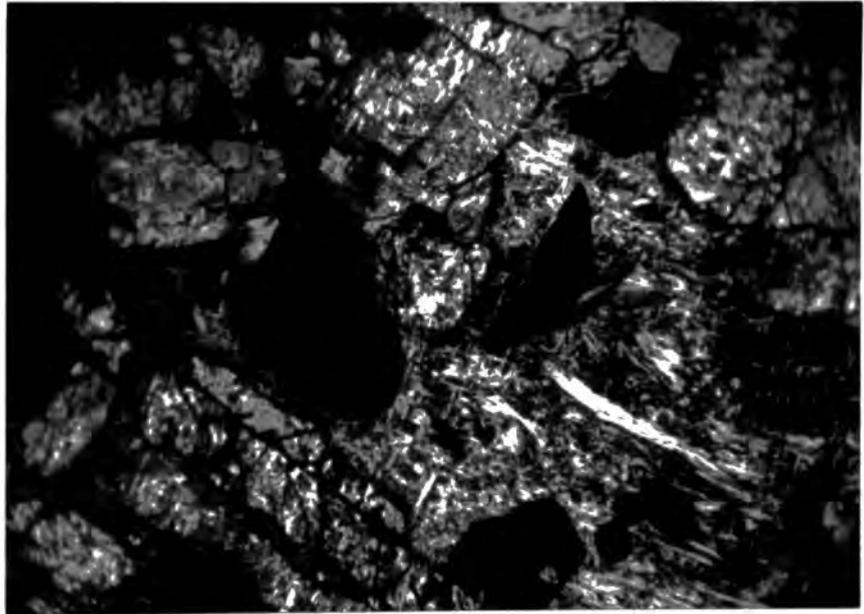
Plate IV C24x 35   Rounded and fragmentary crystals of ilmenite in a
sericitized matrix in which only faint traces
of the original minerals remain; from ilmenite
gabbro within 100' of the hybrid zone.

Plate IV C25 x 35   Late magnetite and pyrite invading and replacing
a chloritic-serpentinous melange of altered
gabbro.

hybrid facies of basic granophyre between the two. The gabbro complex was probably formed by a process of gravity differentiation prior to intrusion; the moderately sharp boundaries of each sheet would seem to rule out differentiation in situ in the way Harker suggested (Soret's principle) or by gravity. The form of the complex may or may not be due to folding after consolidation: the evidence is not conclusive.

Other Titaniferous Gabbroic Intrusions

Many gabbroic complexes in all parts of the world contain portions enriched in ilmenite and titaniferous magnetite. Many of them have features in common with one or more of the main features of the Carrock Fell complex which can be listed as follows:-

(1) A differentiation, rough in comparison with the Bushveld type of complex, varying from a melanocratic to a leucocratic facies.

(2) Association of the opaque minerals with the melanocratic facies.

(3) The presence nearby of a complementary granophyric intrusion.

(4) Hydrothermal alteration of the opaque mineral facies.

Some complexes show a sharp contrast to the second feature in that the opaque minerals have concentrated with the leucocratic anorthositic facies, thus comparing with the large layered complexes. The cause of the different mode of occurrence is not entirely certain; an attempt to evaluate the differences will be made in the discussion which follows.

Abu Ghalqua, Egypt.- At Abu Ghalqua in the eastern Egyptian desert is a gently dipping sheet of highly altered gabbro in contact with a later microgranite intrusion. The similarity with Carrock Fell is quite marked yet there are certain distinct differences. The

gabbro originally consisted of, in order of crystallization, labradorite (An_{60}), titaniferous augite, ilmenite and a little magnetite (4% of opaque minerals). The labradorite, which contains fine needles of rutile, has been altered to kaolinite and sericite and the pyroxene is almost completely uralitized. There is no banding as at Carrock Fell, the only comparable feature being a variation from a fine to a coarse-grained facies, the latter predominating. The ratio ilmenite:magnetite is similar but the ilmenite contains exsolved hematite discs, unknown in the Carrock gabbro. The opaque minerals have accumulated at the top of the gabbro as a late crystallizate. At the gabbro-microgranite contact hybrid quartz-gabbros and hornblende diorites have been formed (see Vol. II p 147 for references).

A similar association of differentiated gabbro and microgranite is found at Pigeon Point, Minnesota and in the Wichita Mountains of Oklahoma (Huang 1955). These intrusions do not, however, contain significant accumulations of ilmenite.

Pervouralsk-Katchkanar deposits, East Urals.- The titaniferous magnetite deposits of Pervouralskoe and Katchkanar in the eastern Urals are an excellent example of oxide mineral accumulation with melanocratic rocks. The ores are associated with an igenous complex composed of diorites, gabbros, pyroxenites, hornblendites, perido-dites and dunites. In the dunites and peridotites chromite has accumulated and in the pyroxenites and hornblendities are a number of orebodies of titaniferous magnetite. The oxide accumulations were late liquid differentiates of the mafic magmas crystallizing after reinjection in a typically pegmatitic habit; crystallization was agpaitic giving rise to a sideronitic texture (Malyshev

1936; Panteleev 1938).

The geochemical distribution among the seven ore horizons of the complex is described on pages 39 and 40 of Volume II. The falling Ti:Fe ratio in the later intrusions, from 0.1 to 0.05 is not in accord with the titanium distribution observed in the large layered noritic complexes where the later oxide accumulates have higher TiO_2 values. The ratio is, however, in accord with Buddington et alia's (1955) observations. Rising chromium:iron ratios are also unusual, and have been ascribed by Panteleev to preferential entry of the Fe'' ion which is not acceptable as a reason in the light of recent geochemical knowledge. However, the overall low content of titanium in the oxides is in accord with the very basic paragenesis, and the mutual connection between chromites and dunite-pyroxenites and titaniferous oxides and more siliceous differentiates, is observed.

Szarvasko, Bukk, Hungary.- The gabbro of Szarvasko (see page 15 Volume II) is a partially differentiated mass containing an ultrabasic lens varying in composition from diallage peridotite to dunite. Certain facies of these ultrabasic differentiates contain up to 90% of oxide minerals. The opaque minerals contain between 32 and 41% TiO_2 and the richest ore is found in diallage-rich rocks where the overall TiO_2 content of the rock is 18%. This is therefore a further example of late-crystallizing oxides associated with the most basic facies of a basic complex, with unfortunately no available details of the structure of the opaque minerals.

Azhinsk, West Siberia.- The Azhinsk basic complex exhibits an interesting distribution of titanium between the various facies present. Pyroxenite is the host to schlieric masses of gabbro containing

ilmenite enclosing exsolved magnetite. The oxide mineral of the pyroxenite is titaniferous magnetite containing exsolved ilmenite. The overall TiO_2 contents of the two rocks is similar 4.04 for the pyroxenite and 4.84 for the gabbro yet the TiO_2 content of the opaque mineral phase is higher in the gabbro. The opaque minerals are closely associated with widespread development of chlorite and serpentine with accessory apatite.

Si-Yonpyong-do, South Korea.- The gabbro of Si-Yonpyong-do contains pyroxenite differentiates rich in ilmenite and titaniferous magnetite accumulates (see page 209 Volume II). The ilmenite, approximately 55% of the ore is probably structureless while the magnetite contains exsolved ilmenite. The overall TiO_2 content of the ore is 19%. The magnetite contains 8% TiO_2.

The contrast between the TiO_2 content of the East Uralian pyroxenite ores and that of the other three examples is striking yet physically the deposits are similar. The key to the variation almost certainly stems from the fact that the East Uralian pyroxenites are salic differentiates of an ultrabasic magma while the others are basic differentiates of a gabbro.

There are a few known examples of the unusual rock-type titaniferous-magnetite olivinite which, while being of comparatively slight economic interest as titanium ores, have a bearing on the present genetic discussion. The most well described occurrence is at Taberg, Sweden while others occur at Cumberland, Rhode Island; Sodra Ulvon, Sweden and Susimaki, Finland. The opaque mineral in every case is titaniferous magnetite containing exsolution lamellae of ilmenite and spinel and sometimes also ulvospinel.

Taberg, Sweden.- The titaniferous magnetite olivinite of Taberg

(Hjelmquist 1949) forms the northern extension of a four kilometre long intrusion of hyperite (olivine diabase with brown feldspar) with which it is genetically connected. The hyperite has been intruded into gneissic granites and the olivinite has, in turn, been intruded into the hyperite. The olivinite consists almost exclusively of olivine and titaniferous magnetite, with accessory labradorite and secondary amphibole. Apatite and biotite are rare constituents. Labradorite is present as zenolithic phenocrysts and interstitially; both varieties are of the same composition, An_{50-57}. The paragenetic sequence is labradorite phenocrysts, olivine, apatite, titaniferous magnetite and interstitial labradorite.

The olivine contains 35% of the fayalite molecule but its optical properties are anomalous and similar only to the olivine in the titaniferous magnetite olivinite (cumberlandite) of Rhode Island U.S.A. with which in all the particulars the Taberg olivinite shows a remarkable similarity. The labradorite phenocrysts are apparently not in equilibrium with the surrounding minerals since they are sometimes rimmed by hornblende with, rarely, some garnet.

The magnetite fills the anhedral spaces between the olivine grains in a distinctly poikilitic fashion. It consists of three distinct minerals. A fine lamellar intergrowth of a green magnesian spinel is oriented in the 110 direction, and it also occurs as dropshaped and octahedral inclusions. The spinel lamellae cut ilmenite lamellae oriented in the 111 direction. The latter are smaller than the exsolved spinel lamellae. In small ore veins which traverse the rock spinel and ilmenite, which occurs in discrete grains, are somewhat more common.

The following modes of chemical analysis of the Taberg olivinite are taken from Hjelmquist (1949).

	1	2	3
Olivine	58.5	45.7	43.0
Magnetite	34.9	28.7	25.7
Labradorite	4.5	9.9	25.2
Amphibole	2.1	15.7	6.0
Apatite	–	–	0.1

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO
21.84	5.04	7.65	15.78	26.39	0.34

MgO	CaO	Na_2O	K_2O	V_2O_3	P_2O_5
18.93	0.73	0.28	0.18	0.24	0.12

S	F	H_2O^+	Total
0.06	0.02	2.09	99.69.

A coarse-grained pegmatitic variant of the olivinite contains a magnetite which is comprised of four mineral phases. The fourth phase which looks like ulvospinel defied strenuous efforts on the part of Hjelmquist to identify it and its true composition remains in doubt. Analyses of the ore mineral are given on page 32 of Volume II.

Inclusions of anorthosite-gabbro are found in the olivinite. The feldspar is the same as the phenocrysts but has a more sodic border zone. The olivine and pyroxene are the same as those of the hyperite; the olivine of the olivinite is more magnesian. An interesting feature of the titaniferous magnetite grains is that where tectonically deformed the Fe_3O_4 has been leached leaving skeletal ilmenite similar to that found in the Carrock Fell gabbro.

Some trace element determinations have been carried out (Hjelmquist)

and it is notable that the chromium content of the magnetite is low, averaging 0.012. The Cumberlandite equivalent contains 0.003% Cr. The vanadium content is also rather low, averaging 0.16% V.

Hjelinquist has adopted a theory of gravitational differentiation of a hyperitic parent magma into anorthosite and olivinite with palingenetic remelting and reinjection of the latter. The evidence for regarding the labradorite phenocrysts as zenolithic is strong and supports his hypothesis. Similarly there is considerable evidence for regarding the hyperite as the parent magma. However the hypothesis requires removal by erosion of the hypothetical anorthosite or its hidden presence at depth for which there is no direct evidence. At Cumberland there is equally no outcropping anorthosite despite the presence of zenolithic phenocrysts hence it would seem that, if present, the anorthosite probably lies below the olivinite. Johnson and Warren considered the olivinite to be a basic differentiate of a gabbro magma but failed to recognise the special character of the phenocrysts.

The olivinites in general present contrasts with both the opaque mineral concentrations of the layered complexes and many of the gabbro accumulations. They can be considered to be magmatic, like their stratified complex counterparts; the high content of TiO_2 in the magnetite (15%) would be in agreement with the concept of a high temperature of intrusion followed by rapid cooling causing freezing of the exsolution process. (There is evidence to suggest that the olivine was molten). However, the high TiO_2 content is not in agreement with the extraordinary basicity of the rock, when compared with the large layered complexes. On the other hand, of

course, the labradorite is remarkably sodic for a rock with such a low silica content, and considering solely the feldspar-ore relationship the TiO_2 content is not abnormally high. The magnetite-olivinites then, represent an extrapolation towards a basic pole of the 'anomalous' deposits, described in the preceeding sections, associated with some gabbros. Also, assuming that they were intruded at high temperature, the high TiO_2 content provides a further example of the 'magnetite thermometer' which has been discussed by Buddington et alia (1955).

In contrast to the ultrabasic titaniferous ores are those which occur in anorthositic gabbros, and which more closely resemble the accumulations in the large highly differentiated layered complexes. In complexes of this type the more high grade ore accumulations are usually found in anorthosite with lower grade disseminated ores in associated gabbro or norite. The plagioclase is usually in the An_{60-70} range.

Tugela River, Natal.- Near the Tugela river at Middle Drift is a gabbro-norite and anorthosite intrusion, possibly funnel-shaped, which contains oxide-rich mineral accumulations. The opaque minerals are titaniferous magnetite with perhaps a little ilmenite (Du Toit 1918). The most common rock-type consists of diallage, hypersthene, hornblende and calcic labradorite with horizons of bytownite anorthosite. The ore horizons consist of 75% opaque minerals, the remainder is mainly plagioclase. The TiO_2 content of the ore varies from 9.2 to 19.7%. Corona structure (clinozoisite and leucoxene to amphibole to actinolite) is well developed around many pyroxenes. One notable absentee from the paragenesis is apatite. Du Toit has suggested that the ore and anorthosite were

lately injected into the gabbro-norite.

Deposits of an essentially similar type consisting of titaniferous magnetite plus a little free ilmenite occur in differentiated gabbros in the San Gabriel Mountains of California and near Tete, Portuguese East Africa.

Chi-chia-tzu, Manchuria.- This deposit consists of injected (Tsuru 1934) lensoid and tabular orebodies comprised of titaniferous magnetite and a little ilmenite (total TiO_2 averages 12.26%) in leucocratic anorthosite gabbro and melagabbro. The massive ores occur only in anorthosite.

Kusinsk-Kopanskoe.- These deposits of the western Urals provide an excellent contrast to the eastern Uralian deposits briefly described above. They occur in a diorite, gabbro and gabbro-anorthosite complex as vein-like orebodies dipping steeply to the south-east. There are four major orebodies with TiO_2 contents ranging from 14.82 to 13.57% from the earliest to the latest intrusion. The titanium:iron ratio falls correspondingly from 0.188 to 0.148 and chromium:iron rises from 0.006 to 0.035 (Malyshev 1936: Panteleev 1938). It seems that the west Uralian deposits are, assuming the order of injection has been correctly established, as anomalous as their eastern counterparts. In these deposits it is interesting that in disseminated gabbroic ore crystallization was agpaitic yet, most unusually, in high grade orebodies the silicates crystallized after the oxides. The critical ratio of oxide: silicate apparently lies between 40 and 60% by volume of oxides. Malyshev considers that a eutectic with a ratio magnetite 60-80%: ilmenite: 35-20% controlled the crystallization of the oxides. This has been discussed elsewhere.

The contrast between the east and west Uralian deposits on the

basis of higher silica, higher TiO_2:Fe ratio can be carried into the realm of chronology. The ultrabasic complexes are Siluro-Devonian in age whereas the anorthositic complex can be dated as pre-Cambrian. It is interesting that most oxide-melagabbro associations can be shown to be post-Cambrian in age (Carrock Fell; Bukk, Hungary) whereas most of the anorthositic gabbros are probably of pre Cambrian age.

Liganga, Tanganyika.- The Liganga titaniferous magnetite intrusive (Harpum 1952) can be included in this group although it is associated with a well differentiated rock series. It differs from the Bushveld in that differentiation preceeded injection. The titaniferous magnetite (12.6% TiO_2) is most closely associated with leucogabbro. In common with many deposits there are two types of orebody one roughly concordant with gradational contacts, the other has sheared margins and is associated with extensive deuteric alteration. Unfortunately petrographic details are lacking.

Duluth Gabbro, Minnesota.- The Duluth gabbro is a large layered gabbroic complex some 125 miles long by 25 miles wide. Within it are many lensoid deposits of titaniferous magnetite and ilmenite. As in the Bushveld complex despite the comparatively low content of TiO_2 (10-20%) of the oxide fraction, ilmenite is commonly developed in discrete grains (Schwartz 1930). In common with the Carrock Fell and other gabbros deuteric minerals are widely developed with the oxide minerals. Genetic considerations are complicated in this case because of the suspected assimilation of sedimentary iron ores by the gabbro and it is not proposed to discuss the occurrence at greater length here. A thorough treatment of the deposits of the Duluth gabbro would be a welcome addition to the literature.

Many intrusive gabbroic plutons throughout the world contain accumulations of ilmenite and titaniferous magnetite without being especially differentiated into anorthosite, leucogabbro and melagabbro. Few of them are of any importance economically, and none for their titanium content. Rodsand, Norway is an example where the magnetite is exploitable but the non-magnetic 'ilmenite' concentrate is rejected on account of its low TiO_2 content. The magnetite is of value as an iron ore probably only because of amphibolitization of the gabbro which has caused partial recrystallization of the ore, a process discussed in the section dealing with Otanmaki.

Singhbhum and Mayurbhanj, India.- The titaniferous magnetite deposits in gabbro at Singbhum, Bihar occur in a generally uniform gabbro and are of interest only mineralogically at the present time although there are several million tons of ore in the ground. The oxides are of two generations the earliest of which consists of titanium-free magnetite and is rare. The bulk of the oxides crystallized after the silicates augite, primary hornblende and plagioclase (An_{40-90}) but before deuteric hornblende and chlorite. The paragenetic sequence in the ore is ilmenite-magnetite, ilmenite, and non-titaniferous magnetite. Secondary hematite, goethite and rutile also occur. The mineralogical curiosity of the ore is coulsonite, a vanadiferous maghemite (?) which occurs within the highly vanadiferous titaniferous magnetite. The ore is thought to be a residual liquid injection associated with H_2O and a little Na_2O, K_2O and SiO_2. Apatite is present in the ore (Dunn and Dey 1937).

Deposits which are unequivocably considered to be metasomatic are rare and other than the instances discussed in Chapter III only

two are known to the writer.

<u>Njombe District, Tanganyika</u>.- According to Harpum (1952) a
potash, alumina, silica metasomatism associated with a
powerful thrust zone has driven Na, Mg, Fe, Ca, Ti and Mn
from amphibolites to form titaniferous magnetite segregations (20%
TiO_2) some distance away. Replacement has occurred randomly without
reference to the host rock. At greater distances hematite
(1% TiO_2), limonite and quartz have been introduced into sediments.

<u>Okorusu, S.W. Africa</u>.- This deposit, mentioned above is a
replacement of limestone by titaniferous magnetite (7.3% TiO_2)
at the contacts of a sheet of fluorite. The replacements are
associated with alkaline vulcanicity.

Otanmaki - A Metamorphosed Gabbroic Complex

<u>Introduction</u>.- The ore-field at Otanmaki is remarkable for the
complexity of its geological relationships and this account does
not presume to offer a complete description or understanding of them.
That will come only after exhaustive exploration of the ore field.
The writer in the following pages aims to present an amplification
and, at the same time, a modification of the description given by
Paakonen (1956), which is based mainly on a study carried out prior to
the opening of the mine in 1953.

The orezone at Otanmaki is situated within an amphibolite mass
bounded to the north by red gneissose granite and to the south
locally by gabbro but generally by a very heterogenous striped gneiss.
All rock groups within the Otanmaki area are very heterogenous and
variable both in composition and texture and it is most difficult to
make generalizations concerning them. The striped gneiss has the

Plate IV Ot 1.   Otanmaki, a village of modern seven-storey flats set
in a wilderness of coniferous forest growing on the
rubbish dump of the Pleistocene.   The solid geology
is obscured beneath moraine, esker and swamp.
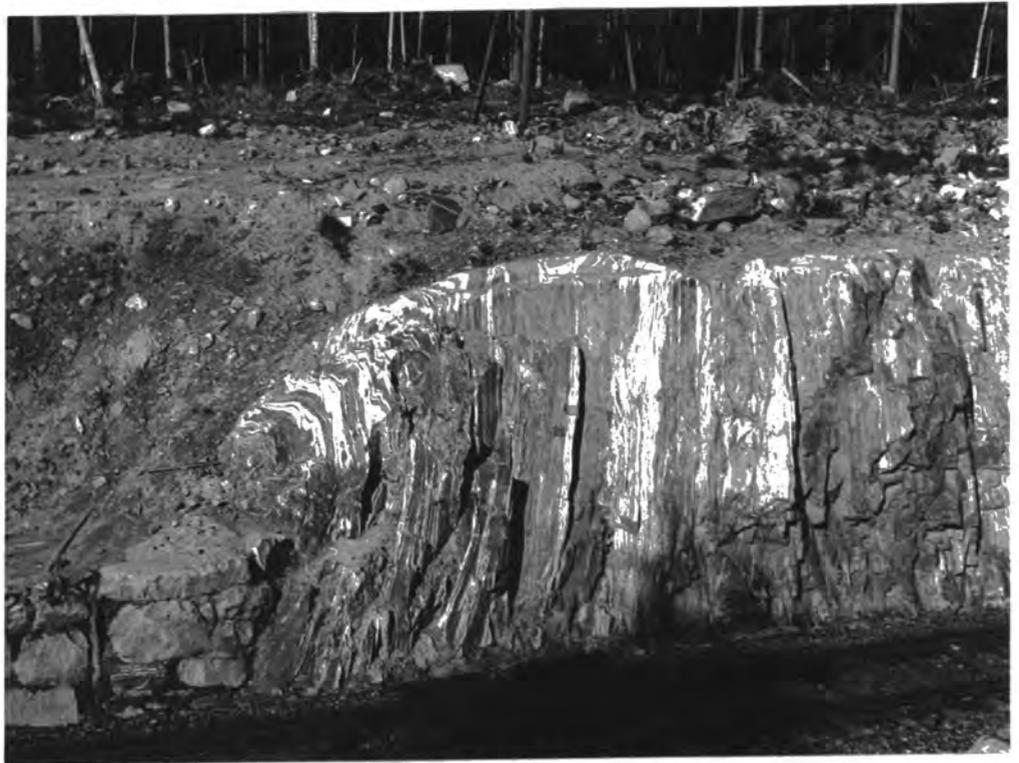Photograph taken from the mine tower.

Plate IV Ot 2.   Striped gneiss and amphibolite, typical rocks of the
area to the south of the Otanmaki ore zone.
Locality:-   railway cutting near Otanmaki village.

distinction of being the most heterogenous of them all. In any geological consideration of the Otanmaki region it must be borne in mind that it is the exceptionally poor exposure of the region that has led to the application of 'sack-names' to heterogenous rock groups. It must also be understood that pronouncements especially regarding the genesis of the ore deposits, are backed only by the limited scope of observation so enforced.

The striped gneiss (Plate IV Ot 2) is the oldest rock group of the region. It is penetrated by dykes of the amphibolite in which the orebodies lie. It is largely granodioritic in character, the striping being caused by a variation in the mafic (mainly hornblende) mineral content. A modal and chemical analysis of a microcline-rich variety published by Paakonen (1956) are given below together with a modal analysis of a more representative specimen made by the writer.

	Paakonen %		Paakonen	Writer
SiO_2	71.88	Quartz	25.8	21.2
TiO_2	0.17	Plagioclase (An_{10})	42.5	67.7
Al_2O_3	15.35	Microcline	23.3	0.8
Fe_2O_3	0.60	Epidote	7.0	"
FeO	0.83	Chlorite	0.6	10.0
MnO	0.02	Ore	0.6	0.2
MgO	0.75	Apatite	0.2	"
CaO	1.77	Pyroxene	–	0.1
Na_2O	5.18			
K_2O	2.88			
P_2O	0.14			
H_2O+	0.57			
H_2O-	0.08			

Where the granodiorite gneiss is penetrated by irregular dykes of amphibolite the plagioclase has altered to a low-grade microcrystalline aggregate of clay mineral and mica which has recrystallised in closer proximity to the amphibolite to form a

more calcic feldspar-usually andesine.   The amphibolite of the
dykes is similar in composition to, but lacks the strongly developed
schistosity of, the main amphibolite mass.

The red gneissose granite which bounds the amphibolite on its
northern side is younger than the amphibolite.   Inclusions of
the older rock are found in the granite, which also veins the
northern edge of the amphibolite mass.   Evidence both from boreholes
(Paakonen 1956) and from the surface indicate that strong crushing of
the granite has occurred since consolidation.

The composition of the rock appears to be rather variable from
granitic to adamellitic-granodioritic.   Its texture is granulated
granitic.   An analysis and a mode of part of a drill core (Paakonen
1956), and a mode of a specimen taken from a surface outcrop of a dyke
in the amphibolite near the concentration plant of the mine, are
given below.

	Paakonen %		Paakonen	Writer
SiO_2	71.55	Quartz	32.1	20.7
TiO_2	0.45	Plagioclase		
Al_2O_3	12.81	(An_{10})	11.6	(An_{16-20}) 46.1
Fe_2O_3	2.80	Microcline	45.5	28.9
FeO	0.94	Amphibole)		2.5
MnO	0.06	Biotite)	9.4	1.0
MgO	0.09	Ore	1.3	0.8
CuO	0.63	Apatite	0.1	–
Na_2O	4.60			
K_2O	4.84			
P_2O_5	0.05			
H_2O+	0.50			
H_2O-	0.35			

The alkalinity of the rock is demonstrated by the nature of
the amphibole (probably riebeckite) which is present in ragged
crystals.   The mineral described by Paakonen seems to be slightly
different to the one seen by the writer.

SERIAL SECTIONS THROUGH THE OTANMAKI OREBODIES

Grid dimensions in metres.

The geology is shown diagrammatically owing
to the gradational contacts and imperfect data.

LEGEND

Ilmenite-Magnetite Ore

Anorthosite

Amphibolite

Feldspar-free Amphibolite

Amphibole Gabbro
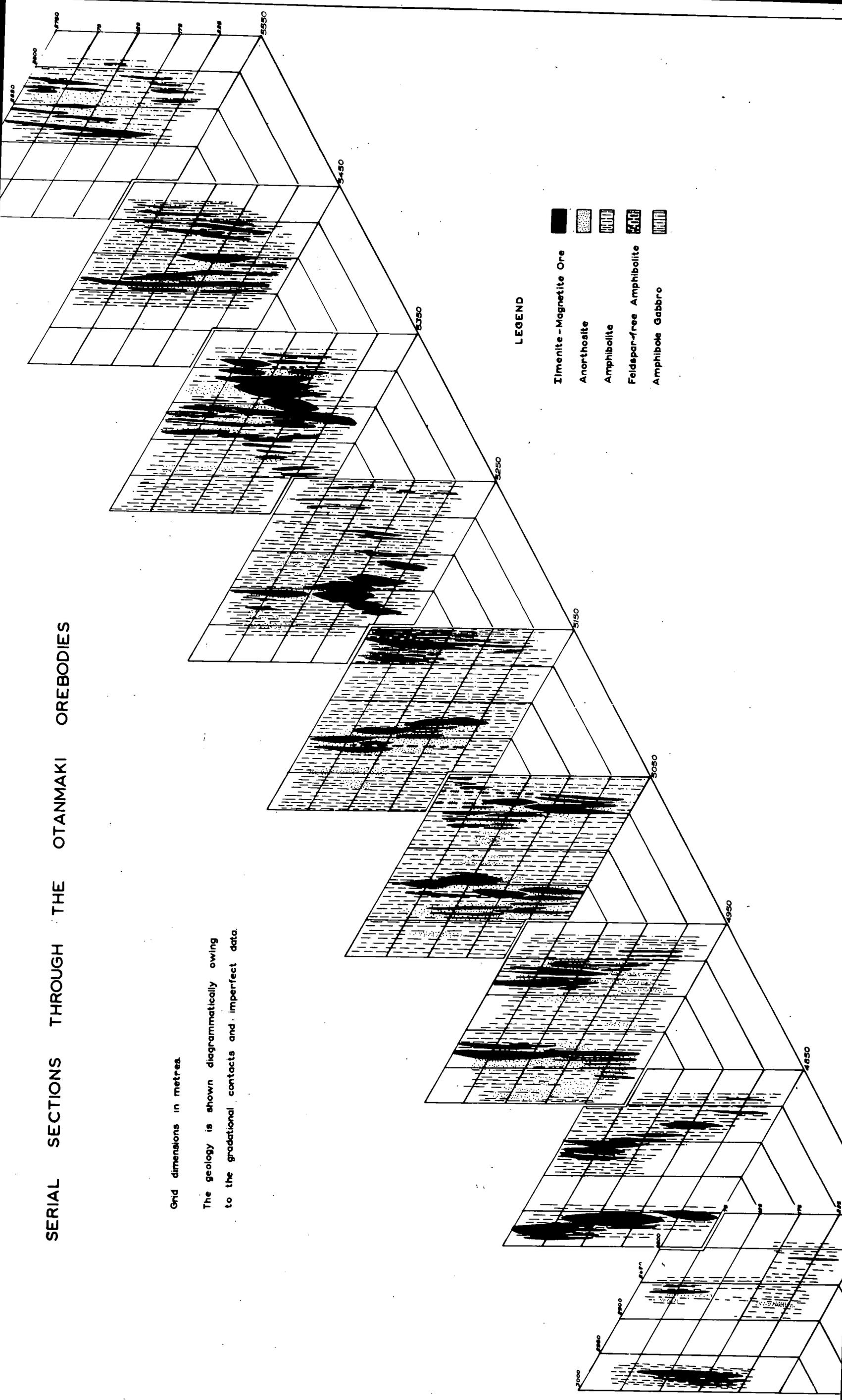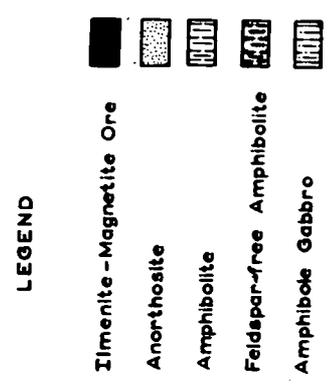
	Paakonen	Writer
α	dark blue 1.692	pale yellow-green
β	yellow green	blue green
γ	deep blue 1.707	very deep blue-green
2V	78°; 80°; 84°	very wide
Z∧c	0°-4°	13°

The Ore Zone.-   The ilmenite-magnetite orebodies at Otanmaki lie

entirely within the amphibolite-gabbro complex.   The amphibolite

forms a sweeping fold closing against the pitch of the lineations

(50°-70° directed 25°-20° south of west).   The dip is 70°-90° south

on the limbs of the fold and a similar amount west on the snout.

The orebodies are located in the limbs of the folds away from the

crest.   The main orezone which forms the subject of this work, is

in the southern limb but another smaller zone is known to occur in

the northern limb.

Within the area of the mine workings the following rock types

can be recognised:-

1.   Plagioclase amphibolite (Plate IV Ot 7)   This grades by

increase in plagioclase (or epidote after plagioclase) content

to hornblende meta-gabbro; and by increase in hornblende content to

hornblendite.

2.   Hornblende meta-gabbro.   This consists of two different

types between which there is complete gradation.   One variety is

distinguished from amphibolite solely by the preponderance of

plagioclase over hornblende.   Texturally it is similar and the

feldspar is not original.   The other variety has a 'magmatic'

texture; the original feldspar is recognisable and schistosity is poorly

developed.

3.   Anorthosite. A rock comprised of over 90% feldspar; it

may grade to either of the two gabbro types by increase in hornblende

content.   Unlike both the preceeding rock types it is sometimes

sharply differentiated from the surrounding rocks.

4.   Ilmenite-magnetite ore.   This varies from a rock consisting

entirely of oxide minerals to an ore-bearing amphibolite and, more

rarely, ore-bearing gabbro.

5.   Hornblendite.   A rock consisting of over 85% hornblende.

It is found only in the vicinity of the ore horizons, and

usually is in immediate contact with them.

6.   Chlorite-epidote rock.   This is found only near ore

horizons and shear zones.

7.   Late discordant veins.   These are usually one of three

types, although overlap between them occurs to a limited extent.

a) Sulphide veins consisting predominantly of pyrite b) Plagioclase

veins (Plate IV Ot 11) c)   Epidote veins.

The general distribution of the rock types is shown in the

text-figure of serial sections taken through the orezone in a

north-south direction which has been compiled from borehole records

and maps provided by Otanmaki company.   The plunge of the mineral

lineations in the mine as measured on the hornblende in the

amphibolite varies from 50°-70° in a direction 15°-20° south of west.

The orebodies are not concordant with the lineation.   Together with

the other rock units they strike more nearly east-west, swinging to

some 10° north of west at the western end of the explored area.

The orebodies are lensoid elipsoids dipping approximately vertically,

with their long axes inclined at 60-70° to the west.   The sections

through the orezone show the two parallel ore belts, each consisting of

numerous separate orebodies, which comprise the orezone.   A

third orebelt has been discovered by exploratory drilling to the

north of the two which are mined at present.   Each
succeeding orebelt to the north is set at a slightly lower level
than the neighbouring orebelt to the south, so that they form a
pattern en echelon.

Anorthosite forms discontinuous vertical bands roughly
concordant with, and almost always in close proximity to, the ore-
bodies.   It is frequently enclosed in the ore as zenolithic masses.
In such cases the white anorthosite blocks always have a rim, some
five or six centimetres thick, of creamy or reddened saussuritized
feldspar.   Similar blocks enclosed in amphibolite do not always
show rims of this type (see plate IV Ot 3 and IV Ot 4).

The relationships between the various rock types can broadly
be divided into three groups:- a) gradational contacts with and
b) without metamorphism   c) sharp intrusive contacts with
accompanying metamorphism.

Contacts between amphibolite and metagabbro (Plate IV Ot 5) are
always gradational, often over a distance of several metres.   There
is often a textural difference between the two rocks other than
the more pronounced schistosity of the former caused by its higher
content of amphibole.   In the amphibolite a larger proportion of
feldspar has either been saussuritized or regenerated to a more
sodic variety which forms finer-grained anhedral crystals.

The contacts of the orebodies are extremely variable (Plate
IV Ot 6 and IV Ot 12). Low-grade orebodies and veins of ore commonly
develop from amphibolite by an increase in its opaque mineral content
forming progressively third, second and first class ore.   An orebody
may consist solely of third class ore and would be virtually an
oxide-rich plagioclase, or epidote amphibolite (Plate IV Ot 16),

Plate IV Ot 3.   Rounded 'boudin' of anorthosite in amphibolite.
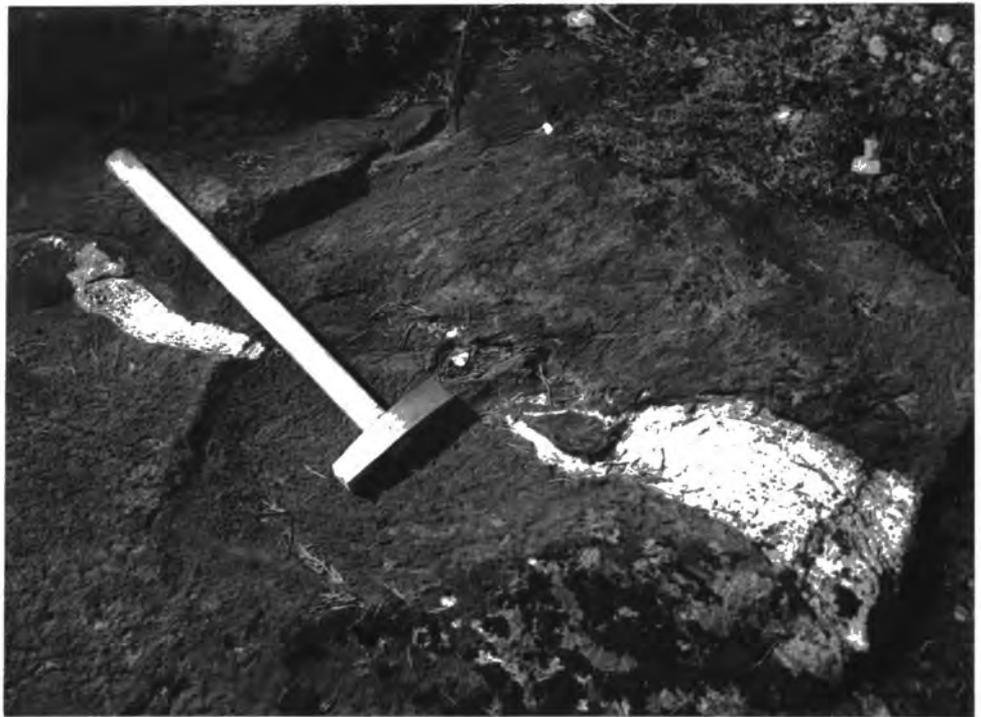Locality:-   Otanmaki mine.

Plate IV Ot 4.   Anorthosite horizon boudinee in amphibolite.
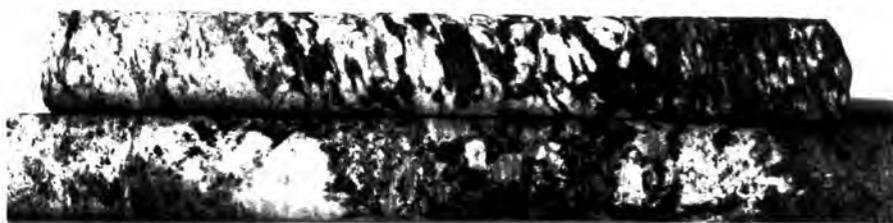Locality:-   Otanmaki mine.

Plate IV Ot 5. x 0.6.   Two drill cores shewing amphibolite-gabbro
contacts, one of which is strongly schistose.
The feldspar in both specimens has been
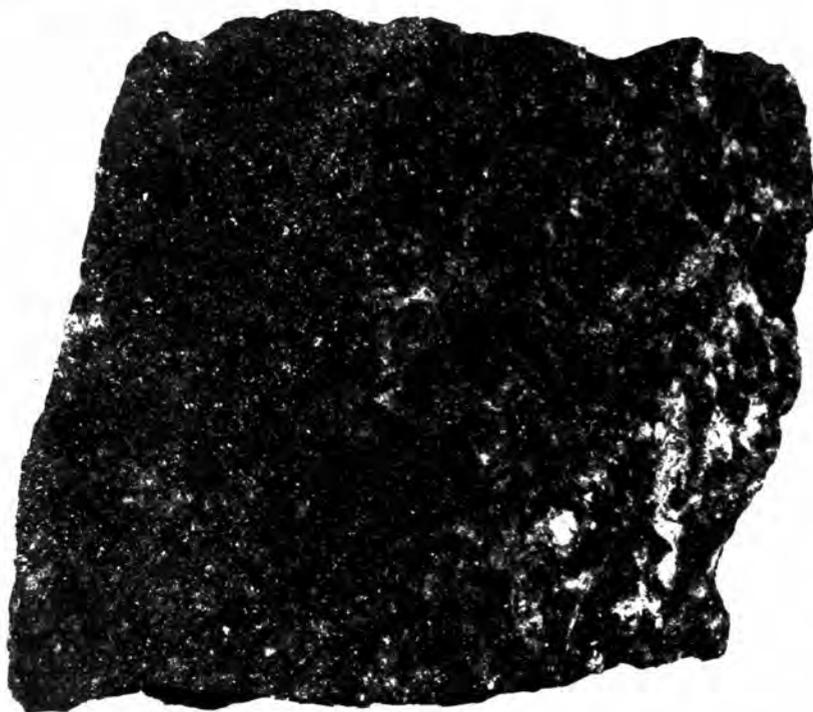converted to epidote and 'sericite'.   Locality
Otanmaki mine.

Plate IV Ot 6 x 1.   Ilmenite-magnetite ore on the left of the
photograph grading, through a chlorite-hornblende
melange, to amphibolite.
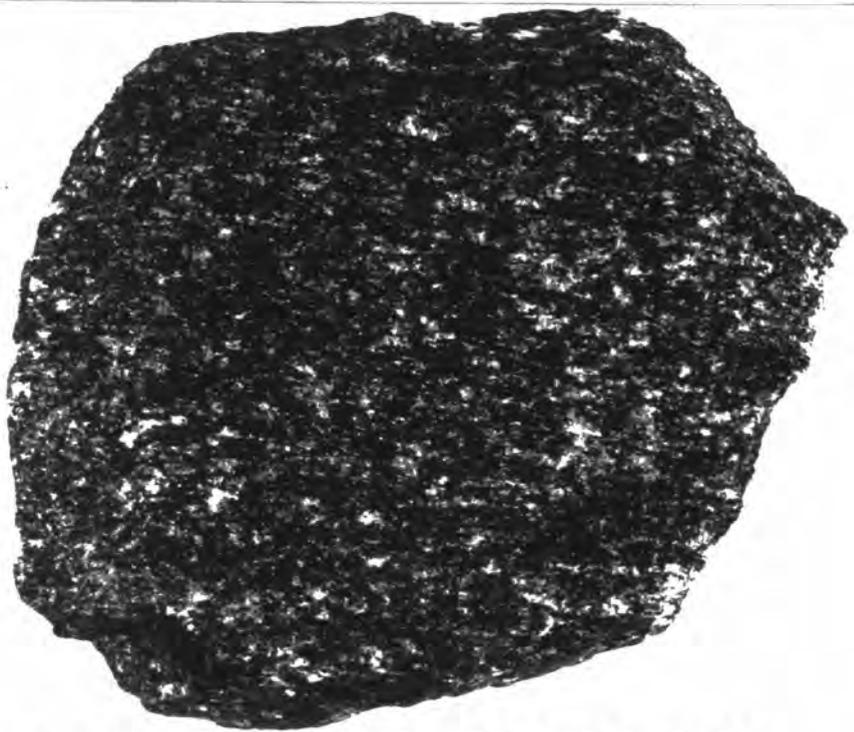
Plate IV Ot 7. x 0.6.   The typical foliated amphibolite of the
                         Otanmaki mine (see accompanying text for rock
                         description).

Plate IV Ot 8. x 0.75.   Feldspathic amphibolite verging on hornblende-
                          gabbro.   Quite sharp differentiation of the
                          plagioclase and hornblende into separate
                          areas is a common feature of rocks with
                          a composition intermediate between amphibolite
                          and metagabbro proper.
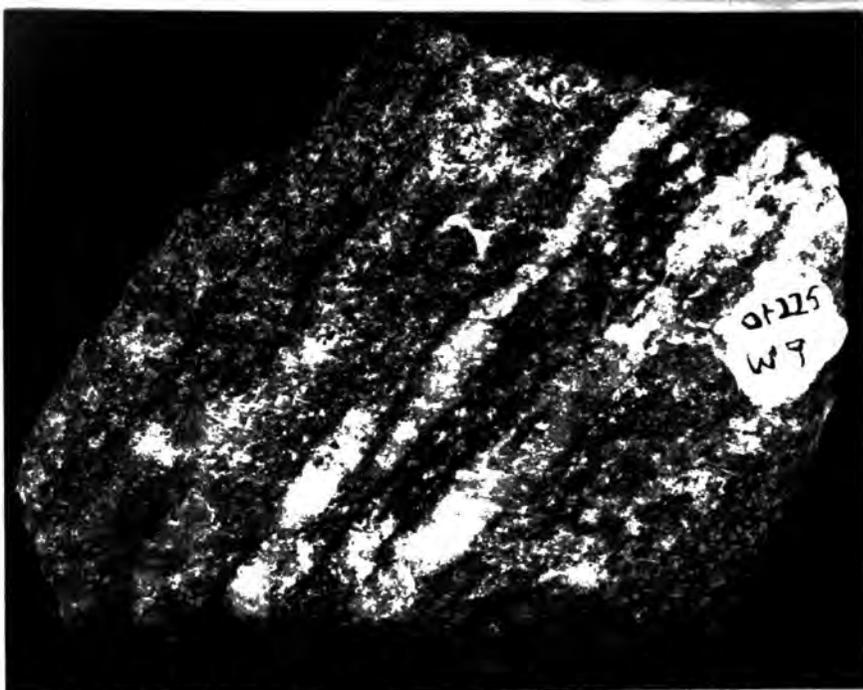
Plate IV Ot 9 x 0.75.   Striped leucogabbro.   The very dark-band
which roughly bisects the specimen is pre-
dominantly hornblende.   The white bands are
plagioclase recrystallised from the darker
and slightly more calcic plagioclase which
forms the bulk of the rock.
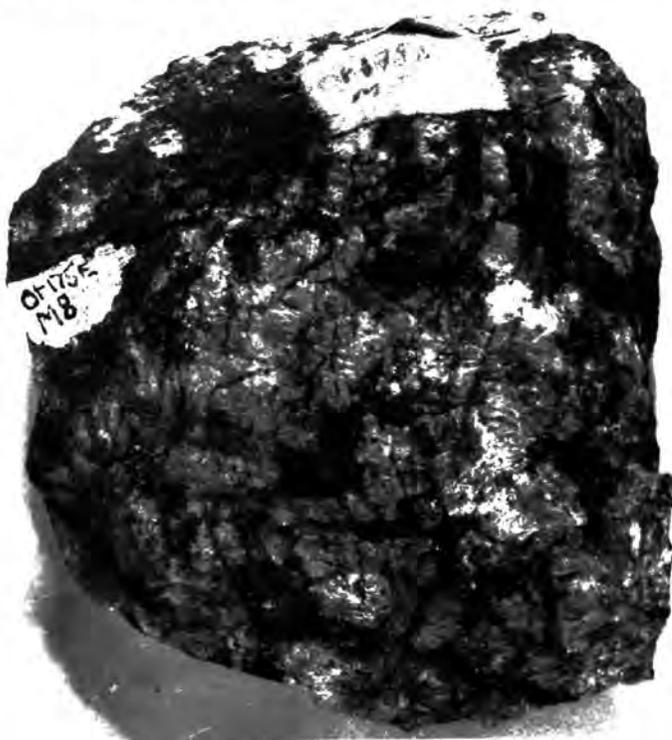
Plate IV Ot 10x 0.75.   Unfoliated hornblende-gabbro.   The texture
is probably similar to that of the original
gabbro Although not visible in the photograph,
the plagioclase on the right-hand side of the
specimen is creamy in colour, thoroughly
recrystallised and saussuritized.   The unaltered
phenocrystic labradorite, clear and glassy,
is set in a finer-grained hornblende matrix.
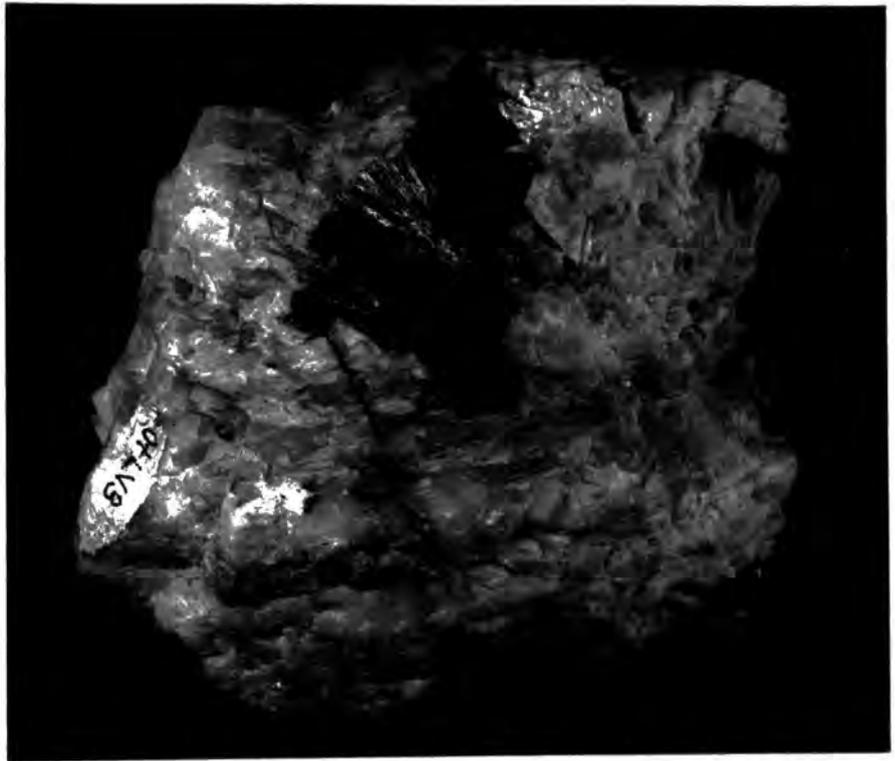
Plate IV Ot 11 x 0.6.   A late vein of white andesine containing
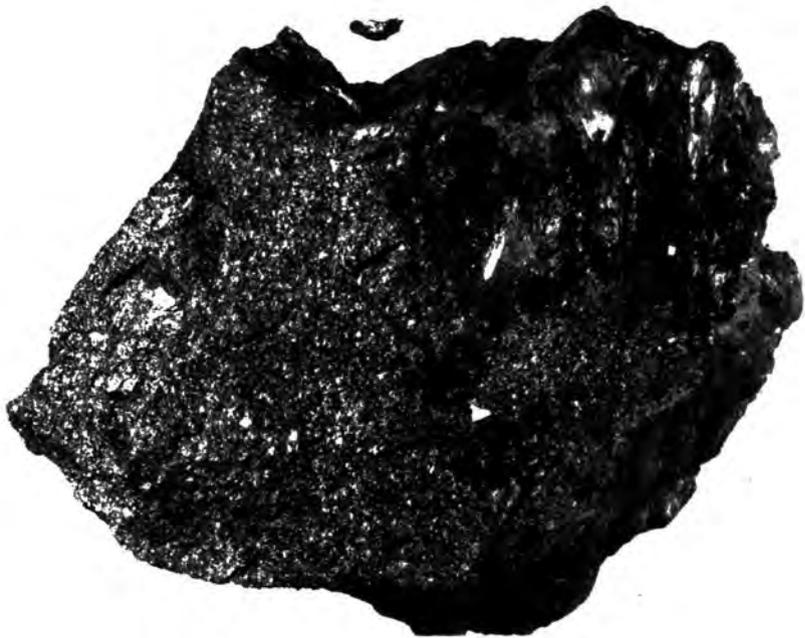   radiating bunches of green epidote crystals.

Plate IV Ot 12 x 0.6.   Massive ilmenite-magnetite ore on the left
                           of the photograph bordered by hornblende-
                           ilmenite pegmatite.

.except that in the normal amphibolite ilmenite is the only opaque mineral and it is always rimmed by sphene (Plate IV Ot 19 and IV Ot 20). As the opaque mineral content rises above about 15% magnetite makes its appearance while sphene gradually disappears and is usually absent from ore better than third grade (over 35% opaque minerals). Second and first grade orebodies are frequently margined by a complex mixed zone in which chlorite is prominent. It is often sheared and invaded by epidote (Plate IV Ot 25). ^{T}he following sequence (encountered in borehole 70, 125 metre level, at a depth of 40 metres) is typical. Plagioclase amphibolite passes gradually to hornblendite consisting of 98% hornblende, 0.5% green chlorite, 1% ilmenite and 0.5% sphene. This is margined by a crushed zone intruded by a vein. It is two millimetres thick and consists of 55.7% green chlorite, 18.5% epidote, 15.5% hornblende, 9.6% sphene and 0.7% ilmenite. By an increase in the hornblende content this passes to a zone containing 49.8% chlorite, 41.5% hornblende, 4.0% epidote 2.9% sphene and 1.8% ilmenite . This is followed by another area of shearing, two millimetres wide, of composition varying from approximately equal parts of epidote, sphene and green chlorite to a mixture of ilmenite, magnetite, pyrite, sphene and chlorite. It then loses its chlorite content. With the reappearance of horn-blende the ore reverts to hornblendite impregnated with opaque minerals, and finally passes to high grade ore with a decrease in the hornblende content.

The ore contact at 66.8 metres depth in the same borehole is. also illustrative. Plagioclase-amphibolite developes from metagabbro by increasing the hornblende ($\beta = 1.679$; $\gamma - \alpha = 0.015$)

content over a distance of three metres (Plate IV Ot 15). The plagioclase has been almost entirely replaced by saussurite, here an epidote, albite, illite (?) intergrowth. The rock consists of 68.9% hornblende, 22.1% epidote etc, 6.5% opaque minerals, 2.0% chlorite and 0.5% plagioclase. Four centimetres nearer to the ore the epidote content has increased and the rock consists of 43.5% epidote, 34.5% hornblende, 11.2% chlorite, 6.9% plagioclase and 3.9% opaque minerals. The hornblende in plain polarised light appears to be the same as in the amphibolite but has a lower birefringence (approx. .012) and slightly lower R.I. (β = 1.676 $\pm$ .002). The cause of the fall in birefringence is uncertain but may be due to incipient chlorite development in the grains. Against the ore the content of low birefringent hornblende rises to 60.6% with 23.8% epidote etc, 8.1% plagioclase, 4.2% opaque minerals and 3.3% chlorite. The hornblende and the interstitial secondary alteration products are filled with opaque dust. The margin of the orebody contains 64.5% opaque minerals, 28.6% hornblende, 3.6% epidote 3.3% chlorite and a trace of biotite. The ore has a schistose habit due to the orientation of the hornblende crystals, but the opaque minerals, of which some 5% are sulphides, do not reflect this schistosity but have a thoroughly granulated habit. The genetic significance of this texture is discussed later.

The relationshp between the orebodies and included anorthosite blocks has already been briefly mentioned. In such instances the anorthosite always has a discoloured saussuritized rim against a thin selvage of chlorite which divides it from the ore.

Against metagabbro anorthosite contacts may be sharp or transitional, Whichever is the case the plagioclase of the

Plate IV Ot 13 x 100   Evenly granular rather coarse ilmenite-
                              magnetite ore from the centre of an orebody.
                              The illumination intensity of the grains is
                              variable on account of the anisotropy of
                              ilmenite.

Plate IV Ot 14 x 100   A large poikilitic grain of magnetite enclosing
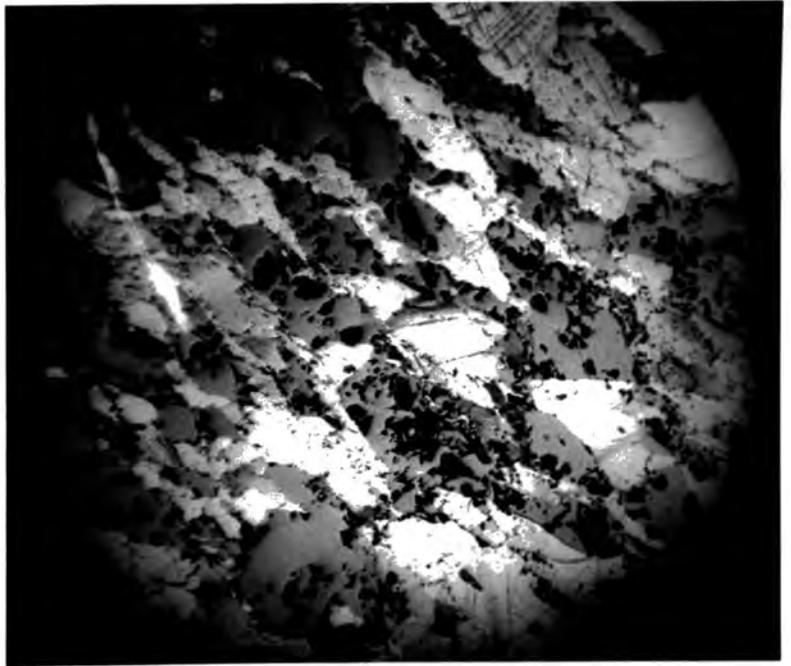   small grains of ilmenite (various greys) in
                              poor ore near the edge of an orebody.

Plate IV Ot 15 x 50   Light grey and white ilmenite and magnetite in
amphibolite (hornblende is a darker grey).
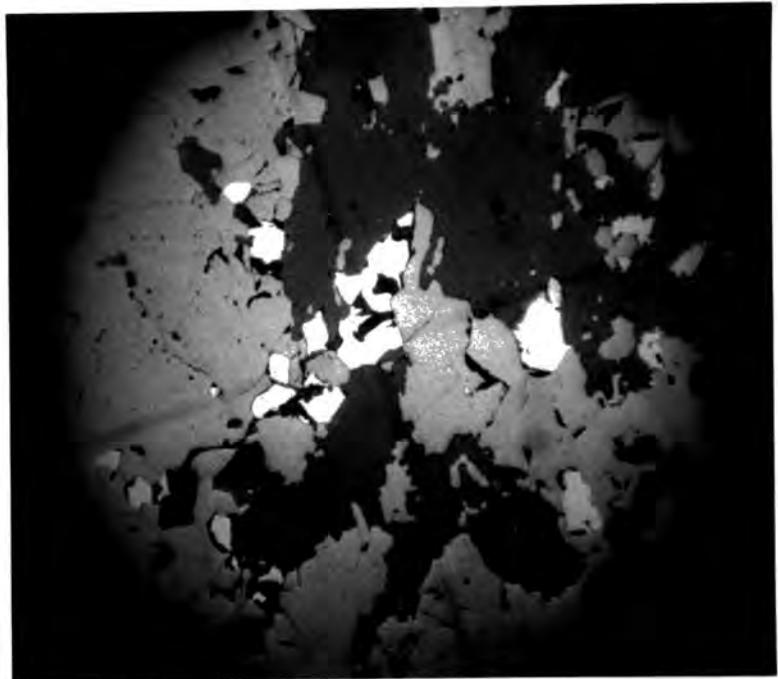This is typical of low grade schistose
amphibolite ore.

Plate IV Ot 16 x 50   Ragged ore in amphibolite at orebody margin.
pyrrhotite-white.

anorthosite always developes a tendency to recrystallise to a more sodic variety when intermixed with hornblende. When out of contact with hornblende it shows only incipient cloudy saussuritization. Any ilmenite which is present is converted to sphene.

<u>The Petrography of the Amphibolite.-</u> The typical amphibolite of Otanmaki is a medium-grained dark, strongly schistose rock. It is figured in plates IV Ot 7, 18, 22. An average modal composition is given below. The average grain size of the hornblende ($\beta = 1.679 \pm 0.001$; $\gamma - \alpha = 0.015 \pm 0.002$) is 0.5 x 0.3 mm. The plagioclase, an andesine of composition $Ab_{61}An_{39}$ ($\alpha = 1.546 \pm 0.002$; $2v = 65-70^{o}$), has a granular habit with grains of average size 0.4 x 0.3 mm. A textural peculiarity of the rock is the manner in which andesine-rich areas are separated from hornblende-rich areas imparting in thin section an inhomogenous character to the rock. The inhomogeneity is probably attributable to the original texture of the rock which may have been porphyritic, with large phenocrysts of feldspar set in a mafic ground-mass. The feldspar is unusual in that it shows reversed zoning-albitic cores surrounded by more anorthitic rims.

Paakonen (1956) gives the following chemical and modal analysis of amphibolite from a drill core.

Modal Composition
Paakonen   Writer

	%		Paakonen %		Writer %
SiO_2	43.11	Plagioclase(An_{45})	31.5	(An_{39})	27.5
TiO_2	6.00	Hornblende	56.4		59.7
Al_2O_3	15.48	Epidote	0.1		--
Fe_2O_3	4.13	Ore	7.5		4.3
FeO	11.30	Sphene	4.4		8.5
MnO	0.16	Apatite	0.1		tr.
MgO	5.38				
CaO	10.92				
NaO	2.38				
K_2O	0.52				
P_2O_5	0.04				
H_2O+	0.62				
H_2O-	0.05				

The obscure inhomogeneity of the 'typical' plagioclase-amphibolte becomes very apparent with an increase in the feldspar content, culminating in a rudely schistose rock consisting of patches of plagioclase and hornblende up to ten centimetres across (see plate IV Ot 8). In rocks of this type the small scale texture also varies. The feldspathic patches are made up of large crystals (up to 2 cm long) of An_{51} composition surrounded by areas of granulated feldspar of 0.4 x 0.3 mm grain size. The hornblendic parts consist of 0.3 x 0.2 mm grain of hornblende with interstitial epidotised plagioclase but developing from, and poikilitically enclosing both minerals are large optically continuous plates of yellow-green to green hornblende. Apatite is accessoric.

Petrography of the Metagabbro.- Texturally the gabbro is as variable as the amphibolite. It may be banded, (Plate IV Ot 9) be irregularly patchy with ragged areas of amphibole, or have a magmatic texture (plate IV Ot 10). In the latter case the rock consists of phenocrysts of feldspar set in a finely-granular matrix of hornblende (Plate IV Ot 17). The phenocrysts are sodic labradorite An_{52}

(α = 1.5549); the hornblende is the common Otanmaki type showing a pleochroism straw yellow-green-blue green. In a single instance gabbro with a mineral composition closer to the original unmetamorphosed rock was encountered. In drill core 70 on the 125 metre level at a depth of 65 metres near a low grade ore impregnation, the composition of the rock is:-

	%
Plagioclase	29.9%
Epidote and Other plagioclase alteration products	43.1%
Enstalite-hypersthene	11.7%
Biotite and chlorite	10.6%
Hornblende	3.8%
Opaque minerals	0.9%
Garnet	Tr. -

The plagioclase is sub- to euhedral, typical magmatic with abundant twin lamellae, An_{51} composition. The orthopyroxene has a weak yellowish pleochroism, a very wide angle of 2v with consequent uncertainty regarding the optic sign. The garnet, colourless and weakly birefringent with relief little higher than the pyroxene, is probably grossularitic. A rock with this composition must originally have been a leuconorite.

Metagabbro and meta-leucogabbro are not infrequently impregnated with opaque minerals. The opaque minerals always bear a corrosive, replacive relationship to the labradorite phenocrysts but appear to be contemporaneously crystallised with the newer more sodic feldspar and hornblende. The following modal composition is of a rock of this type. The abundance of biotite, at the expense of chlorite, is rather abnormal. (Plate IV Ot 23 and 24).
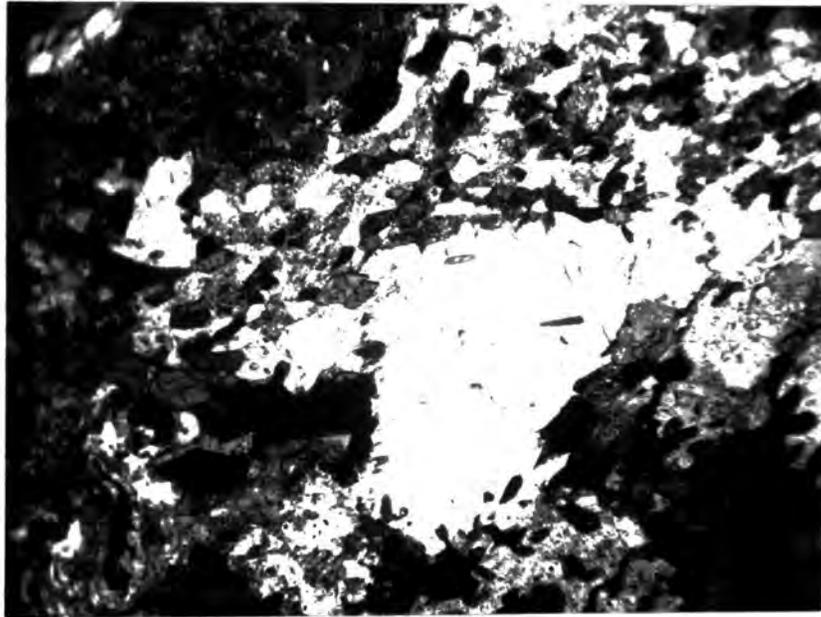
Plate IV Ot 17 x 25   Labradorite phenocryst being resorbed into amphibolite
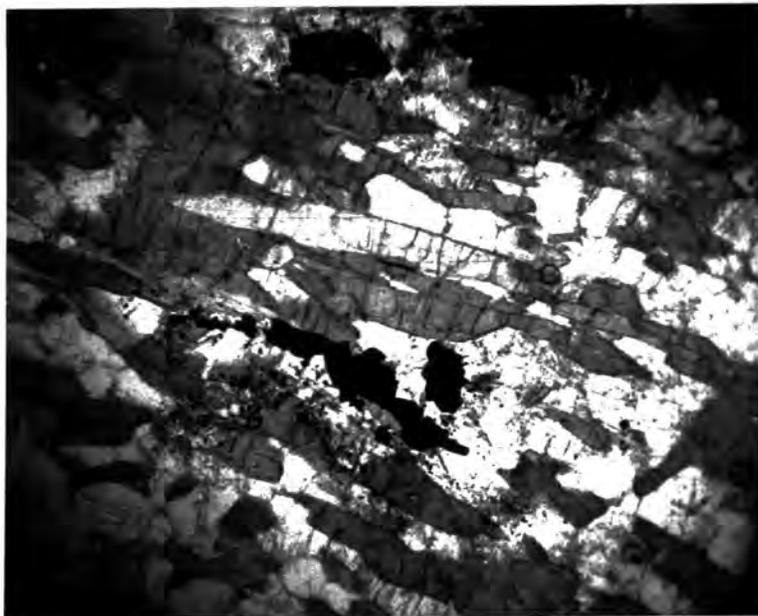consisting of hornblende, andesine and epidote.

Plate IV Ot 18 x 30   Schistose gabbroic amphibolite a common rock-
type at Otanmaki.   A thin section photograph of
a rock similar to, but more feldspathic than,
that illustrated in plate IV Ot 7.   Feldspar is
white;   hornblende-shades of grey;   ore minerals-
black;   and a little relict pyroxene with higher
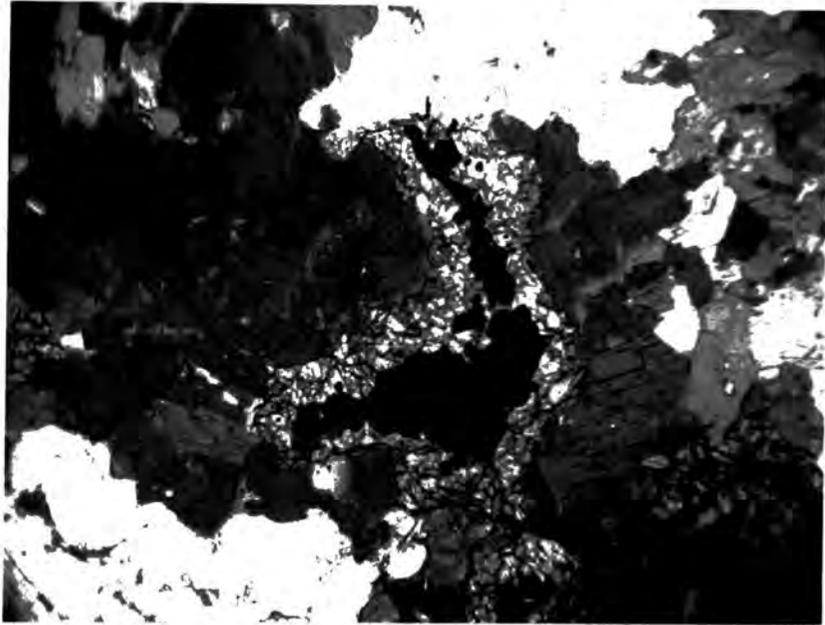relief near the opaque grains.

Plate IV Ot 19 x 35   Sphene coronas around ilmenite (black). These
are typical of the disseminated ilmenite in
amphibolite and have developed in response to
metamorphism at amphibolite grade. In this
illustration local shearing has reduced the grade
further, allowing chlorite to develop. Hornblende-
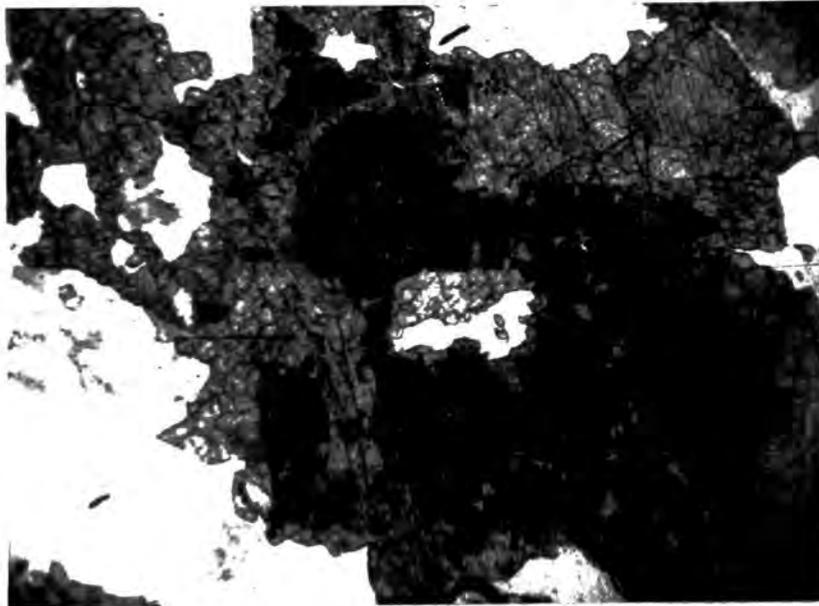shades of medium grey; oligoclase-white;
chlorite-dark grey.

Plate IV Ot 20 x 40   Sphene coronas around ilmenite in a cataclastic
zone at the margin of an orebody. The
titaniferous minerals lie in a matrix of
thoroughly saussuritized plagioclase and calcite
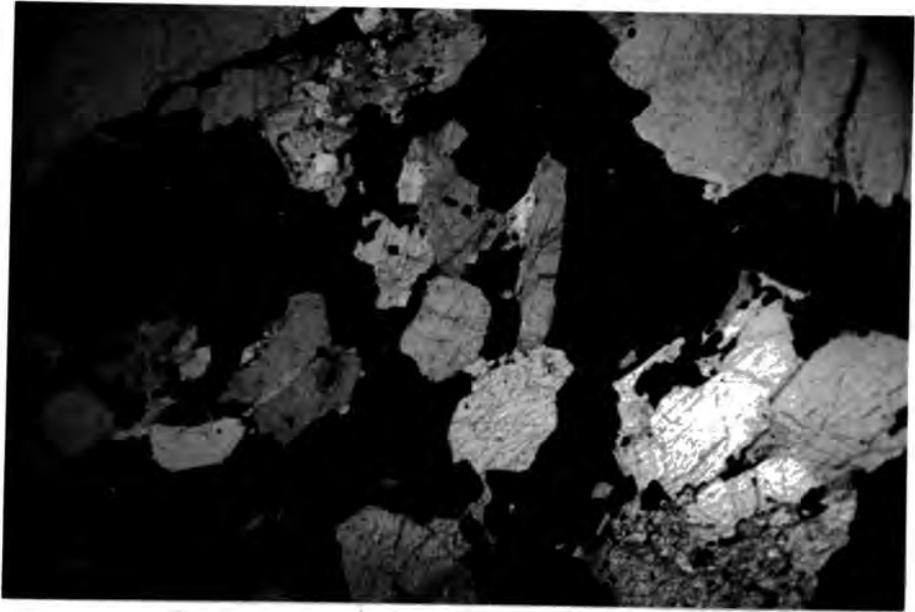(both white).

Plate IV Ot 21 x 35   Thin section photograph of non-schistose medium
grade ore from the edge of an orebody, showing
the sub-poikilitic form of the ore minerals.
Contrast this with the polished section in plate
IV Ot 15.   Ilmenite magnetite-black;   hornblende-
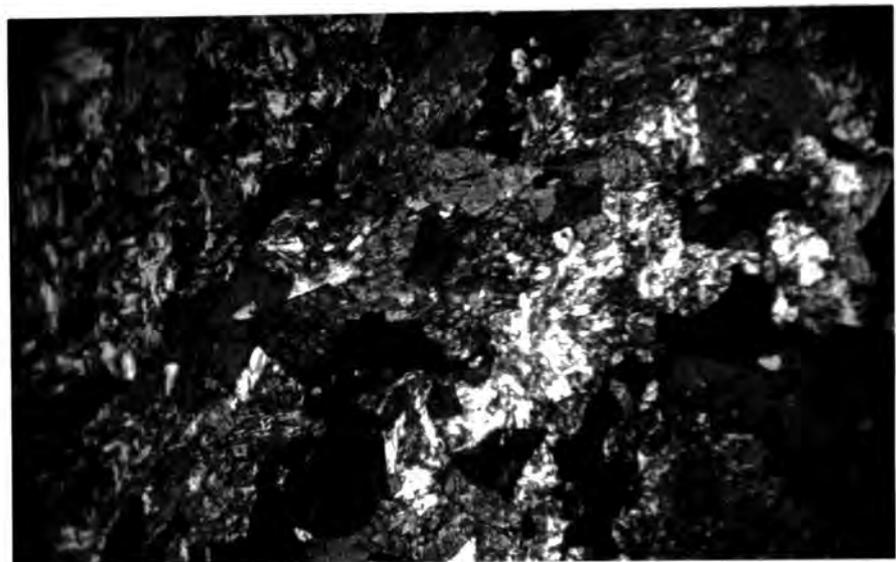shades of grey;   epidote-mottled darker grey.

Plate IV Ot 22 x 35   Feldspathic amphibolite. Hornblende (grey, medium
relief) and ilmenite (black) lie in a matrix of
cloudy saussurite.
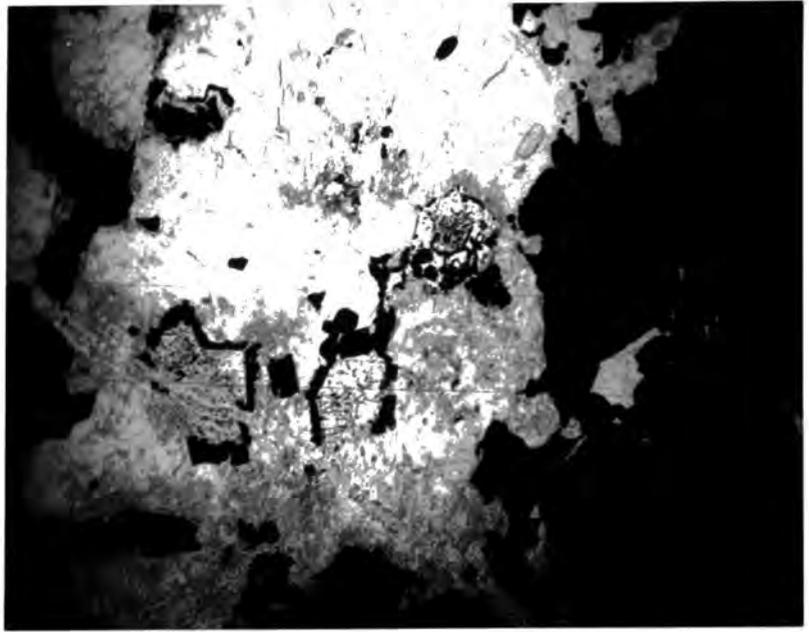
Plate IV Ot 23 x 35   Ilmenite-magnetite ore invading anorthosite.
                         Unaltered plagioclase is a clear white,
                         saussuritized feldspar is cloudy grey shade.   The
                         three crystals rimmed and invested by opaque
                         minerals (late pyrite pyrrhotite and magnetite)
                         are relict pyroxenes.   The narrow vein, which is
                         the focal point of the saussuritization consists
                         of chlorite.
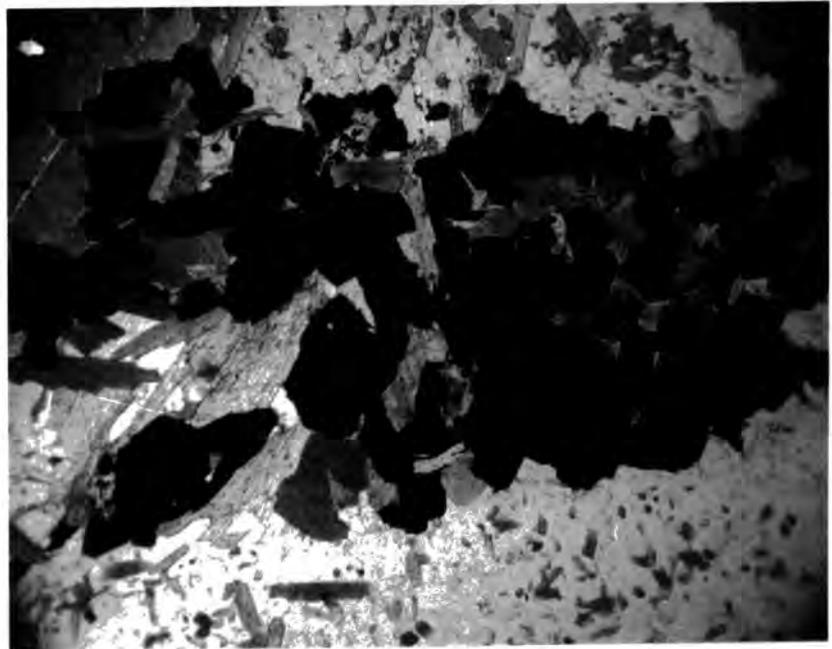

Plate IV Ot 24 x 35   A group of ilmenite and magnetite grains and
                         biotite in an intimate mixture which is separate
                         from almost homogenous areas of partly
                         saussuritized anorthosite on each side.   Biotite
                         is abundant here at the expense of chlorite.

	%
Labradorite (An_{51})	30.7%
Andesine (An_{40} approx.)	33.5%
Opaque minerals	19.0%
Biotite	9.4%
Hornblende	5.5%
Chlorite	0.4%
Relict pyroxene (?) with opaque inclusions	0.5%

Petrography of the Anorthosite.- Anorthosite in the Otanmaki mine is
a very variable rock.   In its original condition it ···· probably
consisted largely of labradorite feldspar with accessory hypersthene,
ilmenite and garnet.   Most anorthositic rocks from Otanmaki are in a
more or less advanced stage of saussuritization or recrystallisation,
depending on whether shearing and granulation alone or 'wet'
metamorphism and metasomatism associated with late veining and
shearing, have been the dominant metamorphising factors.   In
specimens in which the original 'magmatic' texture has been preserved
sufficiently for determinations of the feldspar to be made, the
largest phenocrysts have rarely proved to be as basic as An_{71}.   The
smaller phenocrysts which grade into the matrix of grains vary from
An_{49-60}, but more than 80% of the specimens have a composition
between An_{49} and An_{52}.

On recrystallization, in pure anorthosite the composition varies
little, the anorthite molecule content perhaps falling to An_{46}.
In the presence of hornblende the feldspar is invariably more sodic than
this, usually An_{35-40}, and there is usually at least a little
epidote present.   Recrystallization of leuconorite or leucogabbro
in amphibolite facies would seem to take place according to the
following general equation:-

Hypersthene + Labradorite = Hornblende + Andesine

If any slight pneumatolysis should occur the andesine is replaced by epidote and albite, clay mineral or sericitic mica.

Petrography of the Orebodies: Rock which can strictly be classed as ore varies in composition from an ilmenite-magnetite amphibolite to a hornblende-bearing ilmenite-magnetite ore.   There is no sharp distinction between the varieties, one is gradational to the other.   Structurally and texturally the ore is also variable.   It may be granular (Plate IV Ot 13) consisting of equant crystals of ilmenite and magnetite, a type normally restricted to the centre of ore lenses: schistose (Plate IV Ot 15) again consisting of separate crystals of ilmenite and magnetite or more rarely may be comprised, in part, of poikilitic magnetite enclosing crystals of ilmenite (Plate IV Ot 14).

Originally the ore lenses seem to have consisted almost entirely of equigranular ore and the variations from this texture seem to be due to the post-intrusion metamorphism of the orezone.   It seems fairly certain that the original ore was much coarser-grained than that which now exists.   The manner in which ilmenite and magnetite grains are found in groups throughout rich ore suggests that they represent coarser crystals recrystallized in smaller units. Equigranular and weakly schistose ore generally occurs only in the central parts of ore lenses which must have acted as rigid cores during the period (or periods (?)) of amphibolite facies dynamic metamorphism to which the rocks have been submitted.

Ilmenite in this type of ore is a pale pink-beige colour in polished specimen.   It always contains abundant lamellae of

magnetite along 0001 directions (Plate IV Ot 27) and these
are separated by ilmenite crowded with very small exsolution discs
of hematite about 0.0005 to 0.001 m.m. long.   Between the magnetite
and hematite exsolution bodies there is always a zone of ilmenite,
about five times as wide as the adjacent magnetite lamellae, which
is free from any exsolution structures.   From the appearance of
this structure it appears that the original hemato-ilmenite has
suffered a reduction metamorphism, presumably in conjunction with the
amphibolitization of the original gabbro, with the result that
magnetite has commenced to develop at the expense of hematite.

Magnetite in the same oretype contains only sparse exsolution
structures and irregular inclusions.   There are normal spinel
rods exsolved along the 100 direction and rarer ilmenite lamellae
usually of rather coarse dimensions, along the 111 cleavage direction.
Irregularly shaped ilmenite inclusions are also not uncommon.   They
are probably homogenised groups of ilmenite lamellae.

Sulphides are sparsely represented in rich, evenly crystallised
ore - they always tend to be concentrated at the margins of ore
lenses.   Pyrite is the only common sulphide, and it may contain small
irregular inclusions of chalcopyrite.   Very rarely isolated
crystals of pyrrhotite are present.

A few of the ore lenses at Otanmaki show a poorly developed
banded structure, which seems to be caused by a regular variation
in silicate mineral content.   The effects of the later
metamorphism has obscured the relationships of the bands to such an
extent that it is not possible to be sure of their mode of origin.

Orebody margins are extremely variable in their composition
and internal mineral structures and textures, and in their relationships
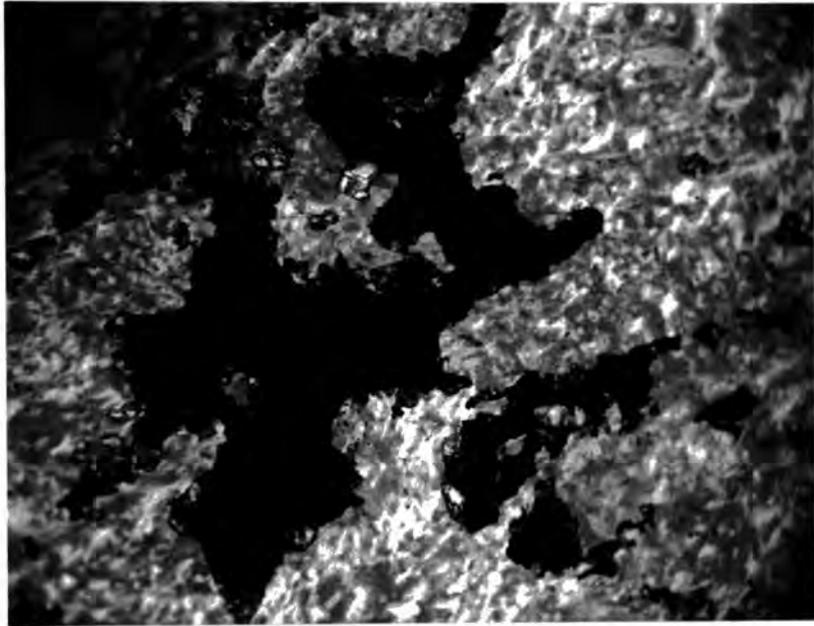to the surrounding silicate-rich rocks.   Certain of the orebody

Plate IV Ot 25 x 35   Sheared ore set in a matrix of chlorite (pennine) at the margin of a low grade orebody. The small grains with a high relief are sphene.
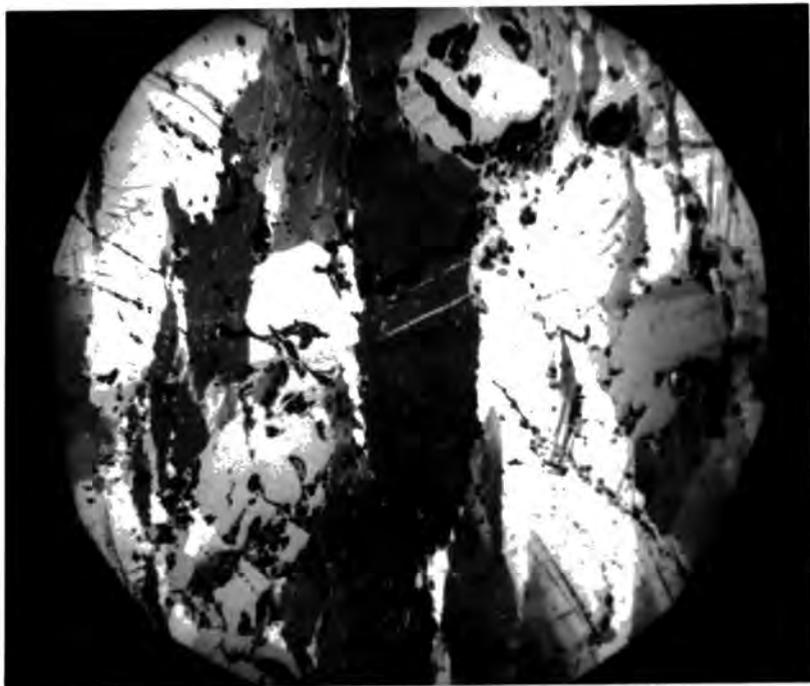

Plate I^V 26 (Nicols at 85°) x 100   Polished section photograph of schistose ore. The present schistosity has been superimposed on an earlier schistosity, traces of which are preserved by the exsolution bodies in the ilmenite. The dark grey central grain, set almost to extinction typical of most in the section, contains fine exsolution bodies of magnetite oriented at about 20° from the direction of the schistosity.
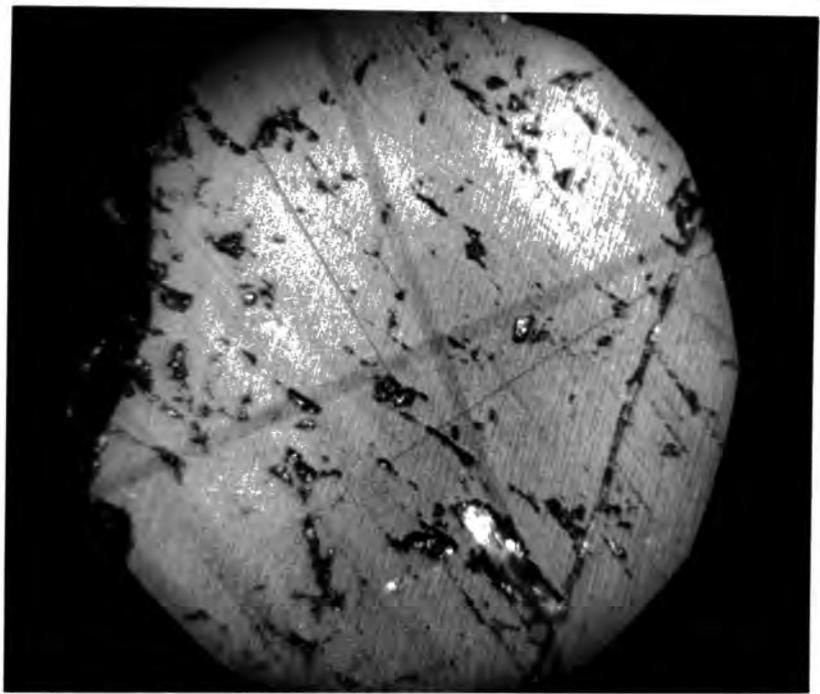
Plate IV Ot 27 x 200xn   An ilmenite grain showing thin exsolution lamellae of magnetite (darker grey) arranged parallel to the basal plane.
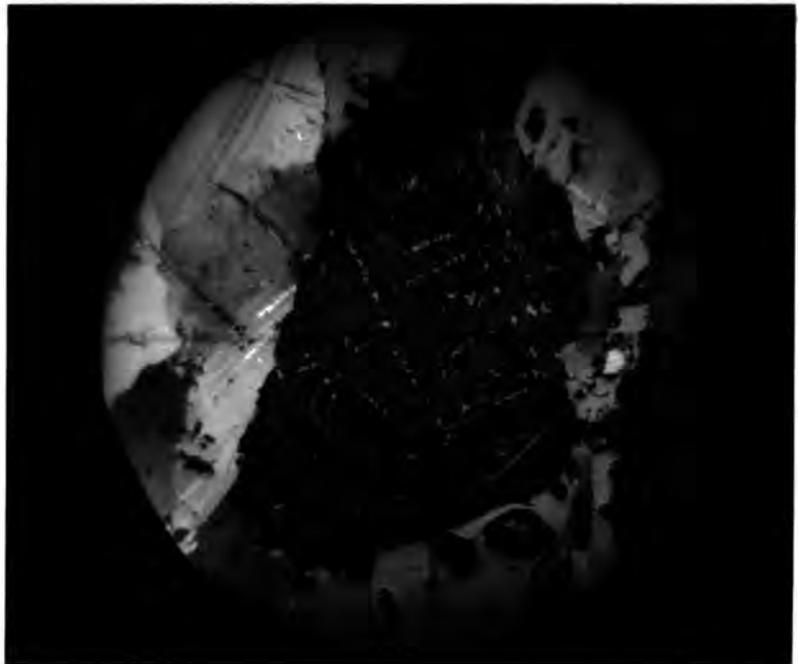
Plate IV Ot 28 x 200xn   Ilmenite (very dark grey) containing exsolved magnetite. The bright white dots arranged in a rudely rectangular pattern are magnetite, the position of which are controlled by the rhombohedral twin planes in the ilmenite. The light grey smaller elongated bodies are also magnetite parallelling the basal plane of the host. Their arrangement in lines roughly at right angles to their length is probably controlled by zones of disturbance in the ilmenite.

Plate IV Ot 29 x 100 (Nicols at 85°)   Polished section of intensely
twinned ilmenite typical of the marginal
areas of the orebodies where stress during
amphibolite facies metamorphism has had most
effect on the ore.

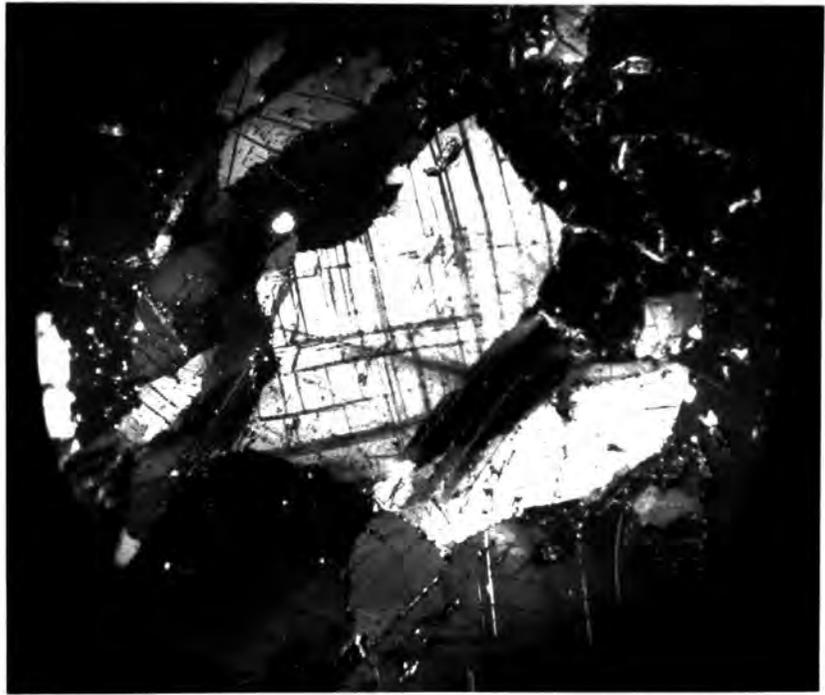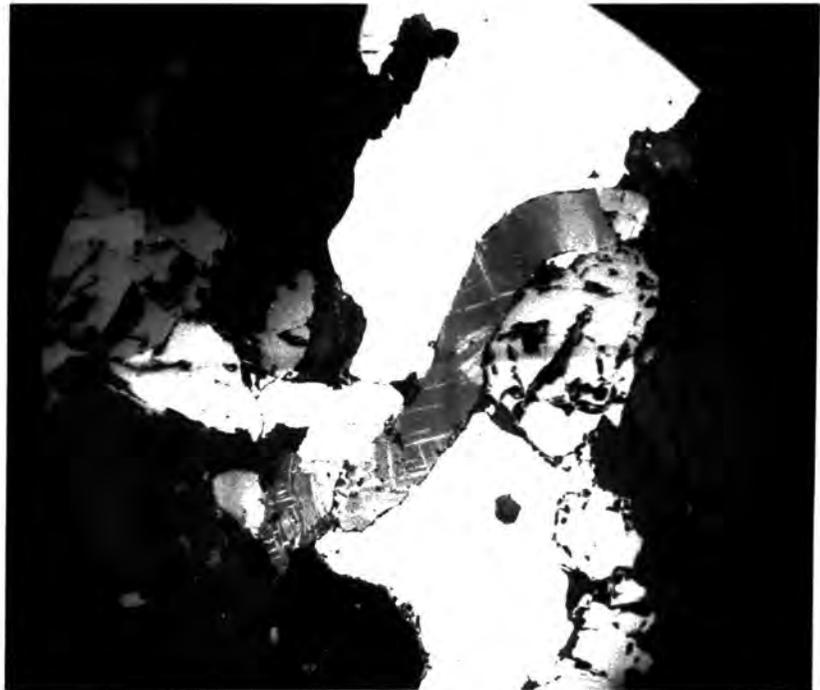Plate IV Ot 30 x 50   (Nicols at 76°)   A late pyrite veinlet (white) which
has bent a long crystal of ilmenite.   The
medium grey untwinned grains are magnetite.

contact phenomena have been considered in the section above which

describes the relationships of the various rock types of the area and

the intention here is to concentrate on the structures within

the ore minerals and the implications of the general relationships.

Ilmenite-magnetite ore at Otanmaki wherever found, except

at the centre of the thickest ore lenses shows many abnormal features

for ores of this type most of which can probably be attributed to

the effects of repeated metamorphism since its original crystallization.

The relative content of ilmenite and magnetite in the ore is

variable within the limits 70:30 with either mineral present in

preponderant amount, but the ratio is more commonly about 60:40

with magnetite predominant.   A cataclastic texture is very common;

the ore minerals are often present in ragged grains and

crystalline bunches which have apparently been torn apart violently

allowing silicate minerals (usually hornblende, or chlorite) to fill

the intervening space.   Where this cataclysm has been very intense

complete recrystallisation, and sometimes mobilization, of the magnetite

and ilmenite has occurred.   A variety of sulphide minerals has been

introduced at the same time.   These are clearly of a later

generation (Plates IV Ot 30 and 31) than the rare disseminated pyrite

which is present in the equigranular ore because they never show the

effects of dynamic metamorphism.

Both magnetite and ilmenite when they have been remobilized lose

most of the exsolution bodies which they originally contained.

Ilmenite seems to lose them rather more completely than magnetite

but this is probably aided by the fact that at Otanmaki reduction

has accompanied cataclasis so that included hematite has been

altered to magnetite which is less soluble in ilmenite, and

which tends to completely exsolve from it more readily.
Magnetite loses coarse spinel and most of the ilmenite lamellae,
but retains the smaller spinel rods.

Recrystallization, and deformation without recrystallization
produce a number of unusual structures in both ilmenite and magnetite:
structures which disappear as the minerals remobilise completely.
Magnetite contains spinel and ilmenite lamellae. Spinel
apparently exsolved first because the lamellae are cut by ilmenite
lamellae. The ilmenite cannot have exsolved directly at right
angles from the adjacent portions of the magnetite but must have
moved along the 111 cleavages from a nucleus of exsolution,
because at the points of intersection with the spinel lamellae
there is no alteration in the thickness of the ilmenite lamellae.
During the course of the metamorphism the ilmenite of some of the
lamellae in the magnetite has migrated to form irregularly shaped
blobs. This has caused local disturbance of the magnetite
lattice with the result that spinel lamellae within it have
become dislocated and terminate against the ilmenite as a rounded
blob. A feature of the spinel lamellae is their discontinuous
nature; they appear as a dashed line, without taper at the end of
each dash, so that these cannot each be regarded as individual
exsolution bodies. The writer suggests that the reason for
the structure may be that the gaps were originally occupied by
ilmenite lamellae which have since migrated to form the irregular
blobs. Magnetite crystals often contain considerable quantities of
silicate inclusions without regular shape or pattern. These are
rarely seen in ilmenite. Magnetite usually appears to be later
in the crystallization sequence than ilmenite, around which it

may be moulded.

Ilmenite, except in the centre of ore lenses or in crystals
which have reformed after mobilization, is always intensely twinned
(Plate IV Ot 29). This has had marked effects on the exsolution
lamellae in the crystals. Magnetite lamellae are normally long
and thin oriented in the 0001 plane of the ilmenite host (Plate
IV Ot 27), but the disordering of the ilmenite lattice in the stress
of dynamic metamorphism has apparently allowed the magnetite to
reorientate itself to a marked degree (Plate IV Ot 28). When
twin planes in the ilmenite cut across magnetite exsolution lamellae
the results are not always similar. The magnetite may thicken
to rounded blodies in the twin lamellae continuing unaltered on the
far side; they may stop short of the lamellae, usually thickening
slightly as well; or lamellae of magnetite may completely
disappear reforming as irregular rounded bodies within, or parallel with,
the twin lamellae. The small hematite discs are always absent in
close proximity to both magnetite lamellae and twin lamellae.

The ilmenite at Otanmaki is usually grey in reflected light
in contrast with ilmenite from the ores of south-west Norway which
are distinctly brown-grey. The ilmenite grains in amphibolite are
usually a more distinct grey than those in the ore which have a
slight brownish cast. The reflectivity of the ilmenite in the ore
(ordinary ray) as measured with a Cooke, Troughton and Sims micro-
photometer is 18.33 in yellow light (λ = 581 m.microns using
an Ilford spectrum filter). This figure is probably slightly high
because of interference from very small hematite exsolution bodies
in the ilmenite .

An analysis of the ilmenite concentrate from the mine is given

on page eight of Volume II and, below, analyses of (1) ilmenite and
(2) magnetite from a specimen of rich ore are reproduced from
Vaasioki (1947).

	Fe_2O_3	FeO	TiO_2	MgO	V_2O_3	Cr_2O_3	MnO	Total
1.	10.85	36.92	48.10	3.48	0.18	tr.	0.24	.99.71
2.	62.09	33.14	2.50	1.08	0.68	0.20	0.03	99.72

The vanadium and chromium ions are concentrated in the magnetite and
the magnesium and manganese in the ilmenite as is normal in this
type of ore.

The marginal relationships of the orebodies with the
surrounding rocks have been described under the heading of contact
phenomena.   It has been seen that the ores may grade
into amphibolite or they may have quite sharp contacts.   In both cases
it is a common phenomenon that evidence of saussuritization or other
low-grade hydrothermal action is seen at the contacts and the
significance of this fact deserves evaluation.   Within the Otanmaki
mine there are a number of veins - never more than a metre wide,
normally much less - of epidote, oligoclase or albite, sphene,
chlorite, pyrite, calcite, marcasite, ilmenite, pyrrhotite and other
sulphides.   These are usually quite discordant to the general
structure.   The veins, in general, fall into two groups 1) an
epidote, feldspar, sphene, chlorite group and 2) a sulphide
group which includes accessory ilmenite and sphene.   The mineralogy
of the first group is very similar to that of the 'hydrothermally'
altered marginal zones of the orebodies and very few of the minerals
in the second group are entirely absent from such zones (the exceptions
are discussed later).   It is suggested that the first group are
probably largely derived from the anorthosite-gabbro-amphibolite

country rocks by low-grade metamorphism in the presence

of hydroxyl ions, according to the following general equation:-

Labradorite + Ilmenite = Epidote (Estacite) + Sphene + Oligoclase-

Andesine.
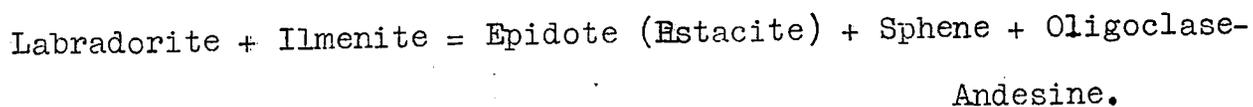
A typical vein consists of Epidote 82%, Sphene 17%, chlorite 1%.

Chlorite is not normally very abundant which is to be expected

since hornblende, from which it is probably derived is rather more

stable than feldspar or ilmenite under these conditions.

The question remains as to the stage in the history of the

deposit at which the marginal saussuritization occurred; whether

it accompanied or post dated the emplacement of the orebodies. On

the available evidence it appears that it very probably accompanied

shearing stress at a very much later stage than the primary ore-

depositing phase.   It is suggested that the close association of ore

and saussuritization in many places is due to the relative rigidity of

the ore lenses at a period when the whole amphibolite complex

was undergoing plastic deformation.   In such an environment shearing

would tend to occur at the margins of such rigid masses providing

channelways for migra ting solutions.   This period of stress

metamorphism was probably associated with the intrusion of the

red gneissose granite which may have been the source of the

aqueous solutions and the late iron sulphides, and rare copper

and nickel sulphides which are found in veins are/orebody near margins

(Plates IV Ot 30-36 and Appendix II).   Further evidence which favours

pre-amphibolitization emplacement of the ore is the smashed and

granulated nature of the marginal portions of the orebodies.   They

have so obviously been resistant to stress that it is difficult to
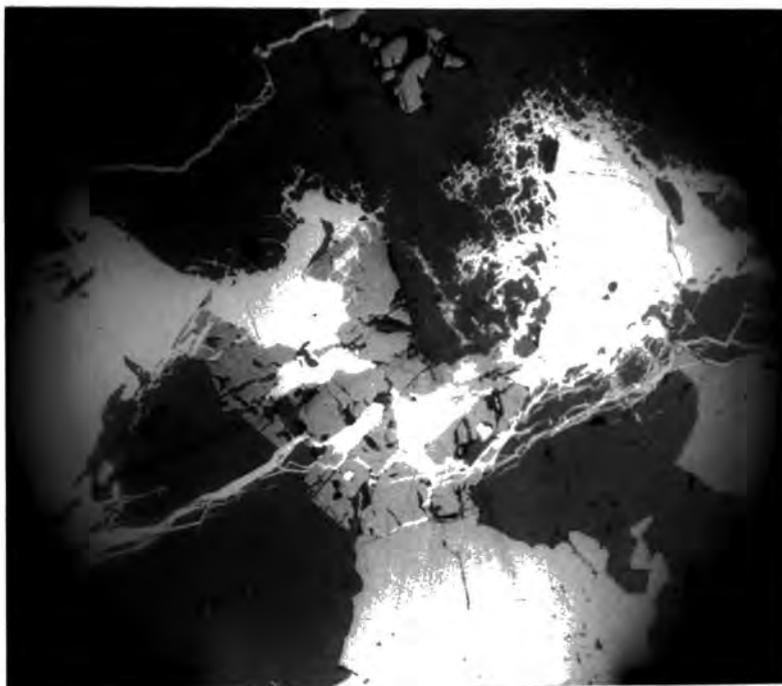
Plate IV Ot 31 x 50   Late pyrite (white) cutting and veining
                         ilmenite and magnetite (both light grey) and
                         silicates (dark grey).
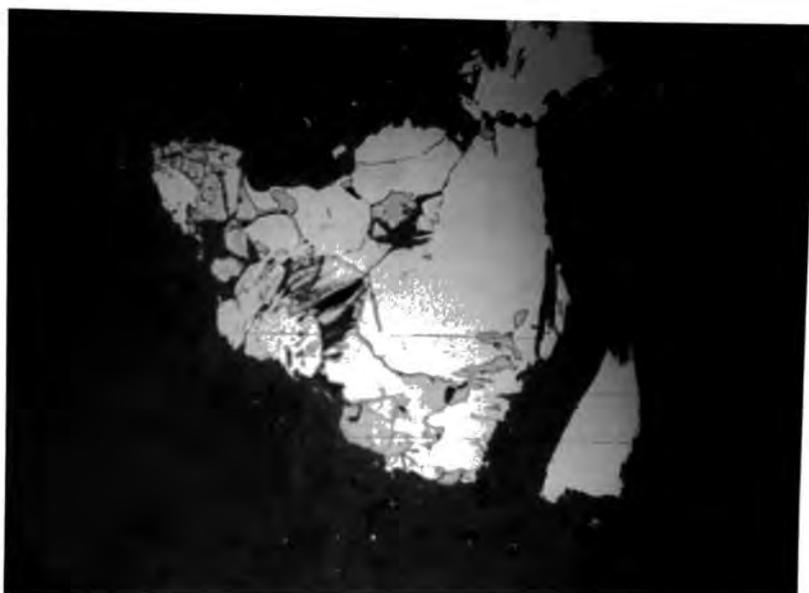
Plate IV Ot 32 x 100   A complex sulphide intergrowth.   Pyrite
                         (white) is host to chalcopyrite (grey) and
                         pyrrhotite (light grey, lower left centre of
                         photograph).
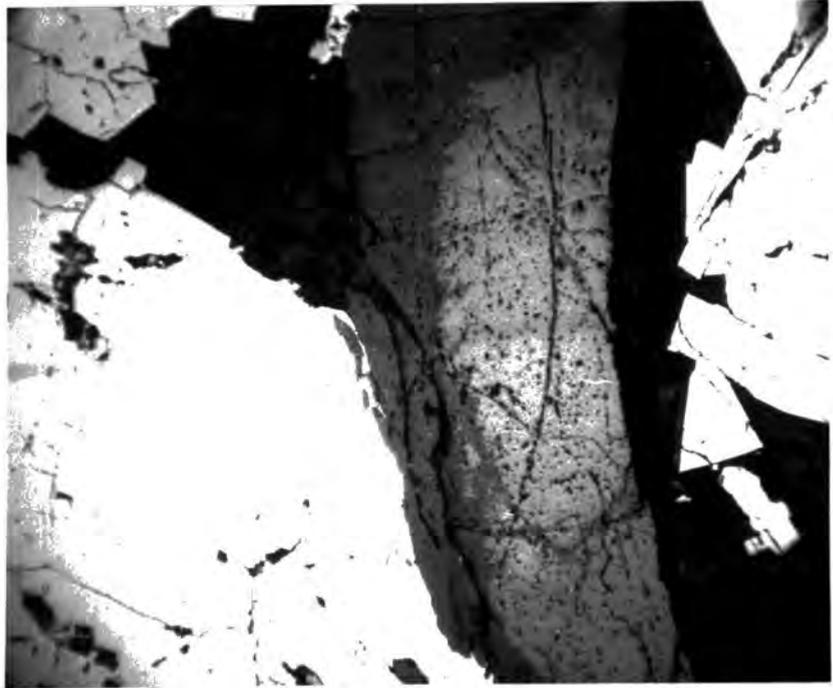
Plate IV Ot 33 x 50   A long narrow plate of ilmenite (section cut
approximately at right angles to the C-axis),
grey in colour, altering to sphene which is a
darker grey.   Pyrite is white.   A late vein
at Otanmaki.
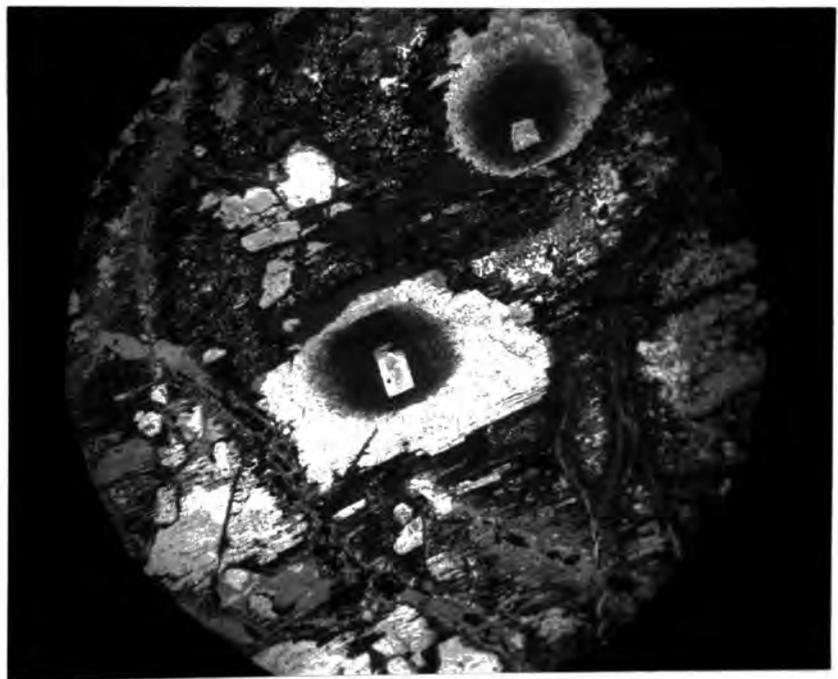
Plate IV Ot 34 x 50   Polished specimen, stained with nitric acid, of a
late sulphide vein.   The zoned crystals have a
core of pyrite surrounded by a pyrite-marcasite
intergrowth, which is in turn surrounded by pyrite.
The rest of the section is pyrite, marcasite and
silicate.
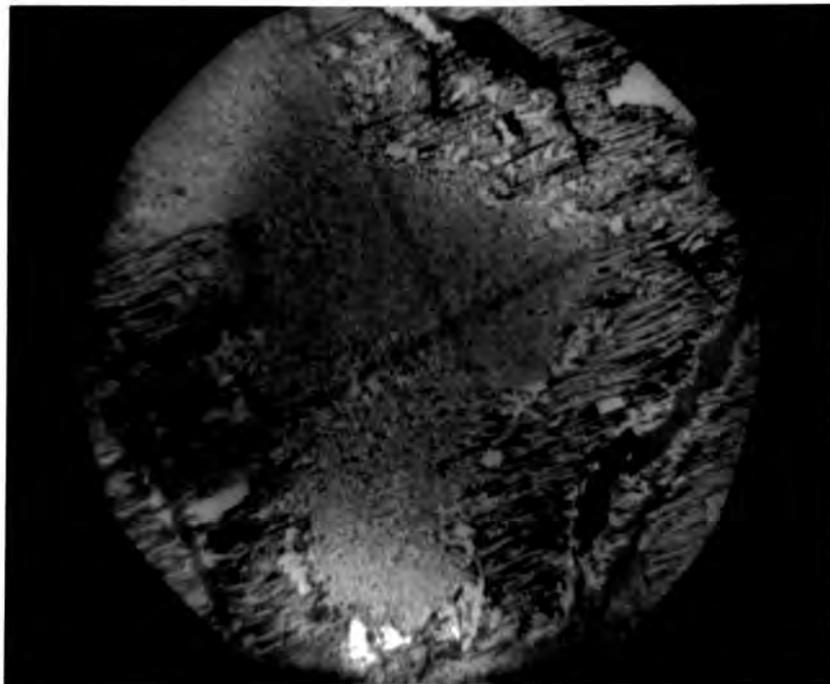
Plate IV Ot 35 x 200   Intergrowth of pyrite (light grey) and marcasite
(dark grey) on a cubic pattern, surrounded by
a pyrite replacement of silicate (streaky
appearance).   Late sulphide vein.
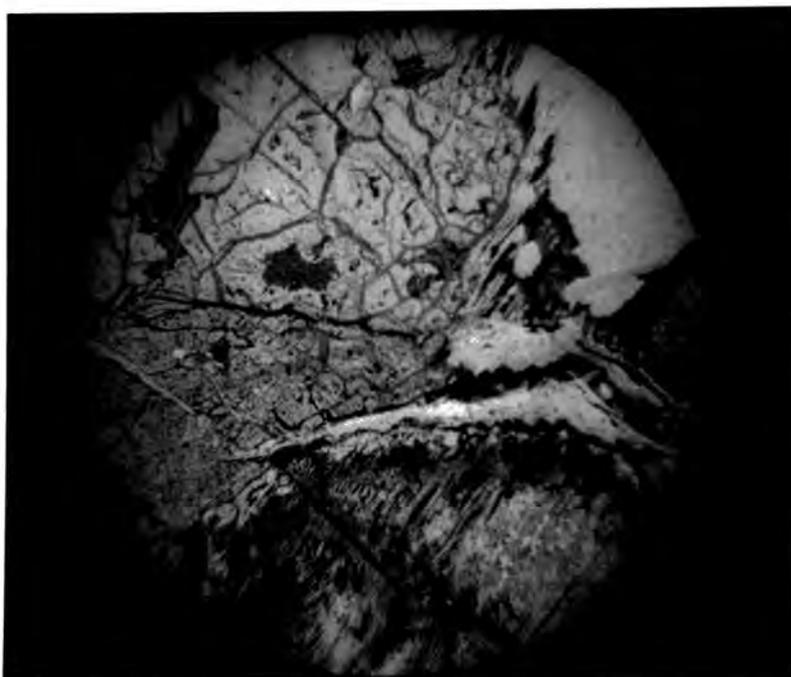
Plate IV Ot 36 x 80   Siegenite (light grey, upper centre) veined by
hematite (medium grey). Pyrite is a lighter
grey-white, mainly at upper right and a pyrite-
marcasite intergrowth occupies most of the
lower part of the photograph.   Late sulphide
vein.

conceive of them as being intruded during <u>at least the latest</u> period
of dynamic metamorphism. The writer wishes to emphasise that the
Otanmaki amphibolite has certainly passed through a complex
history. It is very likely that regional stress exerted during an
earlier orogenic phase maintained a strong structural control over
the present disposition of the orebodies but during the latest period
of stress metamorphism, probably less intense, the ores have behaved
as stable bodies.

<u>Conclusions</u>.- The ilmenite-magnetite orebodies at Otanmaki are
vertically dipping lensoid elipsoids enclosed by a complex of
amphibolite, metagabbro and anorthosite, which is itself surrounded
by granitic and granodioritic rocks. Remnant minerals in the
amphibolite complex indicate that the rocks were originally
leucogabbros or leuconorites and anorthosites where shattered belts
of anorthosite are recognisable in the amphibolite these can
be seen to dip approximately conformably with the orelenses.
Extreme heterogeneity is a marked feature of the amphibolitic rocks
surrounding the ore, and the striped character of most of these is
well developed but quite irregular.

The ore horizons are located on the limbs of a fold which closes
against the lineations in the amphibolite: this is interpreted
to signify structural control over the location of the ore. Paakonen
(1956) assumes a thorough mobilization of the amphibolitized gabbro,
with metasomatic migration of the ore minerals to their present
position; a process of venitization is assumed to have produced
the striped heterogeneity of the amphibolite giving rise to
anorthosite horizons. The present writer considers that the
abundance of magmatic plagioclase phenocrysts, the presence of
pyroxene relicts, and the paragenesis and relationships within and

on the margins of ore lenses is against such widespread meta-
somatic reconstitution and mobilization.   The evidence certainly
indicates orogenic control over the locus of emplacement of the
ores, but the writer would prefer to regard. this as having been
operative during a magmatic gabbroic stage or during a subsequent
stage in granulite facies conditions prior to amphibolitization.
The large-scale banded structure of the rocks is thought to be a
remnant of magmatic differentiation which has <u>survived</u> recrystallization
in the amphibolite facies, not a structure produced by it.

Late stage veining and shearing, involving the introduction of
sulphide minerals, including minute quantities of exotic nickel
sulphides, CO_2 and water are probably to be directly attributed to
the granite in contact with the amphibolite to the north.   It is
possible that the whole process of amphibolite facies recrystallization
was part of a series of events which culminated with the emplacement
of the granite.   The recrystallization at a lower temperature has
been of the utmost economic importance because it has allowed
the separation from each other of ilmenite and magnetite, which
in the original gabbro must certainly have been closely
intergrown with each other.

CHAPTER V

SECONDARY TITANIUM ORE DEPOSITS

Most of the world's production of rutile and a smaller proportion
of the ilmenite production has come from beach sand heavy mineral
deposits. In the future the titanium metal industry, and to a lesser
extent also the titanium dioxide pigment manufacturers, will come to
rely more and more on deposits of this type for two reasons. They
provide easily mineable ore which requires no crushing. The ilmenite
obtained from such deposits is often 'supergrade', i.e. it contains
more than the theoretical content of TiO_2, and is, on account of this,
a more desirable raw material for certain pigment processes than the
unaltered hard rock ilmenites with lower TiO_2 contents. The ilmenite
found in some alluvial deposits is also enriched in TiO_2 but deposits
of this type are frequently of too limited extent to be important
as ore reserves. The Malayan deposits are of course exceptional.

In the past the bulk of the heavy mineral concentrates have been
mined from present-day beaches where diurnal processes renew the
mineral deposits. In recent years, with the increasing demand for
titanium minerals, more attention has been paid to fossil beach and
bar deposits, covered by dunes, which frequently occur on the landward
side of the present-day beaches. These deposits have the disadvantage
that they occur beneath an overburden which in large dunes may be as
much as two hundred feet, but they are not alternately dry and water-
logged like the present beach deposits which are affected by daily tidal
fluctuations.

This chapter is divided into two sections. In section one the
large beach sand heavy mineral accumulations of the world are

described as far as published information will permit, and geologically
and economically important conclusions concerning them are discussed
at the end. The deposits of the east Australian seabord are discussed
in some detail: the remainder more briefly to enable general comparisons
to be drawn. Alluvial deposits are not described in detail owing
to the paucity of information available and the simple character of
such deposits. In section two the mineralogy of the iron-titanium oxide
minerals in secondary deposits, with special reference to ilmenite,
is discussed.

SECTION I

BEACH SAND DEPOSITS

The Beach Sand Heavy Mineral Deposits of the East Australian Seaboard

Workable deposits of zircon, rutile, ilmenite and monazite have
been found along the east coast of Australia between Swansea (New
South Wales), south of the Hunter River and Frazer Island (Queensland),
a distance of about 600 miles. Small accumulations of heavy minerals
of little economic importance have been found both to the north and
south of this stretch of coast. The largest and richest deposits
occur in the 100 mile section of the coast between Tallow Beach,
south of Byron Bay, and the northern end of Stradbroke Island.

There are three main physiographic types of coast developed in
this region:- (a) Rocky shorelines with short beaches between head-
lands. (b i) Low lying coastal plains fringing the consolidated
rocks of the mainland: these are particularly extensive near river
mouths. (b ii) Lagoons and coastal lakes which are locally developed
in place of the coastal plain. (c) A shoreline fringed by extensive
sandy islands; this type is particularly common to the north of
Southport.   All the main areas of sand lie to the north of

the mouths of large rivers. (Gardner 1955).

The Geological Background and its Effects on the Distribution and Heavy Mineral Content of the Beach Sands.-

The country, drained by eastward-flowing streams, which contributes sediment to the coast is underlain by sedimentary and igneous rocks of the Palaeozoic Tasman geosyncline and marginal, Mesozoic, freshwater basins.

The general distribution and relative abundance of heavy mineral deposits along the coast is as follows:- between Shell harbour and South Stradbroke Island zircon and rutile are the dominant heavy minerals, while to the north and south of this portion of the coast ilmenite is generally the most abundant heavy mineral. North of Frazer Island, ilmenite and magnetite together constitute 90% of the heavy minerals.

The sediments of the Mesozoic basins contain a large proportion of comparatively soft sandstone which have undoubtedly contributed the largest quantities of sand to the coast via the Brisbane-Logan-Albert, and especially the Clarence-Richmond, river systems. Beazley (1950) and Gardner (1955) have shown that the beach sand heavy mineral deposits of southern Queensland from the Clarence river to Moreton Island were derived from the New England granites via the Mesozoic Clarence sandstones. The equivalent Mesozoic sandstones of the Brisbane basin (Moreton area) were of smaller importance. The heavy mineral content of these sandstones is 0.1% whereas the sandstones of the Clarence series contain 0.7-1.5%. Andesitic lavas, inter-bedded with the Mesozoic rocks of the Brisbane area, have added a significant proportion of ilmenite and magnetite to the stream sands of which only the former ever reaches the ocean beaches, thus accounting for the higher proportion of ilmenite in the deposits of

the Moreton area. Sand derived from the Moreton area has built all the coastal beaches north of Moreton island.

The Palaeozoic sediments in both areas have contributed little to the beach deposits owing to their dominantly pelitic character. The Tertiary lavas and river gravels in both areas are not yet sufficiently eroded to have contributed large amounts of arenaceous material. Studies of the grain sizes of stream sands in basalt areas in comparison with those of the beach sands on the nearest stretch of coast, in the area north of the Clarence river, have confirmed this statement. Ilmenite in the basalts has a grain size less than 0.104 mm. yet in the finest grained coastal deposits, despite the distances travelled, over half of the grains are larger than 0.110 mm. North of Frazer island where relatively unimportant deposits are derived from nearby basalts the heavy concentrates contain high proportions of magnetite, an abnormal feature for East Australian beaches.

The minerals of commercial interest in the beach sand deposits are zircon, rutile, ilmenite and a small proportion of monazite. These are accompanied by very small amounts of garnet, tourmaline, leucoxene, chromite, epidote, spinel, magnetite and cassiterite. This suite of minerals is typical of those found in granites and surrounding metamorphic rocks though the relative proportions of the minerals are different.

Owing to the dominant role that the minerals derived via the Clarence river system play in the composition of the beach sands their history will be considered in greater detail. The New England granites have not contributed significantly to the ocean beaches direct because

the location of the granites is not suitable for providing large
quantities of detrital material.   The following figures taken from Beazley
(1950) and Gardner (1955) illustrate this statement.

Average content of Heavy Minerals in New England Stream Sands.

Zircon	11.9	Ilmenite	36.7
Monazite	0.9	Leucoxene	tr.
Magnetite	45.5	Sphene	2.7
Rutile	2.4	Anatase	tr.

Average composition of beach sand heavy mineral deposits

Ballina - North Stradbroke Island.

Zircon	40.6	Monazite	0.5
Rutile	31.6	Magnetite	0.1
Ilmenite	21.3		

The lack of sphene and magnetite in the ocean beaches even allowing
for the instability of the latter is significant.

The heavy minerals of the Mesozoic Clarence series sandstones
have largely been derived from the New England granites but the
magnetite and sphene of the latter must have disappeared during
the processes of erosion, sedimentation and diagenesis.   Much of the
ilmenite has also been altered, some to leucoxene but much, together
with the sphene, must have gone to rutile.   In support of this
conclusion, Beazley (1950) found that some of the rutile crystals
in the sandstones were euhedral or nearly so, suggesting that it is
an authigenic constituent. (see Volume I, Chapter II, Rutile).

Taking the mineral changes into account the zircon, monazite and
total TiO_2 content of the sandstones and New England stream sands show
remarkable correspondence and it seems reasonable to conlude that
the Clarence system sandstones were largely derived from the New
England granite.

	Zircon	Monazite	Rutile	Ilmenite	Leucoxene	Sphene	Total TiO_2
N.E. Stream Sands	35.4	2.6					62.0
Clarence Ssts.	33.5	4.1	26.8	16.5	19.0	0.1	
TiO_2 Content			26.8	7.6	18.0*		52.4
Calcd. to %	37.2	4.6					58.2

The composition of leucoxene is assumed to be $TiO_2 nH_2O$ where n is small.

The stream sands of the Clarence basin contain the heavy minerals of the sandstones released again through erosion but the proportions are modified slightly by the addition of ilmenite and magnetite derived from local Tertiary basalts. This has the effect of increasing the ultimate average ilmenite content of the beachsands to about 25%. The magnetite does not affect the final content of the sands because over 90% of it breaks down onto hydrated iron oxides before redeposition on the ocean beaches can take place. The hydrated iron oxides, together with the other lighter minerals present in the stream sands of the Clarence basin, are rapidly reduced by abrasion to a very fine particle size and are carried out to sea to be deposited in deeper water as silt. The decrease in monazite content from 5.0% in the Clarence basin to 0.5% in the beach sands is due to the softer nature of this mineral.

Effects of Eustatic Changes in Sea Level.- The vast accumulations of sand along the Queensland and New South Wales coasts and the consequent abundance of heavy mineral deposits, albeit many of low grade, is largely due to the changes in sea level which have taken place over the 400,000 years or so which have elapsed since the Middle Pleistocene. Whenever the coastline became stabilized for any considerable length

of time, parallel dunes developed along the shore and swamp flats,
later to become heathlands, formed in river estuaries and on the landward
side of shallow bays.   During periods of emergence abundant supplies
of sand were no longer available to continue the formation of parallel
dunes which developed blowouts and became transgressive in character.

At various localities around the Australian coast raised littoral
and estuarine deposits and erosion surfaces attributed to eustatic
changes in sea-level occur at heights of approximately 100, 50 and 20
feet above sea level.   These are noted by David (1950) who gives an
extensive bibliography.   Gardner (1955) records that on the east coast
five transgressive dune stages are developed and he remarks "It is
necessary to postulate a rather abrupt onset of special conditions: a
large accession of sand, and probably a great increase in wind velocity.
Both these conditions applied during the glacial stages of the Pleistocene".
He emphasises many times that the accumulation of the sands was an
intermittent process and not a continuous slow building of dunes.   The
five stages he correlates with the recession of the sea from the + 100', + 45'
+ 20', + 10' and + 5' levels when large quantities of sand would have
been made available by down-cutting of rivers and exposure of the
littoral zone.   The latest recession, from + 2' level has produced only
parallel, dunes.   The accompanying table, slightly adapted from
Gardner summarises the history of the eustatic movements.

Because of the rising sea level and the small magnitude of the
last emergence, at the present time insufficient sand is being transported
down the rivers to maintain the supply required for the dunes immediately
north of their mouths with the result that the + 2 level dunes are being
eroded and redeposited farther north.

Table V.I.

Epoch	Age (yrs.)	European Chronology	Eustatic Movements	Level of Sea related to present Day (in feet)	Sand Deposits
Later	2000(?)		Steady submergence to emergence. Slightly more than 2'	-1	Parallel dunes
Recent	2500(?)		Submergence of at least 7'	+2	Deposition in river valleys, estuaries and along coast
Mid Recent	3000(?)		Emergence of 10'	-5	p 5 dunes
			Emergence of 5'	+5	p 10 dunes; Deposition on coast
Earlier Recent	4000(?)		Submergence of 40'		General deposition
Late Pleistocene	23000	Würm 3	Emergence 50'	-30	p 20 dunes
		Mousterian II	Submergence app. 270'	+20	General deposition
	72000	Würm 2	Emergence app. 295'	-250	p 45 dunes; General deposition
	115,000	Würm 1			
	150,000	Mousterian I	Submergence 295'	+45	
	188,000-235,000	Riss	Emergence 350	-250(?)	p 100 dunes
Middle Pleistocene	250,000-425,000		Mindel-Riss Interglacial	+100	Deposition

Note – p 5 = "post +5 level transgressive"

Similarly p 10 etc.

From a consideration of the history of the eustatic changes in sea level it becomes clear that considerable deposits of sand, with associated heavy mineral seams probably lie at shallow depths offshore.   This has recently been confirmed (Chem. Age 1957):- heavy mineral deposits have been reported lying at depths down to 100 fathoms for distances of up to 15 miles off Nambucca Heads.

The Heavy Mineral Deposits (Gardner 1955).-   Heavy mineral deposits occur on present-day and former beaches hidden beneath parallel dunes and in emerged heathlands.   Deposits below sea level are found on the seaward side of the +5 ft level heathlands.   On North Stradbroke Island heavy minerals from earlier beaches have been blown up into large low grade deposits in some of the later Transgressive dunes.

Beach and Parallel dune deposits.-   A typical beach, composed of white quartz sand, is arcuate in shape.   It may curve round between two headlands or start at a headland, sweep northwards along the edge of a spit to terminate at a river mouth.   Beach surfaces slope up at an angle of a few degrees to steepen suddenly at the foredune which is 50-100 ft wide and, commonly, 15-30 ft high.   During storm periods large quantities of sand are taken into suspension worked towards the shore and thrown on to the beach by surf.   The return seawards of the water is only sufficiently powerful to remove quartz and other light minerals leaving the heavy minerals at the top of the beach.   'Rip' or longshore currents, set up by the steady south-easterly trade winds cause northward migration of sand along the coast from the river mouths, and also play an important part in the selective removal of light minerals from the beaches.   During

calm weather only quartz sand is carried on to the beach where it covers the heavy mineral seams. Some of it is removed by wind to the foredune where it may be quickly stabilized by the growth of native grasses. Beach deposits contain at least 10% by weight of heavy minerals.

During long periods of fine weather, given an excess of sand in the littoral zone, the beach and foredune encroach seawards and may not be eroded during succeeding storms. In this way mineral seams are preserved from marine erosion, and they lie hidden beneath parallel sand ridges on the landward side of the foredune. The seaward advance of the dunes may be attributable to the shallowing of the water offshore due to silting or a fall in sea-level, or both acting together.

Along the stretch of coast from the Clarence River to North Stradbroke Island where the beach sands are derived from the Clarence river basin, on the southern section from the Clarence river to Cudgen the dominant heavy mineral is zircon, while on the northern section it is ilmenite.

	Zircon	Rutile	Ilmenite	Monazite
Clarence River to Cudgen Beach:	52 ± 1	28	19 ± 1	0.6 ± 0.1
Broadbeach to North Stradbroke Island:	35 ± 3	36 ± 1	28 ± 3	0.6 ± 0.2

(Gardner 1955).

(The heavy mineral content of the individual beaches is given in greater detail in Part II of this thesis).

The Coastal Plain:- The coastal plain forms a fringe, of varying width, between the sea and the older consolidated rocks. Two distinct parts can normally be recognised; a low lying portion starting at the landward edge of the beach dunes and a more elevated

portion farther inland.

The low lying part consists of broad sandy flats and narrow arcuate swamp belts alternating with low sand ridges.   The swamp belts have developed in the same way as the dunes - through the silting up of an earlier bay causing seaward advance of the shoreline. The more elevated part of the coastal plain consists of heathland and swamp, commonly displaying a pattern of belts similar to those seen in the low lying part of the coastal plain, but generally more obscured by erosion.   Sections through these sediments display coarse bay floor deposits underlying beach sands which may contain heavy mineral seams.   Mineral deposits within coastal plain sediments are low in grade.

Transgressive Dune Deposits.-   Parts of the coast are fringed by dunes elongated in the direction of the prevailing wind.   Five distinct formations of these transgressive dunes can be differentiated which have developed in successive stages, the dunes of each stage advancing across those of the preceeding stage.   The earlier of the formations contain much larger quantities of sand than the later, which indicates much greater sea-level fluctuations exposing correspondingly larger areas of sand to the eroding action of the wind.   At the present time the deposits in the transgressive dunes are of economic importance only as large low grade reserves.   They contain 2.5 ± 0.5% by volume of heavy minerals of which ilmenite is the most common.   The mineral composition of the dunes is reasonably constant over wide areas.

Transgressive dunes on North Stradbroke Island.   Mineral composition of heavy mineral concentrates.

	Zircon	Rutile	Ilmenite	Monazite
%	28	27	44	0.3

Mineralogy of the Heavy Mineral Deposits.- The minerals of economic importance in the beach sands are in fact the only ones occurring in significant quantities.

Rutile occurs as red-brown or black, opaque, rounded grains with an average median diameter of 0.112-0.114 mm. It is sometimes ferriferous and the black grains may contain chromium (Stillwell, 1949).

Ilmenite is present as sub-rounded, black opaque grains with an average median diameter of 0.116-0.118 mm. 'Leucoxenization' of the ilmenite is sometimes apparent. The ilmenite usually contains chromium as discrete particles of chromite within the grains (Stillwell 1949). Curnow and Parry (1955) have examined ilmenite concentrates from an unnamed deposit, probably in the Swansea area of New South Wales. The ilmenite is incipiently altered, a condition which may or may not be typical of most of the deposits of the east Australian seabord. The ilmenite concentrates examined however, if they are taken from the coast south of the Clarence river, are unlikely to be of quite the same character as those being mined farther north.

The monazite grains are well-rounded, pale honey-yellow in colour, with an average median diameter of 0.086 mm. The following analysis is of monazite from Byron Bay.

	La_2O_3	Ce_2O_3	Pr_2O_3	Nd_2O_3	Sm_2O_3	ThO_2
%	15.5	27.2	3.37	11.9	2.24	7.35

Zircon occurs as rounded, clear, colourless grains with a high refractive index. The average median diameter of the grains is 0.112-0.114 mm.

Size composition.- The heavy minerals within any one deposit are usually well sorted and the grains have median diameters which vary over a small size range. The range in grain size in all the South Queensland beaches is only 0.023 mm; within a single deposit it would be far less than this (Whitworth 1931; Gardner 1955).

The following data give average grain size values for the various types of deposit (adapted from Beazley 1950).

	Average Median Diameter of Grains
Eight beach seams (average)	0.113 mm
Average of four transgressive dune deposits on North Stradbroke island	0.110 mm
A beach seam, at Point Arkwright, modified by rip currents and containing material from a nearby peatland	0.180 mm

The grain sizes reflect the conditions of deposition. Bay-floor littoral deposits are composed of coarse material which storm waves were unable to carry as far as the beaches. Beach seams contain medium-size grains except where local influences such as rip currents or nearby headlands have a modifying effect and the finest grained deposits are the wind-borne sands which have been blown up into dunes from the beaches.

The Distribution of the heavy minerals within Seams.- Vertical distribution. In beach areas where zircon, rutile, ilmenite and monazite are all available the higher the concentration of heavy minerals, the higher is the concentration of zircon and monazite. These are the heaviest minerals present and in a rich seam where the sorting action of the waves has been most effective they will naturally tend to be more concentrated (Gardner 1955). The lower part of a seam is always richest in heavy minerals, and it normally has a moderately

sharp lower contact grading gradually upwards into barren quartz sand. This may be related to the sudden onset of storm activity and its more gradual abatement, with the increasing effect of the wind carrying quartz sand in the latter stages and mixing it into the upper surface of the heavy mineral seam.

Distribution across seams.   There is a variation in the constituent seams of a deposit.   Most deposits consist of a number of parallel seams, each a little lower than the succeeding one in a landward direction, which were the products of a receding sea. Individual seams underlying large parallel dunes were laid down during periods of stable sea level and such seams have high zircon and monazite contents (see above).   Rutile and ilmenite increase in importance in seams deposited during transitional periods.

Longitudinal distribution.   'Rip' or longshore currents control the longitudinal distribution of heavy minerals in a deposit, but they are in turn controlled by local physiographic features.   In general, rutile and ilmenite contents vary inversely with the zircon and monazite contents, but changes in the ilmenite and monazite contents are very small so that in effect zircon and rutile contents vary inversely independently.   Deposits which terminate northwards at stream or river mouths show slight increases in rutile content at the expense of zircon.   This is due to selective removal of rutile from the southern ends of the beaches and redeposition at the northern end.   Deposits which terminate northwards at a headland also increase in rutile content from south to north, but in the immediate vicinity of the headland there is a sharp drop in rutile content due to its selective removal by strong rip currents induced by the headland.

The principles of distribution just described are not for universal application because local factors appear to have variable effects on deposits. Small creeks and sandspits have effects out of all proportion to their size. A creek may, for instance, cause the removal of rutile by increasing turbulence, or may add rutile if it happens to carry rutile-rich sands to the coastline.

Conclusions.- The peculiarly widespread development of sandy coastal areas and heavy mineral deposits on the East Australian coast seems to be due to four independent factors.

1. The availability of large volumes of easily eroded sedimentary rock with a relatively high heavy mineral content.

2. A coastline of plains with intermittent headlands, which behave as natural traps for sand.

3. Strong south-east winds blowing consistently for much of the year directed against an approximately north-south coastline.

4. Variations in sea level during the last half million years which have (a) allowed considerable reworking of the sand deposits, and (b) caused large quantities of sand to be rapidly delivered to the sea from silted river valleys during emergent periods.

Beach Sand Deposits on the Brazilian Seabord

There are heavy mineral deposits in beach sands at a number of localities on the Atlantic coast of Brazil. They lie 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. In Bahia state is another belt of deposits, 40 km long. Other deposits occur on the 'hump' of Brazil in Paraiba do Norte and Rio Grande do Norte states.

Five types of deposit are represented on the Brazilian coast:- (1) Elevated beaches. (2) Elevated bars. (3) Modern beaches. (4) Dune deposits formed by wind action on types (1), (2) and (3). (5) Deltaic deposits. Only deposits of the first three types are worked at the present day for their heavy mineral content.

Geological background and history of the deposits.- (Gillson 1950).

A very large area of east central Brazil is underlain by pre-Cambrian gneisses. On the coast a gneiss belt extends north from Santa Catharina state for 2,000 miles to the coast of Ceara state, varying from 150 to 400 miles in width. Between the southernmost coastal outcrop in Rio de Janeiro state and the northernmost in Ceara state, the coastline is cut in Tertiary sediments which have built up a coastal plain fringing the inland higher ground which is underlain by the old rocks. There is a consistency in the occurrence of heavy mineral deposits with coastal outcrops of the lower Tertiary strata that is not coincidental. These strata contain rather high concentrations of heavy minerals as accessory constituents whereas the Upper Tertiary rocks, which outcrop and are thickly developed in the Sao Salvador region, do not.

The pre-Cambrian gneiss area suffered two peneplanations, one in Cretaceous and the other in Tertiary times. On the Cretaceous land surface soils developed in which the heavy minerals resistant to decay remained as unaltered grains while less stable constituents were reconstituted to mineral phases stable within the environment. The important result of this soil-forming period was the elimination of magnetite which otherwise would have been concentrated as a mineral of high specific gravity, along with zircon, ilmenite and rutile in the coastal sands. The Rio Doce deltaic ilmenite deposit contains

titaniferous magnetite because the sediments in the delta have been
derived from gneisses which are rapidly being eroded in a deeply
dissected valley region where deep soil development is inhibited.

Following the Cretaceous peneplanation, uplift caused rejuvenation
of the drainage system and the soils were eroded rapidly to be dumped
into a shelf sea where sands were laid down, the accompanying clay material
being washed out to deeper areas of the basin. These early
Tertiary sands contain an unusually high proportion of heavy minerals
as accessories, insufficiently concentrated to form ore deposits in
themselves, but quite enough to make the sands important raw material
given a further natural concentration process to sort the heavy
minerals from the 'gangue'. The later Tertiary deposits, derived in
much larger part directly from the gneisses underlying the deep soils
of the Cretaceous peneplain, contain lower concentrations of heavy
minerals and are thus less important as potential suppliers of
economically important minerals to the coastal beaches.

More recently the Brazilian coastal areas have suffered severe
downfaulting to the east separating, with a fault scarp, the coastal
plains from the elevated Cretaceous and Tertiary peneplains inland.
At a stage when dissection of the scarp was well advanced, probably
in early Pleistocene times, submergence of part of the coastal plain
took place, drowning valleys and low lying areas. Processes of
coastline straightening immediately began to operate; headlands of
soft semi-indurated Tertiary sediments were removed and bars developed
across bays, leaving lagoonal areas on their inland margins. In areas
where the soft lower Tertiary sands were cut back into cliffs at this
period, black beach sand deposits developed at the cliff foot by
selective removal of lighter material, and at the same time
offshore bars were enriched in heavy minerals. Sand removed

from headlands suffering rapid erosion was moved coastwise under the influence of longshore currents to be deposited in shallow bays. Under the influence of ocean swell, across-bay bars were formed which gradually became enriched in heavy minerals due to the selective removal landwards of the lighter quartz-rich sand, which was deposited in lagoonal areas behind the bars.

In recent geological time the coast has been uplifted about 5 metres, in many cases removing the cliff foot beaches and offshore bars from the eroding action of the waves. The elevated sea cliffs now lie inland and are known as the 'barreira'. In some areas the eroding action of the sea has already cancelled out the effects of uplift by removing the cliff foot beaches, and the sea cliffs are again being eroded.

Dune deposits are rarely important in Brazil probably owing to the climate which causes rapid vegetation growth which effectively and speedily fixes any areas of recently formed sand.

Modern beaches may contain heavy mineral deposits if the sea is locally eroding an elevated bar deposit, or is attacking the cliffs of lower Tertiary sands after removal of the protective cliff foot deposits. Where the beaches are formed of the strands, originally below sea level on the offshore side of the offshore bars, they are usually barren of heavy mineral concentrations.

Thus, in summary, the formation of beach deposits in Brazil, on Gillson's (1950) evidence, is due to the following factors. (1) The presence of suitable 'basement' rocks in the coastal areas of the continent (2) Peneplanation of the old land surface translating the heavy minerals from a hard resistant host to a soft semi-consolidated matrix which could, with facility, be rapidly removed (This is an

important stage because it also induces the chemical breakdown of unwanted, less stable, heavy minerals). (3) A period of uplift and erosion which resulted in the dumping of heavy mineral-rich sediments as the basal beds of a shallow water marine series. (4) Further uplift of the newly formed sediments raising them to a level where they became susceptible to marine erosion. (5) Formation of coastal sands locally rich in heavy minerals from the sediments of stage (4). (6) Slight uplift, removing the deposits of heavy minerals from the level where they might suffer rapid marine erosion.

The beach and inland placer deposits of Florida

The geological relationships and history of the Florida heavy mineral deposits as a single unit have never been adequately described, although many mineralogical descriptions have been published. The following account, based on information culled from many sources, gives only a very general picture of the geological background to the history of the deposits.

In Florida there are two distinct types of heavy mineral deposit occurring in a) present-day beaches and recently-formed dune sands and b) fossil beach and bar deposits now found at considerable distances inland from the coast. The latter types of deposit are the more important economically because, although their content of heavy minerals is low, the deposits are of large size and the ore grade is reasonably constant over large areas.

During Cretaceous and Tertiary times the Appalachian-Piedmont region of the south-eastern U.S.A. was undergoing peneplanation and a thick soil cover probably developed on the crystalline sub-surface rocks. Transportation of the heavy mineral content of the schists,

gneisses and granites of the region to the sea took place via a large
river flowing into the Florida area.   The sandy sediments built
up a large delta which now underlies much of Northern Florida.
Removal of sediment was probably an intermittent process, and during
the periods of non-delivery, erosion, reworking and redeposition of
the sediments occurred.   The high sand ridge known as Trail Ridge,
now the site of the largest titanium mineral mining venture in Florida,
and the central highlands which form the physiographic backbone of the
state, are probably the remnants of a barrier island or spit formed
during such a period.   The deposits of this ridge area are cross-bedded,
highly oxidised, clastic sediments that indicate channelling
associated with strong currents.   Concurrently with, or prior to,
the formation of this spit an extensive delta plain was formed.   This
is a recognisable feature over a large area of Florida, southern
Alabama and Georgia (Theonen and Warne 1949).

During the Pleistocene epoch variations in sea level occurred
which profoundly affected the loosely consolidated delta sands as,
in a precisely similar way, the sands of the Australian seabord were
being affected at the same time.   Raised strand lines have been
recognised in Florida at 25', 42', 70', 100', 215' and 270' above
present sea level.   These correlate quite well with those quoted by
Gardner for Australia, at 100', 45', 20', 5', and 2', although the
highest beaches have not been recognised in Australia, nor the lowest
in Florida.   The figures suggest that there has been a slight
relative uplift of Florida since the 100' (Mindel-Riss interglacial?)
level.   The sediments of the delta plain and the marine sands were
reworked during the periods of fluctuating sea-level and the sands were

reconcentrated into beach ridges, spits and bars. During later fluctuations these were eroded, reconcentrated and redeposited, with an increase in their heavy mineral content. Periods during which the sea stood at very low levels were particularly important in that large quantities of material were removed rapidly from the source areas and introduced to the coastal waters, due to the imcreased eroding power of rivers and streams working to a lower base-level. As a result of the effect of these interacting processes of erosion, deposition and heavy mineral concentration, at the close of the last glacial stage of the Pleistocene, when sea level became reasonably stable at its present height, Florida consisted of a huge sandy delta raised above sea level, containing sedimentary heavy mineral concentrations over wide areas to considerable depths with, locally, more perfect concentrations forming 'black sand' seams.

Since the last glacial stage of the Pleistocene, by which time the large river delivering its sedimentary load to the ocean to form the peninsula of Florida had long disappeared, the eastward flowing rivers of Virginia, the Carolinas, and Georgia have been steadily eroding the basement rocks and soil cover of the Appalachian-Piedmont region, and the softer, younger sedimentary formations of the coastal plain. The heavy minerals of the schists and gneisses of the region, in part removed directly from their Pre-Cambrian parent, but largely eroded from secondary hosts among the younger coast plain sediments, have thus been delivered to the ocean, have suffered its concentrating processes, and have been left as layers and bands in the ocean beach and dune sands of the coast. With the passage of time, under the influence of the inshore southward-setting Gulf Stream counter-current and the impact of east to north-east storm waves, the

mineral grains have gradually drifted south towards Florida.   In the
course of their journey they have received additions in the form of
heavy minerals released from local coast plain sediments by frontal
marine erosion, and other additions from local rivers and streams.
On reaching southern Georgia and Florida, heavy minerals eroded
from the Tertiary delta sediments are also added to the coastwise
drifting sands.   Thus it is recognised that the heavy minerals in
the Florida coast sands have been derived from the Appalachian-
Piedmont basement rocks along three routes which are 1.   Direct erosion
from the basement rocks and transport. southward by sea: 2.
Erosion, redeposition in Tertiary sediments, recent erosion and
transport southwards by sea?   3. Erosion by river, deposition in a
deltaic environment, uplift, erosion and reworking by the
Pleistocene sea, redeposition, uplift, erosion again and transport to
the coast by river followed by a final concentration by wave action
and redeposition on the beaches.

The sequence of events which has led to the presence of large
volumes of heavy mineral-bearing sands, of both Pleistocene and recent
age in Florida, serves to emphasise the importance of the intermediate
sedimentary stage in the history of the deposits.   This stage has a
twofold importance since it ensures that both large supplies of
easily eroded sand are always at hand to replenish the ocean beaches
and, of equal importance, that the ilmenite and rutile grains in
the sands are free from adulteration by minerals such as magnetite.
The extremely weathered state of the bulk of the Florida ilmenite,
particularly that which is in the fossil dune deposits, is due to
the protracted length of time the minerals have spent being subjected

to the hazards of subaerial weathering processes since they were
extracted from their Pre-Cambrian host rocks.   The increase in the
tenor of TiO_2 of the ilmenite derived in this way has rendered it
a more saleable mineral, and although the TiO_2 is present as a
separate mineral phase and not in combination with iron as $Fe\ TiO_3$,
it appears that its reactivity is not affected in most industrial
pigment processes.   This, as suggested by Hockin (1957) in
reference to the Malayan deposits, is probably due to the extremely
small particle size of the TiO_2 formed.   The high specific
surface of such grains alone will render them more reactive.

The Beach Sand Deposits of the South-East African Coast

Deposits of heavy minerals containing high percentages of ilmenite
and small percentages of rutile occur along the beaches of Natal
and eastern Cape Province in the Union of South Africa.   The four
hundred mile long stretch of coast from Durban to East London has
been prospected and it is known that there are many areas where the
ocean beaches and inland dunes contain concentrations of heavy minerals,
but the greater part of the coastline lies within native reserves
and it is unlikely that these deposits will be made available for
exploitation by the government.

In the neighbourhood of Durban large fossil dunes, probably of
Pliocene-Pleistocene age, extend inland from the coast.   These dunes
are now completely stabilised and form rounded hills rising to 400 ft
above sea level.   They underwent several periods of lateritization
during their formation, a fact demonstrated by the number of thick
soil layers intercalated with the sands.   At Umgababa, twenty-five
miles south of Durban, sand dunes of this type are being mined for

their titanium mineral content. The heavy minerals in the sands, present in average amounts of 8%, are ilmenite 87%, rutile 5%, zircon 7% and magnetite and garnet 1%.

Farther to the south-west along the coast in Cape Province, the beaches at Port St. Johns, and at Morgan's Bay, north of East London, also contain considerable amounts of heavy minerals. Behind the beaches there are large areas of dune sands, superficially similar to those at Durban, but closer examination has revealed that they are of a different character. These dunes do not contain the laterite horizons present in the Durban dunes and they are not fully stabilized. The inference to be drawn from these observations is that the dunes are younger than their northerly counterparts. The dunes in the East-London area are of a size similar to those near Durban, and the similarity in composition of their respective heavy mineral contents is quite remarkable. At Morgan's Bay the heavy minerals are present in the following quantities:- ilmenite 83%, rutile 6%, zircon 9%, magnetite 1% and garnet 1%. (Personal communication from Professor K.C. Dunham).

The similarity in the content of heavy mineral concentrations of the two areas renders it fairly certain that one type of source rock provided the sands for both areas. To the north in Mocambique, other beach sand areas contain significantly different mineral concentrations. The presence of radioactive minerals such as monazite, columbite and tantalite suggests a sharply distinct provenance, one that is rich in rare-earth bearing pegmatites. The sands of the Natal and Cape Province coastline have probably been delivered to the sea by the Tugela and other eastward flowing rivers such as the Great Kei, draining the Drakensberg and Stormberg mountain ranges.

The Mocambique sands were probably derived from basement rocks in the Limpopo basin.

The agents of concentration which have been at work on the beaches of the south-east coast are wind and ocean water but the precise history of their activity remains obscure. It seems almost certain that the fluctuations in sea level which occurred during the Pleistocene, and, perhaps, before then, have played a major part in the processes of concentration and purification of the heavy minerals, in just the same way as they did in Florida and Australia. The severe south south-east gales which are prevalent along this coast have been, at least in part, responsible for the size of the dunes backing the coastline, and there is no reason to suppose that they were any less effective during the glacial and interglacial phases of the Pleistocene.

Littoral deposits are known to occur at levels of up to at least 400! above sea-level along the south-east coast and the highest of these has been attributed to the maximum rise of sea-level of the Pleistocene epoch. Du Toit (1954) has suggested that the lowest level reached is marked by a submarine shelf, in fact the upper part of the continental shelf of that part of Africa, which lies at various levels down to a maximum depth of about 400! The upper part of the 400! dunes in the Durban area were supposedly formed during the period of maximum submergence and the lower and more seaward portions of the dune complexes at successive stages during the retreat of the sea, or during later submergences of smaller magnitude.

The coastwise movement of the beach sands is a subject on which definite information is lacking. The set of the main current off the coast is to the south-west, but the presence, at least locally, of

an inshore counter current is to be suspected. The prevailing
wind direction is south-east, which would also tend to move sand
northwards. A further point in favour of assuming a general northerly
drift of sand is the lack of radioactive minerals in the Natal
sands, when they are known to occur on the beaches of Mocambique to
the north.

The nature of the minerals present in the sands, and in particular
their restricted mineralogy strongly suggests that they have been
derived mainly from a sedimentary rock rather than an igneous or
regional metamorphic environment. Undoubtedly small quantities of
ilmenite and magnetite have been added from local dolerite intrusions,
and a small proportion of the minerals may have been derived from
basement rocks outcropping in the Durban region, although the lack of
staurolite, kyanite and epidote suggests that these rocks have not
played an important role as a source of sediment, but the mineralogy
of the sands points most strongly to an area of sediments as the
immediate source of material, and it is suggested that the Beaufort
series, which outcrops over a wide area may fulfil the necessary
conditions.

The conclusions which can be formed, although based on scanty
evidence, suggest a similar sort of history for the heavy mineral
beach concentrates in south-east Africa, as for most of the other
large scale deposits in the world. The analogy with Australia is
particularly striking. In brief it appears that the minerals
were removed from the basement system during the Permo-Trias and
deposited in the sediments of the Beaufort series. This series was
later uplifted and eroded probably mainly during the Tertiary. Since

the Tertiary the sediments so delivered to the sea have been
reworked and reconcentrated a number of times during the Pleistocene
sea-level fluctuations before finally being deposited in the form
in which they are seen today.

The Beach sand deposits of the Senegal coast

There are no detailed geological accounts describing the Senegal
deposits in the literature. The only descriptions of any value are
those of Legoux and Faucheux (1935) and they do not discuss the
geological history of the coast as a whole.

It appears probable that the minerals have been derived from
basement rocks of the interior via laterite soils and Tertiary
and Quaternary sediments. The quantities of sand in existence imply
that easily eroded rocks must have been available for rapid erosion
in the geologically recent past. The mineralogy of the sands equally
emphasises that the heavy minerals have not been derived directly
from primary igneous or regional metamorphic rocks. The ilmenite in
the black sands has a higher tenor in TiO_2 than that permitted by the
formula $FeTiO_3$, in consequence of which the mineral has been variously
described as 'arizonite' or 'ilmenorutile'. It is in fact ilmenite
with part of the iron leached out. The high content of ferric iron
(approx. 32% Fe_2O_3) demonstrates the oxidised state of the iron.

The immediate hinterland of the Senegal coast (Carte geologique
de l'Afrique occidentale francaise) is underlain by a large area of
Tertiary rocks. East of the Tertiary plains are plateau areas of
Palaeozoic and Archaen rocks. From a general consideration of
African geology it is quite probable that the plateau region was
uplifted in Tertiary times causing the rapid accumulation of the

Tertiary sediments in a manner essentially similar to the processes which operated in Brazil. It cannot at this stage be certain whether delivery of material to the ocean beaches has followed to the Australian pattern where rivers are most important on the Brazilian where erosion of Lower Tertiary sands provides the heavy minerals.

The Beach Sand Mineral Deposits of Travancore, India

There are two beaches in Travancore which contain very large accumulations of ilmenite, zircon, rutile and monazite. Manavalakurichi lies a few miles west of Cape Comorin while Quilon, where a beach extends for fifteen miles from Neendakara inlet to Kayankulam inlet, is 80 miles further north. The deposits, both of which are worked, are modern beaches but of slightly different types. 'MK' is a normal modern beach placer; Quilon is an offshore modern bar.

Geological background and history of the deposits (Gillson 1949).-
The hinterland of Travancore is an uplifted plateau underlain by gabbro and diorite gneisses containing normal accessory amounts of heavy minerals. This is bordered by a laterite plain which in the south of the state reaches the sea to form the coastline. The laterite soils of this plain contain low concentrations of the more resistant heavy minerals. In the Quilon region and even more widely developed farther north around Cochin, is a very low lying coastal area recently emerged from beneath the sea.

The area of gneissic rocks forming the basement of Southern India apparently suffered a period of prolonged peneplanation, possibly throughout much of the late Mesozoic and early Tertiary. Extremely deep weathering zones were developed under tropical conditions in which the breakdown of the gneisses into lateritic soils and

the destruction of the chemically unstable minerals was complete.

Faulting, probably in late Tertiary times, uplifted the gneissic basement and the lateritic cover was rapidly stripped off and dumped into the sea. This process continued until submergence of the coast (in Pleistocene times?) effectively prevented the delivery of sand detritus to the sea. During the period of submergence initial concentration of the heavy minerals was brought about by the development of underwater strands and sand spits containing low concentrations of heavy minerals.

The final act in the geological and physiographic history of the coastline was an emergence of 5-8 metres which lifted the sand bars and old strand lines into a zone where they are eroded during storm periods and the heavy minerals become concentrated on the modern beaches.

The localization of the MK deposit is due to a number of unusual and coincidental factors. The Travancore beach deposits, in contrast to the Brazilian deposits, are controlled by the location of large rivers which have supplied the detrital minerals. The MK deposit lies across the mouth of the old channel of the Paralayar river which was captured some fifteen miles inland by the Tambraparvi river at about the time of the Pleistocene (?) submergence, e.g. after the river had delivered to the sea material stripped from the uplifted inland plateaux. A local headland was at that time an island and a spit formed linking it with the mainland. Heavy minerals became concentrated in the spit as the light minerals were washed over it into a lagoon. The 5-8 metre emergence, at a late stage historically, raised the spit into the zone of active wave erosion which further concentrated the heavy minerals. A simultaneous seaward advance of the

shoreline left some deposits inland where they were covered by lighter sand.

The Quilon deposit is an offshore barrier beach formed across the mouths of two large rivers, the Panalur and the Pallikal Todu of which the latter, in geologically recent times, was diverted north into the lagoon behind the bar. As at MK an old headland played an important formative role in the history of the deposit, acting as an anchor from which the bar extended northwards.

Conclusions

The large commercially important beach sand accumulations of heavy minerals in India, Australia, Brazil, Florida and Senegal, and the potentially important South African deposits have certain morphological, mineralogical and genetic features in common with each other. The following set of conditions, based on these similarities, are tentatively formulated as essential for the formation of extensive beach sand deposits containing rutile and commercially acceptable ilmenite. (1) There must be a suitable hinterland in which ilmenite and rutile occur. This invariably demands the existence of areas of Pre-Cambrian basement in which there are large volumes of igneous and regional metamorphic rocks. Thick sandstones may satisfy this requirement if they are derived from basement complexes and contain the requisite heavy minerals as common accessory constituents. Sandstones in such a case are really acting only as an intermediate host for the heavy minerals. (2) A period of peneplanation, acting over a long interval of time under sub-tropical or tropical conditions so that thick lateritic soils may develop, is necessary to break down

the unwanted less stable heavy minerals such as staurolite, garnet,
magnetite etc. which will then disperse during the transportation stage.
If these remain the final deposit will be of lower grade due to their
admixture.   (3) Uplift accompanied by rapid erosion is required to
remove the lateritic material to the coast before it has time to be
diluted with other material during long periods spent in stream and
river courses.   Fault bounded mountains close to the coast provide
the optimum conditions.   (4) Deposition of the rapidly eroded sediments
into lightly consolidated sandy sediments, and then later wave
erosion of these sediments after uplift, with re-deposition after sorting
is desirable but not necessary.   This does not appear to have occurred
in India, Australia or south-east Africa.   In the absence of stage (4)
the sands brought into the sea directly by the rivers usually require
a longer period to elapse during which, with the aid of sea-level
fluctuation, they are several times reworked and re-concentrated.   The
recent Pleistocene glaciation has probably been an important factor
in this process.   The fluctuations of sea level caused by the advances
and retreats of the ice caps has caused the beach sands to be
regularly reworked by the sea and at least in Australia and Florida
the effects have been very marked.   With more detailed study of
the other beach sand deposits, these effects may prove to have been
equally important everywhere.   The broad pattern of emergence, followed
by submergence and then slight emergence can be traced almost on a
world wide scale but evidence for the smaller fluctuations has not
everywhere been so well preserved as in Australia.   However, it can
be regarded as highly probable that the deposits of heavy minerals in
inland sands everywhere owe their existence largely to the Pleistocene
sea-level variations.

The history of a heavy mineral deposit is of importance not
only to the grade of a deposit but also to the chemical condition
of the ilmenite.   Rutile and zircon are so stable under any surface
conditions that their environment is unimportant.   The more that
an ilmenite-bearing sand can be exposed to the effects of chemical
weathering the higher will be the TiO_2 content of the ilmenite
owing to oxidation and then leaching of ferrous iron.   (The nature of
these changes is discussed in the second section of this chapter).
It is within dunes and lightly consolidated old deltaic sediment
or sandy alluvium in a warm or hot climate with at least a moderate
rainfall that conditions are at an optimum for the furtherance of
this process.   The freedom with which ground water can circulate in
such an environment ensures an adequate supply of oxygen and provides
a vehicle for the removal of the hydrated ferric oxide formed.   Hence,
the ideal deposit to contain a high TiO_2 ilmenite concentrate,
regardless of the manner in which the TiO_2 may be combined, is an old
unconsolidated sand of which Trail Ridge, Florida is a good example.
The ilmenite in a deposit of this kind has benefited from a long
history of deposition and re-deposition since removal from its
hard rock source, which has concentrated the mineral adequately
for exploitation but, unlike ilmenite in the continuously moving ocean
beach deposits, chemical weathering has been carried out in static
conditions so that the soft weathering products of the ilmenite with a
high TiO_2 content have not been abraded.   This is well illustrated
in table V.X in which the curves for alluvial ilmenites in an
advanced state of alteration have wide standard deviations with
means near leucoxene.   This does not mean that all alluvial ilmenites
will have a broad peaked curve.   If leucoxene has not been formed

the curve will have a narrow standard deviation.

From the conclusions elaborated in the foregoing paragraph it is obvious that ilmenite in sandy alluvium of sufficient age in a suitable climatic zone should, chemically, satisfy the conditions for a high TiO_2 content quite admirably, and such is indeed the case. However, low grade and limited extent often reduce the economic value of this type of deposit, with the outstanding exception of the Malayan alluvial sands.

From the discussion above it is apparent that a limiting clause must be added to the conclusion regarding the value of the laterite development - peneplanation stage in the history of an ocean beach deposit. It is obviously not desirable that this stage should be prolonged to such an extent that the ilmenite becomes completely leucoxenised before being released to travel to the ocean beaches. Its resistance to abrasion would be so reduced that it would be unable to withstand the severe conditions it would encounter and it would rapidly break down to be dispersed into deeper water. offshore.

A conclusion of economic importance can be inferred from these various observations. It is <u>unlikely</u> that <u>large</u> deposits of <u>high grade</u> ilmenite will be found on the beaches of the Northern Hemisphere north of about latitude 40°. The intense Pleistocene glaciation has either removed and diluted, by admixture with other material, any superficial deposits which might have been potential beach sands, or pushed the sub-tropical weathering zone too far south beyond the 40th parallel for deep soils to have developed.

A study of some sands taken from beaches in Labrador, Quebec and Greenland (Martens 1929), derived from pre-Cambrian crystalline

rocks of a type which would satisfy premise (1) above, lends support to this conclusion. In each case the sand contained high proportions of heavy silicate minerals, and even feldspars which have been stabilized by the absence of chemical weathering in subarctic climatic conditions. These silicates maintain the ratio of useful heavy minerals to silicates at approximately the same level as in the original rock.

The possibility that smaller areas of beach sands may contain ilmenite of economic grade is not precluded, but it is most unlikely that 'super grade' weathered ilmenites, with TiO_2 contents of about 60% plus, will be found in quantity in the temperate and cold latitudes of the northern hemisphere.

SECTION II

THE MINERALOGY OF IRON-TITANIUM OXIDE MINERALS IN SECONDARY DEPOSITS

In 1909 Palmer described a mineral which he considered had the formula $Fe_2O_3.3TiO_2$, and which he named 'Arizonite'. Since then the iron-titanium mineral occurring in beach sands has often been referred to as arizonite on account of an abnormally high Fe_2O_3 and TiO_2 content which ilmenite does not contain (Gillson 1949; et alia). Despite the fact that 'arizonite' has never been recorded to occur in unaltered rocks, many authors persisted in applying the name to the ilmenite of beach sands, even bemoaning the reluctance of the commercial world to accept the name. In this respect the business man and mining engineer have shown more circumspection in the application of new mineral names than the mineralogist!

Koenigsberger (1939) and Moore (1939) both concluded that 'leucoxene' could not form from ilmenite below about $150^{\circ}C$ and that

it was in fact a hydrothermal alteration product which could not form in sand deposits. 'Leucoxene' has since been shown to be not a mineral species but merely an alteration product of ilmenite, the composition of which varies in a manner dependent upon the conditions of alteration. It may be finely comminuted rutile, anatase or sphene. (Allen 1950; Creitz and McVay 1948; Broughton, Chadwick and Deans 1950; Hutton 1950; Coil 1933; Tyler and Marsden 1938).

Since the work of Koenigberger and Moore further evidence has come to light which demonstrates the fallacy in their conclusions, and shows that 'leucoxene' and hence 'arizonite' forms in beach sands. Miller (1945) examined the 'arizonite' from Florida and concluded that it was certainly unlike the original material described by Palmer (op. cit.). Creitz and McVay (1948) and Spencer (1948) concluded that the heavy black mineral in the Florida sands was leucoxene formed by weathering of the ilmenite originally present in the deposit, supporting their conclusions with X-ray evidence. Cannon (1950) believed that the ilmenite, or arizonite, in the Florida deposits was in fact altered ilmenite, formed by the loss of the ferrous iron, molecule by molecule throughout the mineral, and that there was thus a continuous series of mineral mixtures from ilmenite to rutile loosely termed 'leucoxene'.

A restudy of Palmer's original x-ray powder photographs of arizonite by Overholt, Vaux and Rodda (1950) has shown that all the lines in the pattern can be accounted for if the 'arizonite' is an impure mixture of hematite, ilmenite, anatase and rutile. They therefore concluded that arizonite is altered ilmenite and further concluded, on less sound evidence, "that ilmenite oxidation could be expected in months at $100^{o}C$ and at room temperature in years". The

Table V. II
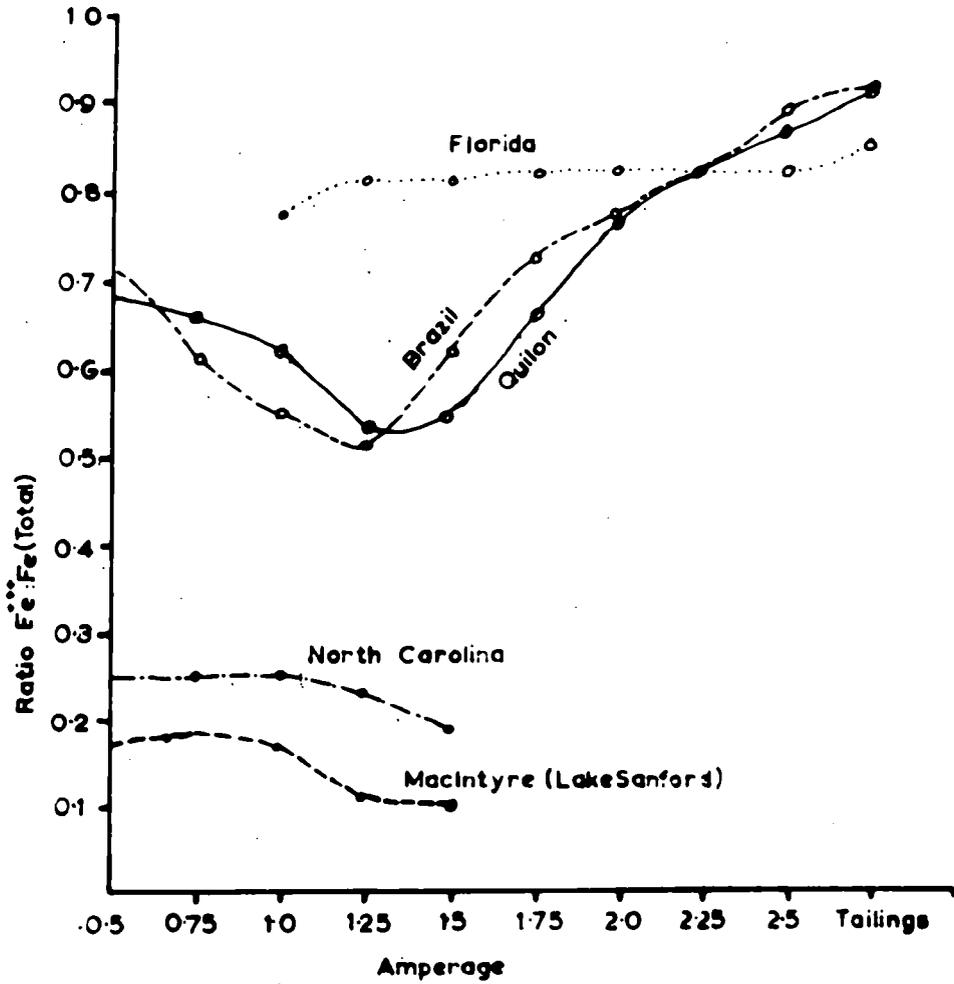
occurrence of practically unaltered ilmenite-magnetite intergrowths on many beaches of the world throws considerable doubt upon the latter conclusions unless they mean only that oxidation would _commence_ after the periods of time which they suggest. It has been shown (see section I of this chapter) that for ilmenite and magnetite to be altered to any appreciable extent a relatively long period must be spent by the minerals in lateritic soils or other loosely consolidated rock under subtropical or tropical conditions; or alternatively, the sands containing the iron titanium oxides must have been reworked by the sea several times over long periods of years. Magnetite is known to be oxidised more quickly than ilmenite, but if merely a matter of a few years were required for it to be broken down to hydrated iron oxides then the large deposits of titaniferous magnetite on the coasts of North Island, New Zealand, to quote but one example, would contain considerably more TiO_2 and less Fe_3O_4 than they actually do.

Summary of Mineral Compositions of ilmenite concentrates based on X-ray pattern, interpreted from data provided by chemical, microscopic and electron microscopic methods (adapted from Lynd et alia. 1950).

Table V.III   Relative percentages of constituents based on pattern strengths.

Approx. Wt. % of original	amp. concentrate	Ilmenite	Hematite	Rutile	Unidentified
	North Carolina ore				
84%	1.25	over 90	10	–	–
	Quilon ore				
2.9	0.5	50-75	10-20	10-20	–
31	1.25	50-75	25-40	–	–
33	2.0	25-40	25-40	25-40	10
15	2.5	10-20	10-20	50-75	10
	Guarapary ore				
3.8	1.0	50-75	10-20	10-20	–
52	2.25	10-20	10-20	25-40	10
	Trail Ridge ore				
3.5	1.0	25-40	10-20	50-75	10
57	2.5	10-20	10-20	50-75	10

Lynd, Sigurdson, North and Anderson (1954) investigated beach sand 'ilmenites', from several localities, in a more thorough manner, carrying out various magnetic concentration tests, ore microscopic and X-ray studies. Some of their data is presented in Tables V.II., V.III and V.IV. As a result of their investigations they were able to arrive at the following conclusions:-

1. "That ilmenite is present in various amounts in several fractions of each ore (examined) and that nearly all the non-ilmenite portions of the ores consist of a porous mixture of fine-grained rutile and iron oxide which formed as a result of alteration of the ilmenite".

2. "That ores may be listed in order of decreasing magnetic susceptibility and increasing alteration".

3. "That Quilon, Brazil and Florida concentrates all contain ore grains ranging in composition from fresh ilmenite to a highly altered product approaching pure TiO_2 in composition". (The fresh ilmenites represent the latest additions to the deposits which have not been through the rigorous oxidising stages in the history of the deposits).

4. "The ratios of Fe_2O_3 to total iron in the different deposits indicate that oxidation has accompanied alteration. The higher

Table V. IV. Concentration, Chemical, and Mineralogical Data on Concentrates of Various Titaniferous Ores

(adapted from Lynd, Sigurdson, North and Anderson (1954))

Amp.	Prod. Dist. Wt Pet	Analyses—Weight, Pet TiO₂	FeO	Fe₂O₃	Others (Gangue)	Weight Ratio $\frac{Fe(Total)}{TiO_2}$	$\frac{Fe^{2+}}{Fe(Total)}$	Mineralogical Composition, Total Ore Fraction, Pet Fresh Ilmenite	Altered Ilmenite	Others
Lake Sanford										
0.5	9.5	36.2	31.5	6.9	25.4	0.81	0.17	95+	0	5 magnetite
0.75	15.5	44.0	35.0	8.3	12.7	0.75	0.18	95+	0	Trace magnetite
1.0	27.3	48.4	38.3	8.4	4.9	0.74	0.17	100	0	
1.25	37.3	49.6	39.6	5.4	5.4	0.70	0.11	100	0	
1.50	5.2	45.9	36.8	4.7	12.6	0.70	0.10	100	0	
1.75	0.9	19.9	22.7	8.9	48.5	1.2	0.26	100	0	
Tailing	4.3	2.2	10.6	9.3	77.9	6.7	0.44			
Total	100.0									
North Carolina										
0.5	5.0	49.0	35.1	13.0	2.9	0.74	0.25	90	5	5 magnetite
0.75	12.0	49.5	35.1	13.3	2.1	0.74	0.25	95	5	Trace magnetite
1.0	30.0	49.4	35.5	13.1	2.0	0.74	0.25	90	5	5 magnetite
1.25	36.7	50.8	34.5	11.4	3.3	0.69	0.23	90	5	5 magnetite
1.50	8.3	51.3	34.4	8.9	5.4	0.64	0.19	90	8	2 magnetite
1.75	5.9	42.9	24.7	14.6	17.8	0.68	0.35	80 to 85	15	5 magnetite
2.0	2.1	22.4	12.8	13.0	51.8	0.85	0.48	20	80	
Total	100.0									
Quilon										
0.5	2.9	60.5	10.9	25.3	3.3	0.43	0.68	20	80	
0.75	6.5	59.5	11.7	25.3	3.5	0.45	0.66	25	75	
1.0	12.3	59.1	13.5	24.2	3.2	0.46	0.62	30	70	
1.25	13.1	58.3	17.1	21.5	3.1	0.49	0.53	35	65	
1.50	15.5	58.7	16.3	21.7	3.3	0.47	0.54	35	65	
1.75	10.1	59.7	12.1	24.2	4.0	0.44	0.66	20	80	
2.0	8.3	60.1	7.8	27.2	4.9	0.42	0.76	10	90	
2.25	7.9	60.8	5.6	28.8	4.8	0.40	0.82	5	95	
2.5	7.0	60.7	4.1	29.5	5.7	0.39	0.86	2	98	
Tailing	16.4	52.0	2.2	25.7	20.1	0.38	0.91	0	100	
Total	100.0									
Brazil										
0.5	0.5	30.4	12.6	45.5	5.5	1.1	0.71	30	50	magnetite
0.75	0.9	52.4	16.3	28.0	3.3	0.62	0.61	40	60	Trace magnetite
1.0	2.4	54.4	17.9	24.3	3.8	0.57	0.55	50	50	Trace magnetite
1.25	7.5	54.6	18.6	21.7	5.1	0.54	0.51	40	60	
1.50	7.6	55.6	13.4	24.6	6.4	0.50	0.62	25	75	
1.75	10.1	55.3	9.2	26.2	9.3	0.46	0.72	15	80	
2.0	12.3	53.3	7.4	26.9	12.4	0.46	0.77	10	90	
2.25	14.9	56.4	5.6	29.4	9.6	0.43	0.82	1	95	
2.5	22.0	59.7	3.5	30.7	6.1	0.41	0.89	0	100	
Tailing	21.8	55.1	2.9	29.4	12.6	0.41	0.90	0	100	
Total	100.0									
Florida										
1.0	3.5	61.4	6.5	27.0	5.1	0.39	0.77	5	95	
1.25	4.7	62.6	5.6	27.0	4.8	0.37	0.81	2	98	
1.50	6.9	63.0	5.5	26.6	4.9	0.36	0.81	2	98	
1.75	7.7	63.4	5.4	26.4	5.2	0.36	0.82	1	98	
2.0	8.5	63.2	5.1	26.3	5.2	0.35	0.82	0	99	
2.25	9.3	63.2	5.3	26.3	4.9	0.36	0.82	0	100	
2.5	19.3	63.1	5.0	26.3	5.6	0.35	0.82	0	100	
Tailing	40.1	66.1	3.8	24.4	5.7	0.30	0.85	0	100	
Total	100.0									
Theoretical ilmenite		52.7	47.3			0.70	0.00			

TiO_2 to Fe ratio ..... is good evidence that leaching of iron has occurred".

Bailey, Cameron, Spedden and Weege (1956) have carried the work of Lynd and his co-workers one stage further, in the process confirming most of their conclusions. They examined beach sands from Portuguese East Africa (Mozambique); Trail Ridge and Panama City, Florida; Pulmoddai, Ceylon; and the Amazon valley, Brazil. Polished grains of ilmenite were first studied by reflected light and then individual grains of similar physical character were assembled and examined (a) as single grains and (b) as powders by x-ray methods. Magnetic concentrations tests were also carried out. Lynd et alia examined only magnetic concentrates and not carefully selected individual grains and groups of grains.

Three stages in the alteration of ilmenite were recognised under the microscope.

"Stage I. (Patchy ilmenite). The products of the first stage of alteration are patchy intergrowths of altered and unaltered ilmenite. The first indication of alteration is the appearance of elongated stringers, rims or rounded patches of a material having a reflectively near that of rutile but slightly lower. The colour of this material is grey, in contrast to the pinkish caste of ilmenite. It is near the color of rutile but is slightly darker..... In the more advanced stages, alteration spreads until unaltered ilmenite is no longer visible, and as the grains become optically homogenous, stage one passes into stage two .....

The first stage of alteration of ilmenite is accompanied by progressive decrease of anisotropism and this can be shown quantitatively by measurement of rotation properties of unaltered

and altered grains. Altered grains give lower values of the apparent angle and show less dispersion. Where altered and unaltered ilmenite are present in the same grain, the angle of apparent rotation of the altered material is always lower than that of the unaltered ilmenite. The decrease in rotation angle and dispersion appears to be progressive. For those grains in which alteration approaches stage two, dispersion is lacking and the angle of rotation becomes too small to measure.

Stage II (Amorphous iron-titanium oxide). The end product of stage I is essentially amorphous and is here designated amorphous iron-titanium oxide. The alteration has now reached stage 2. At this stage the material gives the polarization figure of an isotropic substance. All traces of the pinkish colour of ilmenite have disappeared, and the reflectivity of the material is visibly higher than that of ilmenite and close to that of rutile. It is slightly greyer, however, and is opaque, showing no internal reflections.

Stage III. (Leucoxene). The final stage of alteration is marked by the development of leucoxene at the expense of amorphous iron-titanium oxide. The alteration may proceed in a variety of ways. In some grains it spreads inwards from the rims, from cracks in the grains, or from both. In others the development of leucoxene starts at points irregularly distributed throughout the grain. The areas formed of leucoxene are readily distinguished from amorphous iron-titanium oxide by their bright internal reflections, under crossed nicols. In still other grains leucoxene develops at innumerable points either evenly distributed within a grain or in bands (layers) parallel to the basal plane of the original ilmenite. As this type of alteration progresses, the grain becomes more and more

luminous under crossed nicols owing to increase in the strength
of internal reflections.

In the ideal case, stage one is complete and stage two is
thereby reached, before the beginning of stage three. In many grains,
however, stage three overlaps stage one, and at no time in the
alteration of such grains do they consist wholly of amorphous
iron-titanium oxide. The result is that many grains are composites
of unaltered ilmenite, amorphous material and leucoxene. In the
materials studied, however, alteration of part of a grain to leucoxene
is always preceded by alteration of that part to amorphous iron-
titanium oxide. Leucoxene developed along a fracture, along the
rim of a grain, or in patches in a grain is therefore always
separated from fresh ilmenite by amorphous material.

The leucoxene developed in the third stage of alteration is
finely crystalline and has a color in ordinary light that is close
to or the same as that of rutile. Under crossed nicols it shows
mass internal reflections ranging from brown to white. It differs
microscopically from ordinary rutile only in texture. Grains
of ordinary rutile are either single optical units, or, if composite,
consist of distinct units showing anisotropism and twinning normal
to this mineral".

The writer, from studies carried out on ilmenite concentrates
from Travancore, Natal and Cape Province South Africa, Malaya,
East and West Australia, New Zealand, Burma, Senegal, Sierra Leone,
Florida and Nyasaland, finds himself in agreement with the alteration
stages described by Bailey. Many of the features described in the
text are illustrated in the polished section photographs which,
together with reproductions from Bailey et alia accompany this
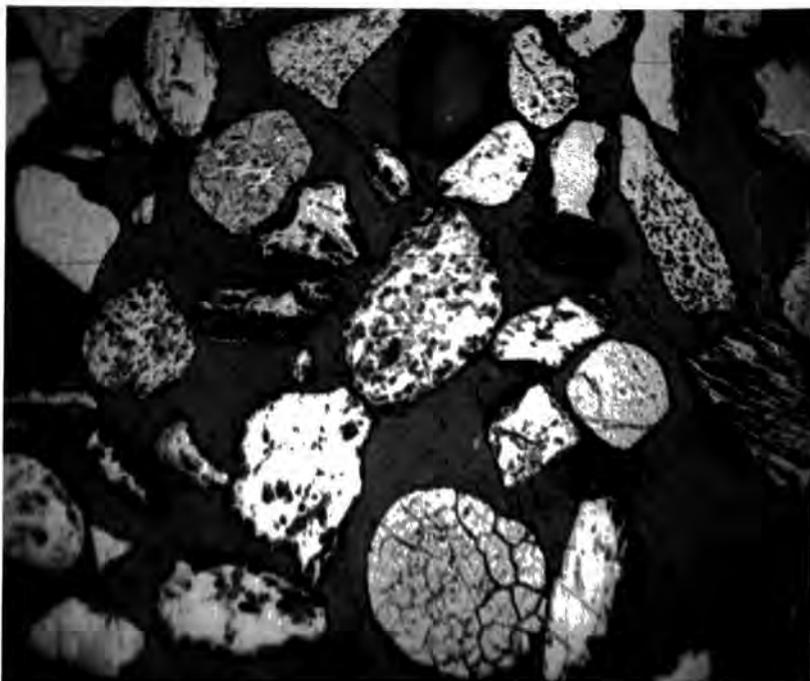
Plate V 1.   West Australia x 125.   This is a typical beachsand
               ilmenite shewing a variety of grain shapes.   Note that
               the more rounded grains shew more intensive alteration,
               most noticably in the cracked, almost spherical grain,
               which consists of brown leucoxene and a little amorphous
               Ti-Fe oxide.   The heavily striped grains although more
               spectacular are not at such an advanced stage of altera-
               tion.   The great difference in hardness between the
               light grey ilmenite areas and the black Fe-Ti-oxide and
               leucoxene makes polishing difficult hence the striking
               result.   The softer more completely leucoxenised grains
               take a better polish.
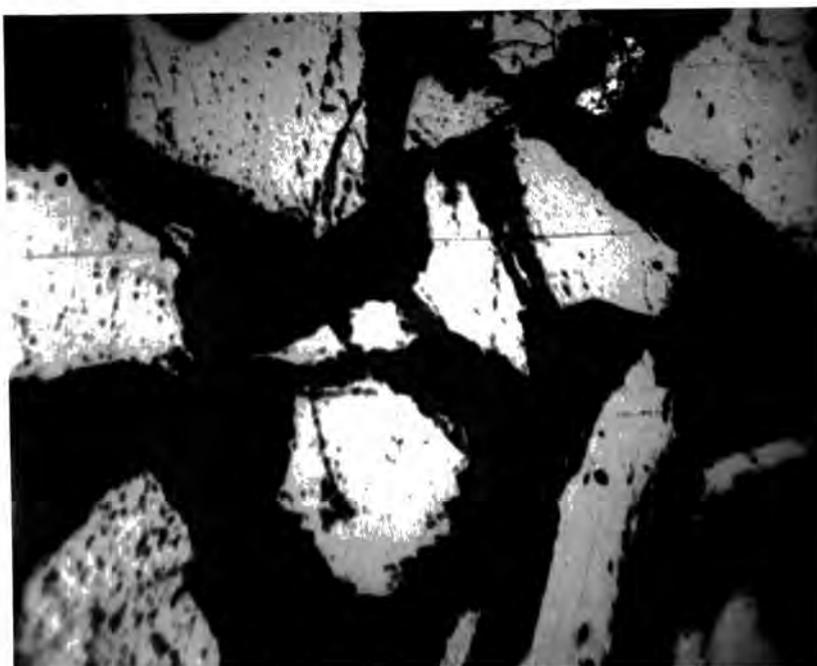

Plate V 2.   Storgangen Norway x 100.   An ilmenite mill concentrate
               illustrating the angularity of the grains.   The ilmenite
               is completely unaltered.   The larger included black dots
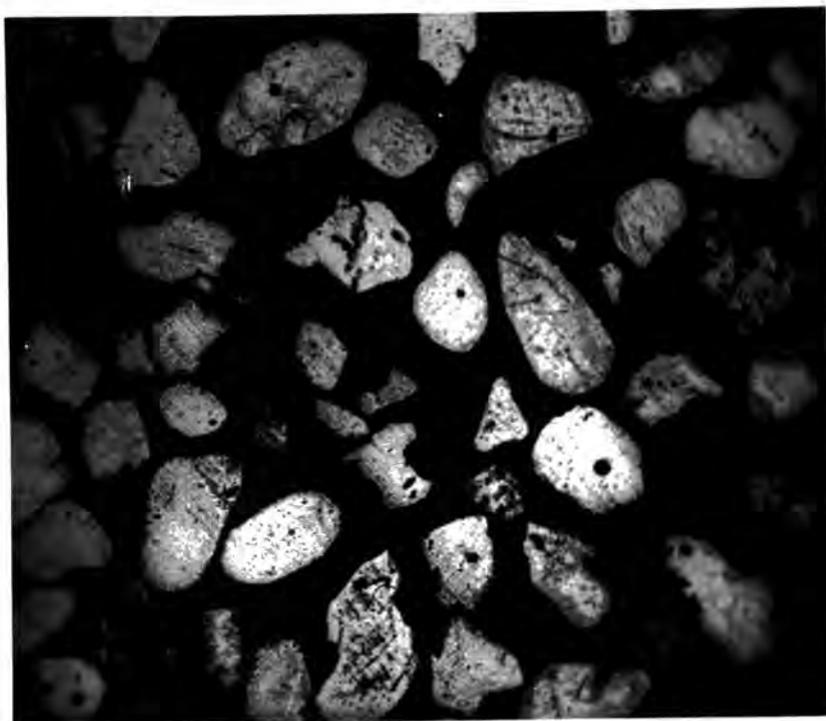   are silicate;   the smaller ones are polishing pits.

Plate V 3.   Quilon, Travancore x 125.   This is a beachsand containing
the maximum TiO_2 content encountered in this type of
deposit (61%).   Every grain has reached the early
leucoxene stage of development while some are completely
leucoxenised.   Note the rounded character of these softer
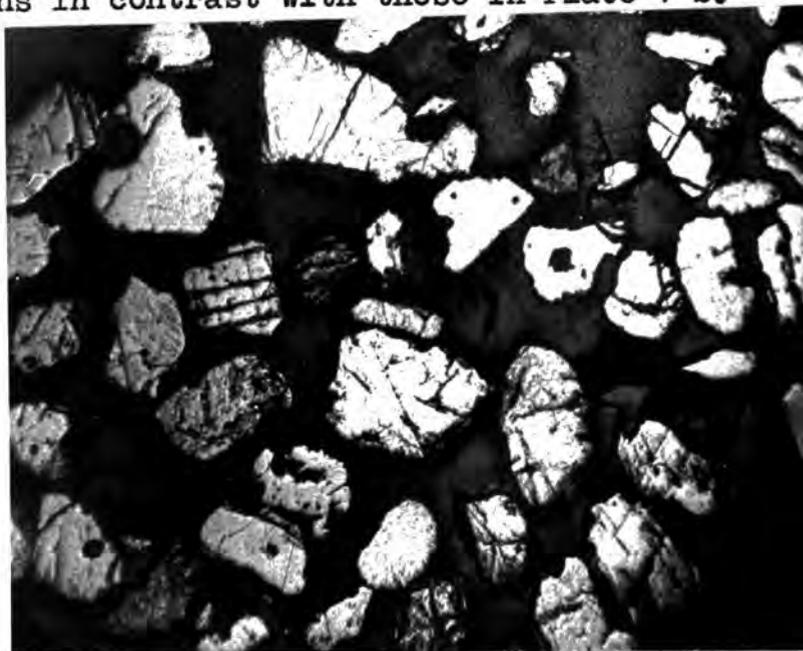grains in contrast with those in Plate V 2.

Plate V 4.   Sunkai, Malaya x 125.   The Sunkai 'ilmenite' concentrate
contains 69% TiO_2. Every grain has reached, usually on
the margins, a completely leucoxenised state.   Each
grain has a finely pitted surface which is produced in
polishing owing to the metamict state of grain constituents.
Note that although the TiO_2 content is high the
grains remain angular in an alluvial deposit.   Contrast
Plate V 3.

narrative.   It has been noted, however, that the transition from
unaltered ilmenite to brown leucoxene can often be very rapid in a
single grain.   The leucoxene is often separated from unaltered ilmenite
by only a very thin zone of the intermediate alteration products
which can sometimes only be detected with the aid of microscope
objectives of high magnification.   The loss of anisotropy in early
altered ilmenite which is accompanied by an increase in the ferric
iron content is presumably due to the development of dispersed
amorphous oxides, but it is also not improbable that the first
result of oxidation is the replacement within the ilmenite lattice
of ferrous by ferric iron.   Most of the leucoxene examined has shewn
brown-orange or red internal reflections and has presumably consisted
of rutile crystallites mixed with considerable amounts of amorphous (?)
hydrated ferric oxide.   White leucoxene formed from brown leucoxene
has proved to be quite a rare constituent in the ilmenite concentrates
listed above, but in some concentrates, notably the South African,
white leucoxene forms directlyfrom amorphous iron-titanium oxide.   The
causes leading to the formation of white leucoxene instead of brown
are unknown.

The conclusion of Lynd and his co-workers that the alteration
of ilmenite has been accompanied by oxidation, and leaching of iron
is strongly indicated by their data which is reproduced in Tables
V.II., V.III. and V.IV.   However, while their conclusions are almost
certainly correct, some of their results are peculiar in that wide
ranges of amperages were required to concentrate single mineral
fractions, and many of the figures they used to demonstrate leaching
of iron with concomitant increase of TiO_2 percentage in given ore
samples are scarcely conclusive.   For instance ilmenite from the

MacIntyre mine, Lake Sanford, used as a standard for comparison, was collected over an amperage range of 1.5.   Since the material was quite fresh and, apart from small quantities of exsolved hematite and possibly a little magnetite, pure, one could expect the mineral to be concentrated within a much narrower amperage range.   Another feature of their results, on which Bailey et alia have remarked, is the very small variation in TiO_2 content of the various concentrates. For example the successive magnetic fractions (see Table V.IV) of Quilon ilmenite show a range of only 2.7% TiO_2.   The ratio of Fe^{111}/total Fe varies only from 0.68 to 0.86 and in the Florida ore from 0.71 to 0.89. One would expect greater variations than these if indeed the alteration of ilmenite is due to progressive oxidation and iron leaching as the evidence obtained from the microscope studies suggests. In part this criticism of Lynd's results is not entirely fair because in the case of the Floridan material, and probably in the case of the other samples as well, ilmenite concentrates, which may have lacked the more highly weathered and relatively non-magnetic leucoxene fraction, were studied.

The cause of the spread of individual mineral fractions over such wide amperage ranges may have been due to the type of apparatus used.   It is suggested that the machine was perhaps insufficiently sensitive for the investigation carried out.

The ambiguity of Lynd and his co-workers results led Bailey and his associates to carry out similar tests on total heavy mineral fractions from beach sands from Brazil, Ceylon and Mozambique, using a Franz isodynamic separator.   Their results are recorded in table V.V, V.VI, and V.VII.   The broad pattern of their results is quite similar to those obtained by Lynd et al. but concentration of the

TABLE V.V

MINERALOGICAL ANALYSES OF SUBFRACTIONS OBTAINED FROM HEAVY MINERAL CONCENTRATE FROM A SAND FROM BRAZIL

(Bailey et. al.)

Minerals	Fraction No. 1 Magnetic at 0.25 amp		Fraction No. 2 Magnetic at 0.8 amp		Fraction No. 3 Magnetic at 1.5 amp		Fraction No. 4 Non-magnetic at 1.5 amp		Total heavy mineral percent in original concent.
	% of fraction	% of original concent.	% of fraction	% of original concent.	% of fraction	% of original concent.	% of fraction	% of original concent.	
Unaltered ilmenite.	5.3	4.4	1.7	0.2	1.3	tr.	tr.	-	4.6
Altered ilmenite of stage one.	14.3	11.7	0.2	tr.	-	-	-	-	11.7
Amorphous iron-titanium oxide.	25.4	20.8	6.0	0.5	-	-	-	-	21.3
Amorphous iron-titanium oxide-brown leucoxene composites.	36.9	30.3	9.6	0.9	-	-	-	-	31.2
Ilmenite-silicate composites.	0.2	0.2	0.3	tr.	-	-	-	-	0.2
Brown leucoxene.	17.7	14.6	58.7	5.3	-	-	-	-	19.9
White leucoxene.	-	-	4.5	0.4	19.6	0.5	1.9	0.1	1.0
Rutile	-	-	3.0	0.3	38.7	1.0	8.1	0.5	1.8
Rutile-leucoxene-silicate composites.	-	-	-	-	-	-	0.1	-	-
Rutile-silicate and leucoxene-silicate composites.	-	-	tr.	-	2.2	tr.	1.6	0.1	0.2
Zircon.	0.3	0.2	8.0	0.7	34.3	0.9	76.1	4.8	6.6
Other.	-	-	8.0	0.7	3.9	0.1	12.8	0.8	1.6
Totals	100.1	82.2	100.1	9.0	100.1	2.5	100.1	6.3	100.0

TABLE V.VI

MINERALOGICAL ANALYSES OF HEAVY MINERAL CONCENTRATE FROM BEACH SAND, PULMODDAI, CEYLON

Minerals	Magnetic at 0.05 amp		Magnetic at 0.15 amp		Magnetic at 0.25 amp		Magnetic at 0.80 amp		Magnetic at 1.5 amp		Non-magnetic at 1.5 amp		Percent of total heavy mineral concentrate
	% of fraction	% of total heavy mineral content	% of fraction	% of total heavy mineral content	% of fraction	% of total heavy mineral content	% of fraction	% of total heavy mineral content	% of fraction	% of total heavy mineral content	% of fraction	% of total heavy mineral content	
Unaltered ilmenite	25.8	2.3	17.0	7.4	9.4	2.3	-	-	-	-	-	-	12.0
Altered ilmenite (Stage 1)	60.3	5.3	53.0	23.2	35.1	8.6	0.8	tr.	-	-	-	-	37.1
Amorphous iron-titanium oxide	3.9	0.4	17.7	7.6	20.2	4.9	10.3	0.5	-	-	-	-	13.4
Ilmenite-rutile composites	-	-	0.2	0.1	0.2	0.1	0.4	tr.	-	-	-	-	0.2
Menaccanite	1.3	0.1	3.7	1.6	0.5	0.1	0.6	tr.	-	-	-	-	1.8
Composites of ilmenite, amorphous iron-titanium oxide, and leucoxene	7.2	0.6	6.1	2.7	19.4	4.7	6.1	0.3	-	-	-	-	8.3
Titaniferous magnetite	0.3	tr.	-	-	-	-	-	-	-	-	-	-	tr.
Brown leucoxene	-	-	1.5	0.6	12.4	3.0	60.8	2.8	1.1	tr.	-	-	6.4
White leucoxene	0.7	0.1	-	-	0.3	0.1	1.9	0.1	6.6	0.1	-	-	0.4
Rutile	-	-	0.2	0.1	0.3	0.1	4.6	0.2	63.7	0.8	37.5	6.6	7.8
Zircon	-	-	0.2	0.1	0.7	tr.	3.9	0.2	18.9	0.2	61.6	10.7	11.3
Heavy silicates	-	-	-	-	0.7	0.3	10.4	0.5	9.6	0.1	0.7	0.1	1.0
Hematite	-	-	-	-	-	-	-	-	-	-	0.2	tr.	tr.
Unidentified	0.4	tr.	0.4	0.2	0.3	0.1	-	-	-	-	-	-	0.3
Totals	99.9	8.8	100.0	43.6	100.1	24.4	99.8	4.6	99.9	1.2	100.0	17.4	100.0

TABLE V.VII

MINERALOGICAL ANALYSES OF THREE MAGNETIC SUBFRACTIONS OF A BEACH SAND

SAND FROM VILLA LUISA, MOZAMBIQUE

	Fraction No. 1 Magnetic at 0.25 amp		Fraction No. 2 Magnetic at 0.8 amp		Fraction No. 3 Non-magnetic at 0.8 amp		Total Percentage in original material
	% of fraction	% of original material	% of fraction	% of original material	% of fraction	% of original material	
Altered ilmenite of stage one	10.4	2.4	0.5	0.2	1.0	0.3	2.9
Amorphous iron-titanium oxide	24.2	5.7	2.8	1.2	2.0	0.6	7.5
Altered ilmenite-leucoxene composites	43.8	10.3	25.0	10.8	1.2	0.4	21.5
Brown leucoxene	5.4	1.3	22.8	9.9	12.0	4.0	15.2
White leucoxene	0.2	0.1	21.4	9.3	19.5	6.5	15.9
Altered ilmenite-silicate composites	0.2	0.1	1.0	0.4	-	-	0.5
Rutile	2.1	0.5	22.4	9.7	62.0	20.6	30.8
Rutile-silicate composites	0.2	0.1	0.4	0.2	-	-	0.3
Ilmenite-hematite intergrowths	0.3	0.1	-	-	-	-	0.1
Zircon	-	-	1.3	0.5	0.7	0.2	0.7
Other minerals	11.4	2.6	1.7	0.7	0.2	0.1	3.4
Unidentified	1.8	0.4	.7	0.3	1.4	0.5	1.2
Totals	100.0	23.6	100.0	43.2	100.0	33.2	100.0

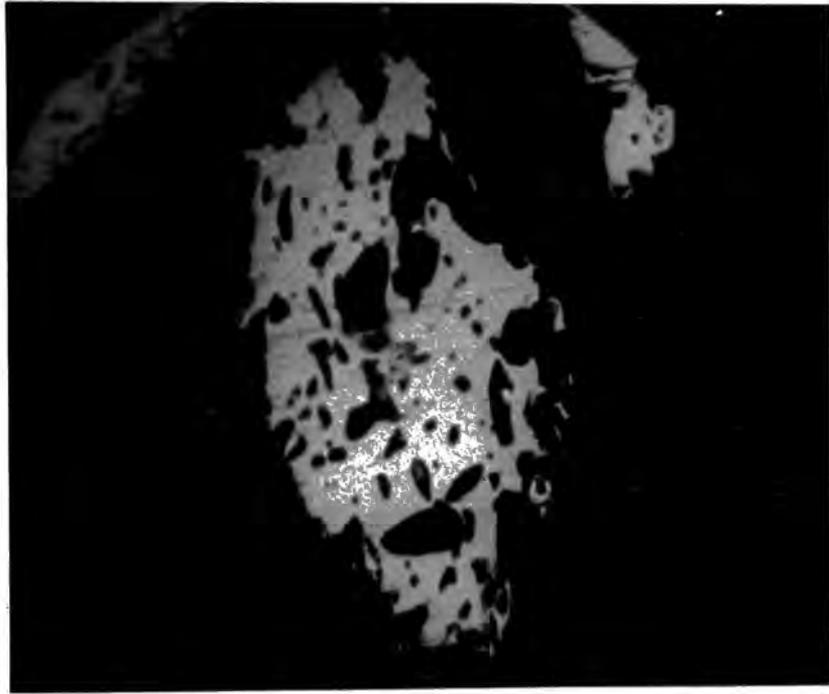Plate V 5.   New Zealand x 250. Sieve texture in an ilmenite grain
               from a New Zealand beachsand.   The inclusions are
               silicates.   This texture is undesirable in commercial
               ilmenites because the TiO_2 content is lowered.

Plate V 6.   Mozambique x 1100 xn.   Part of an ilmenite grain in
               the early stages of dendritic amorphous iron-titanium
               oxide development.   Reproduced from Bailey et alia
               1956.
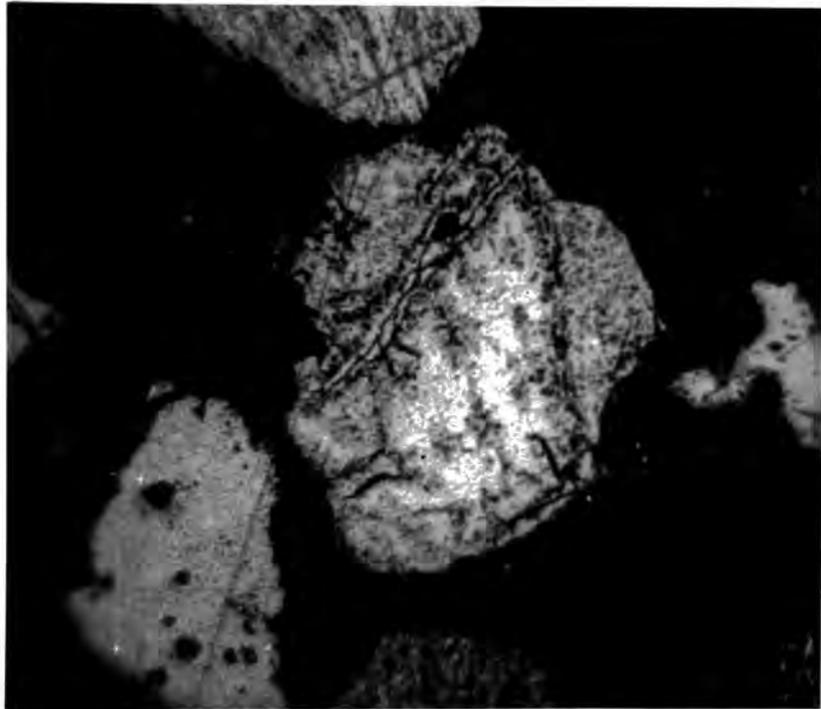
Plate V 7.   Malaya x 250.   The even grey irregular areas are
               ilmenite which has suffered early alteration with
               decrease of anisotropy.   Surrounding them are areas
               of amorphous Fe-Ti-oxide and early leucoxene intimately
               intermixed.   Leucoxene, slightly darker than ilmenite,
               has already formed along a crack traversing the grain.
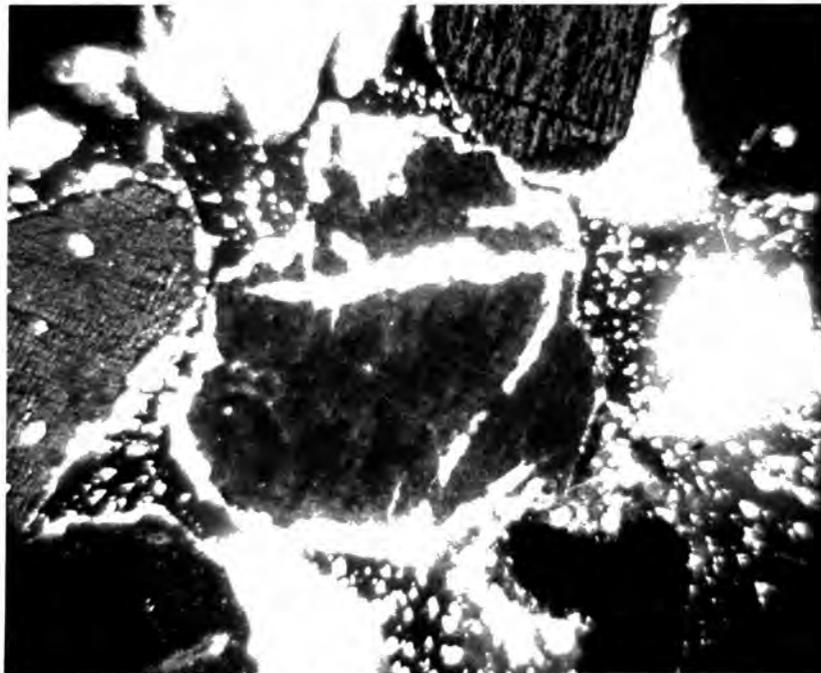

Plate V 8.   Malaya x n. x 250.   The same grain as in Plate V 7.
               The white areas are leucoxene, the dark grey areas
               Fe-Ti-oxide and early leucoxene, and the black (almost
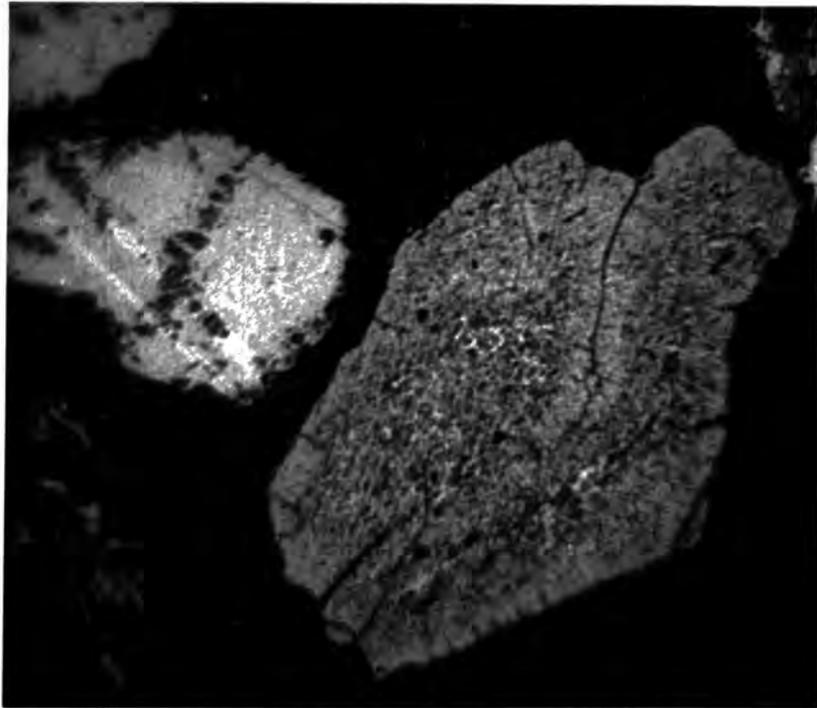   isotropic) areas are slightly altered ilmenite.

Plate V 9.   x 300.   Malaya.   The light grey root-like areas are
relictual ilmenite surrounded by pitted amorphous
iron-titanium oxide.   The margins of the medium
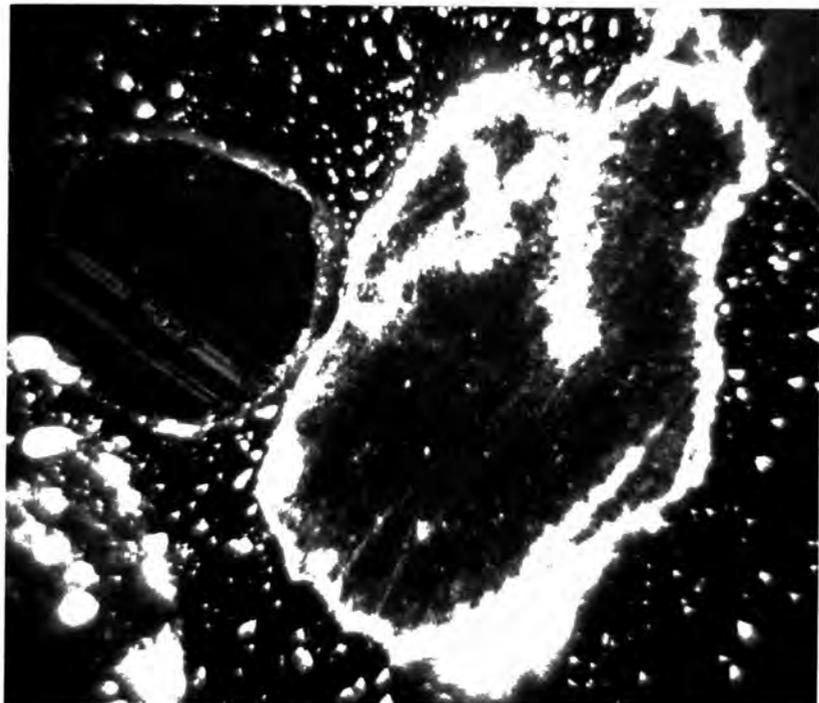grey grain and the borders of the crack are leucoxene.

Plate V 10.   xn. x 300.   The same grain as in Plate V 9.   White
areas are leucoxene.

Plate V 11.   x n x 1100.   Mozambique.   An advanced stage of
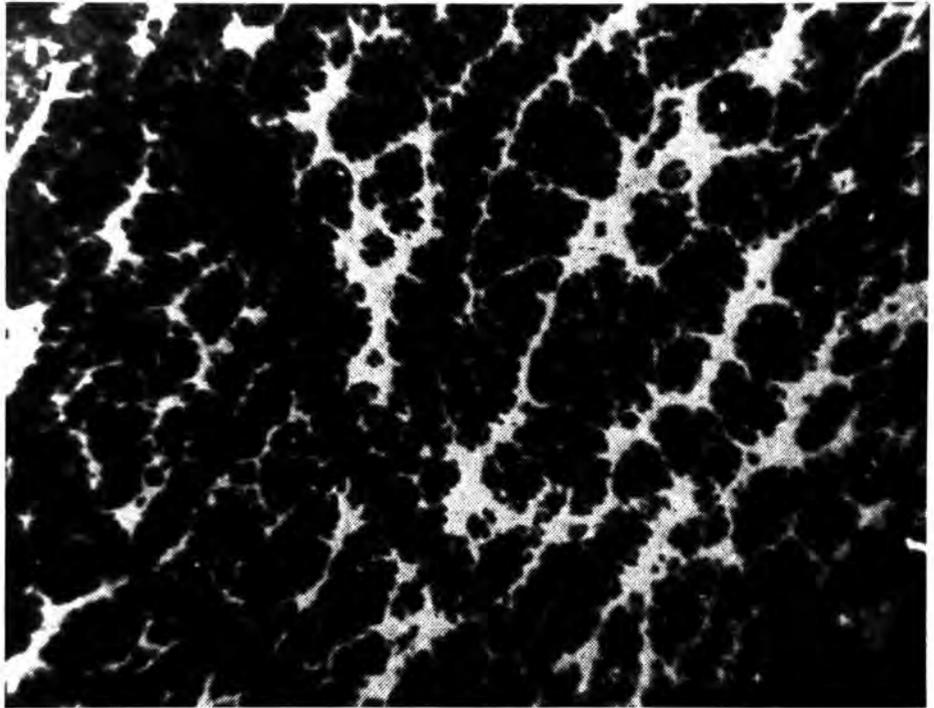amorphous iron-titanium .oxide development.   Ilmenite-
light grey, amorphous oxide-black.   Reproduced from Bailey
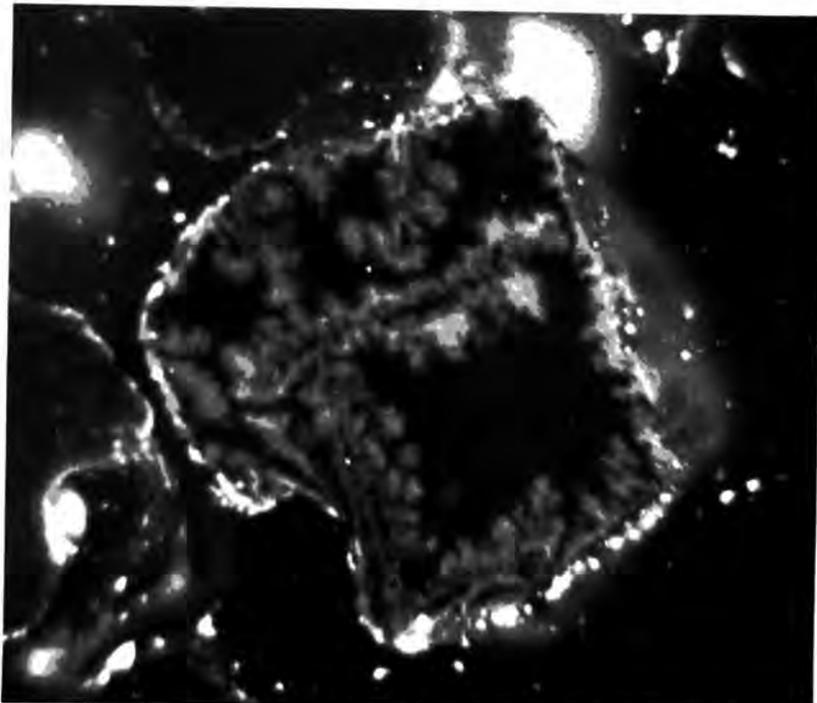et alia 1956.

Plate V 12.   New Jersey x n.x250.   A grain shewing a similar
dendritic-arborescent structure except that it is
at a more advanced stage of development with leucoxene
beginning to replace altered ilmenite and amorphous
Fe-Ti oxide (black).

mineral constituents of the sand has been obtained over much ampere narrower ranges.   The continuous process of alteration from ilmenite to leucoxene, through the amorphous iron-titanium oxide and brown leucoxene stages, accounts for the failure to obtain clean separations of these intermediate stages.

The conclusions of importance both to mineralogists and concentration plant engineers which can be drawn from Bailey and his co-workers magnetic concentration results are that (a) there is no difference in magnetic properties between unaltered ilmenite and patchy altered ilmenite (stage I).   This stage probably represents oxidation without leaching of iron.   (b) amorphous iron-titanium oxide has a magnetic susceptibility definitely below that of altered ilmenite (see Table V.VII)   (c) Brown leucoxene has a higher magnetic susceptibility than white leucoxene.   This is probably due to small quantities of amorphous iron-titanium oxide and goethite or hematite in the brown leucoxene.

From Lynd et alia's work Bailey et alia noted, by comparing the chemical analyses of magnetic fractions of different beach sands taken at similar amperages, that there was apparently no direct correlation between the amounts of iron and titanium present and the magnetic susceptibilities of the samples.   This indication was confirmed by their own work and they concluded that no simple relationship exists between chemistry of alteration, physical appearance and magnetic susceptibility.   However, although no precise correlation may be possible there appears to be a general sort of correlation detectable.   Hockin (1957) working on ilmenites from the Malayan alluvial deposits found that incipiently altered grains predominated in concentrates with a TiO_2 content of 52-53% and that

ilmenite in an advanced state of alteration (roughly corresponding with Bailey's stage III) predominates in concentrates containing 60-65% TiO_2. Following up this work the writer has found that with concentrates from a wide variety of localities listed in Table V.XI., some of which are illustrated with accompanying notes, quite good estimates (not better than $\pm$ 3% though!) of the TiO_2 content can be made by counting the number of grains falling into each of Bailey's classes. Allowance must, of course, be made for individual grains which overlap the stages' of alteration. Table V.XI, illustrated graphically by table V.X is based on far too scanty data to establish any soundly based hypothesis, but there is strong indication that a curve plotted for ilmenite alteration stages, which has a narrow standard deviation about an amorphous oxide stage mean, points to the ilmenite concentrate having a TiO_2 content between 54 and 60%. If the mean is nearer to leucoxene the TiO_2 content will be over 60%. In compiling table V.X., it was found necessary to erect an intermediate stage of alteration combining the characteristics of alteration stages II and the commencement of III owing to the fine intergrowth of these two stages in many grains. The estimates of the composition of the concentrates were obtained by a point-counting technique using a Swift instrument.

Chemical analyses of the three magnetic subfractions of the Mozambique beach sand, the mineralogical compositions of which are quoted in Table V.VII. are given in Table V.VIII. taken from Bailey et alia, together with recalculations which eliminate the TiO_2 content due to non-authigenic rutile so that the results reflect only the compositions of ilmenite and leucoxene. No allowance has been made for the possible iron and titanium contents of other unidentified
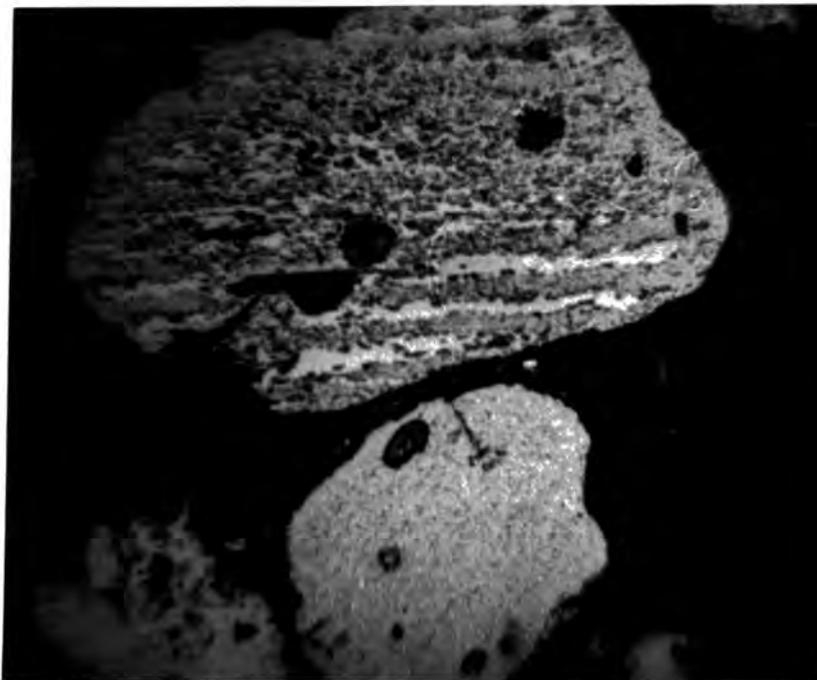
Plate V 13.   x 250. Malaya. Bands of unaltered ilmenite interspersed
with an intergrowth of early altered ilmenite amorphous
Fe-Ti-oxide and a little early leucoxene.   The bands
follow the 0001 direction in the ilmenite.
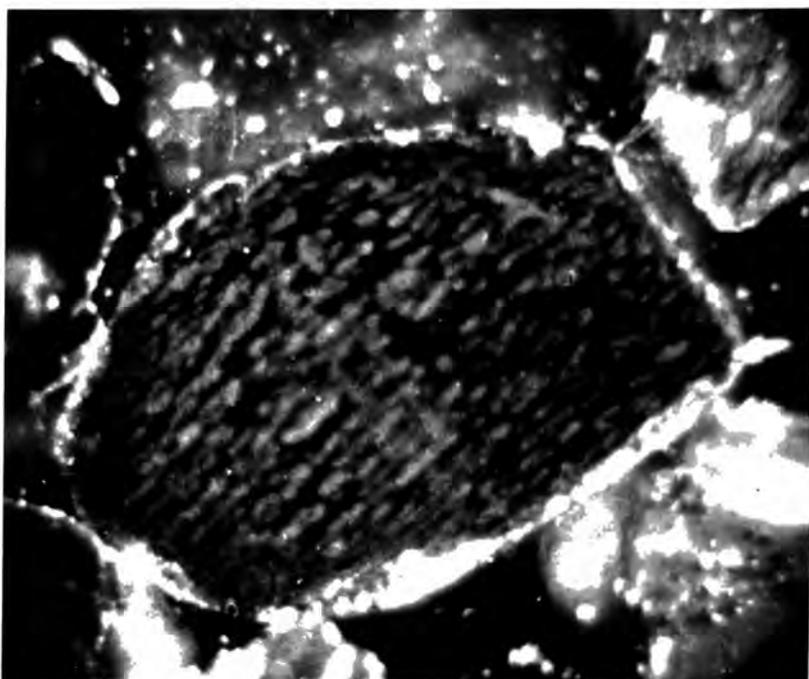
Plate V 14.   New Jersey. xn x 250. Early brown leucoxene (light
grey) forming at the expense of amorphous Fe-Ti-oxide
(black.)   The bright white rim of the grain is an
advanced stage of brown leucoxene development.
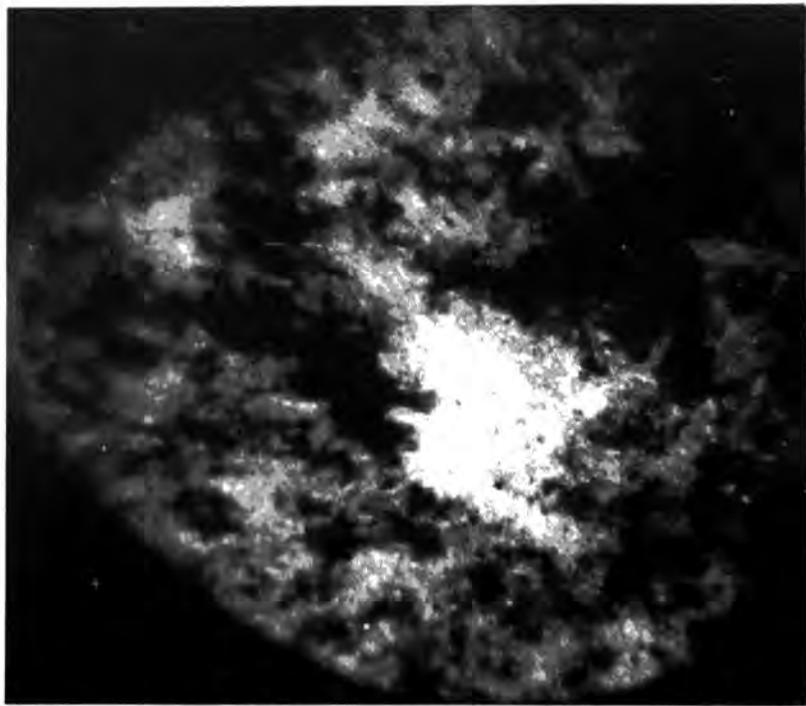
Plate V 15.   New Jersey xn. x 300.   White leucoxene (light grey)
with an edging of brown leucoxene (dark grey) developing
from amorphous Fe-Ti-oxide (black).   Note that
white leucoxene forms only within brown leucoxene.
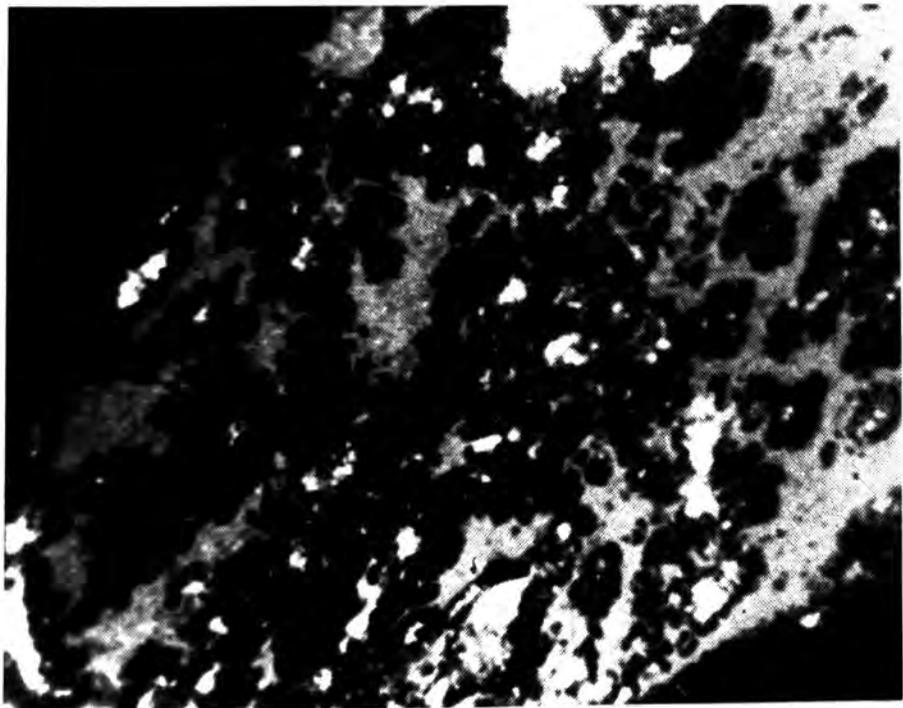
Plate V 16.   Mozambique xn. x 1000.   An enlargement of part of a
grain of ilmenite shewing leucoxene (white) developing
within amorphous iron titanium oxide (black) which is
forming at the expense of ilmenite (grey.)   Reproduced
from Bailey et alia 1956.
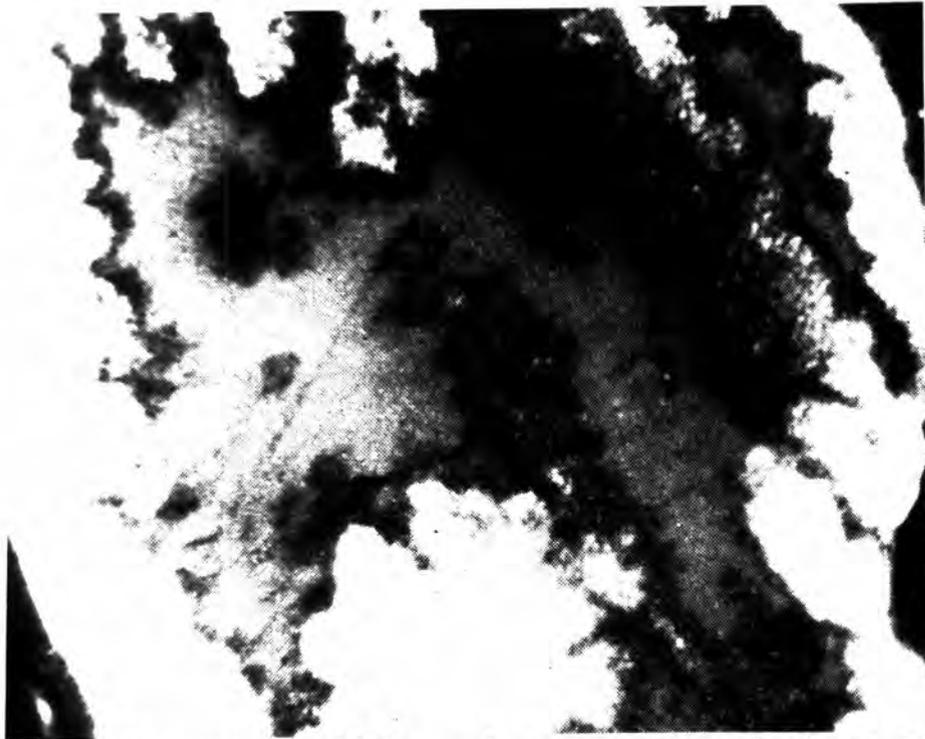
Plate V 17.   Mozambique xn. x 1100.   A more advanced stage of
leucoxene development.   Leucoxene is white, amorphous
Fe-Ti-oxide black, and ilmenite grey.   Reproduced
from Bailey et alia 1956.
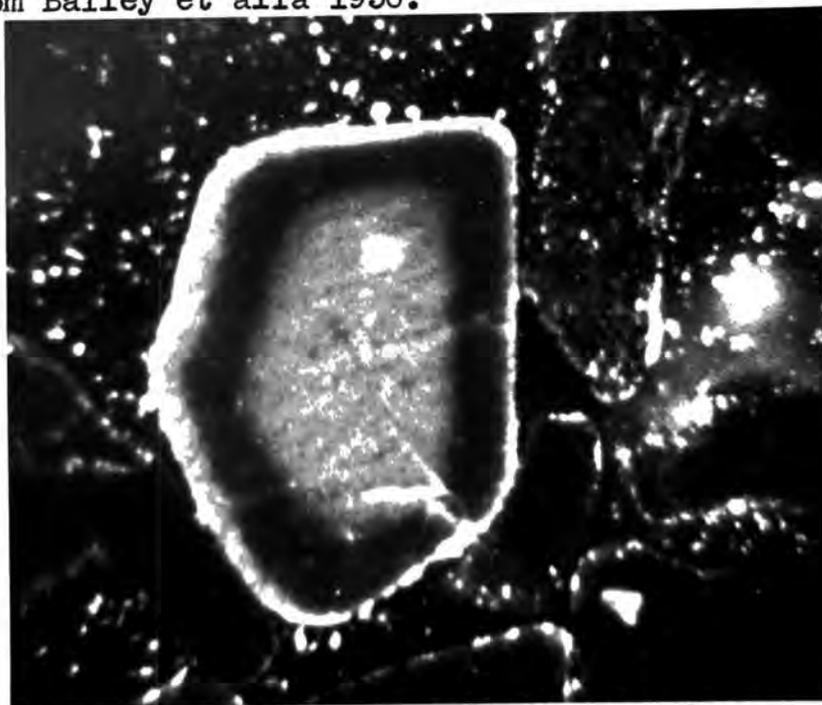
Plate V 18.   New Jersey xn. 250.   A grain of brown leucoxene shewing
zoning.   Each rim is a shade of orange brown
except for the narrow (white) outer zone which is very
pale yellow.   It is converting to white leucoxene by
loss of iron.   In ordinary light the grain is a
homogenous grey-white colour.

minerals listed in Table V.VII.   The effect of these will be
negligible in the final results for subfractions 2 and 3 but may
be slightly significant for subfraction 1.

These results substantiate further the conclusion that leaching
of iron has occurred during the alteration of ilmenite.

X-ray studies of the altered ilmenites have been carried out
by Lynd et alia, Bailey and his co-workers and the present writer.
Some of the results obtained by Lynd are included in Table V.III.
From these results they were able to conclude that the leucoxene
produced by the alteration of ilmenite could be either rutile or
anatase and that much of it was of a/crystalline size, that is less
than 100A° in diameter, such that it was amorphous to x-rays.   Lynd
also re-studied the original arizonite of Palmer and found that it
consisted of 40% hematite, 40% anatase, and 20% rutile thus agreeing
with Overholt, Vaux and Rodda (1950).

Bailey and his colleagues carried the x-ray studies a step
farther in that they photographed single crystal-grains of the various
stages of alteration of ilmenite.   They found that as alteration by
leaching and oxidation increased, so the x-ray pattern produced
developed from a sharp spot pattern to a diffuse spot pattern and
finally, by coalescence of the spots, to a pattern of concentric rings
typical of a powder.   They also noticed that in many cases the circles
did not have a uniform circumferential density, but that there was
a distinct orientation of the most dense sectors indicating an
orientation of the mineral crystallites within the alteration products.
During the course of mineralogical investigations the writer has noted
that in ilmenite grains completely replaced by rutile relect twinning
is often detectable, each half of the twin showing internal reflections

Table V.VIII.   Three Magnetic Subfractions of a Mozambique beach
sand.

	Chemical Analysis		Recalculated Analysis	
	% FeO*	% TiO_2	% FeO*	% TiO_2
Ilmenite (theoretical)	47.34	52.66	47.34	52.66
1. Subfraction magnetic at .25 amps.	28.15	56.90	29.3	55.9
2. Subfraction magnetic at 0.8 amps.	6.9	82.1	8.9	76.8
3. Subfraction non-magnetic at 0.8 amps.	0.9	95.2	2.6	86.8

* All iron calculated as FeO.

Table V.IX.   Results of x-ray studies of grains from beach sands,
Mozambique.

Microscopic Identification	X-ray Identification
1. Ilmenite, unaltered	Ilmenite single crystal. Sharp pattern
2. Ilmenite, patchily altered (Stage I)	Ilmenite single crystal. Slightly diffuse spots plus powder line at d=2.0A°.
3. Ilmenite, patchily altered (Stage I)	Ilmenite single crystal. Medium diffuse spots plus powder lines at d=6.6, 3.3, 2.0A°.
4. Amorphous iron titanium oxide (Stage II)	Ilmenite single crystal. Few and extremely diffuse spots.
5. Ilmenite-brown leucoxene composite	Ilmenite single crystal plus rutile (oriented aggregate) plus powder line at d 7.3A°. Sharp ilmenite spots; rutile powder lines have intensities concentrated along certain arcs. Rutile (oriented
6. Brown leucoxene	aggregate) plus powder lines at d=7.0, 2.8, 2.38A°.
7. White leucoxene	Rutile (oriented aggregate)
8. White leucoxene	Brookite (oriented aggregate)

TABLE V. X

Ilmenite and its alteration products in beach and alluvial sands.

Locality Key.

Sunkai	— · — ·
New Jersey	— — — —
Travancore	— — — — —
Senegal	— · — · · —
Malaya (unspec.)	· · · · · · · · · ·
East Australia	— ⊬ — ⊬
West Australia	— — · · · — —
South Africa	— — · · — —
Nyasaland	—————

%

80

70

60

50

40

30

20

10

0

Unaltered
Ilmenite.

Amorphous
Fe-Ti-Oxide.

Amorph. Fe-Ti-Oxide
& early Brown Leucox.

Brown
Leucoxene.

White
Leucoxene
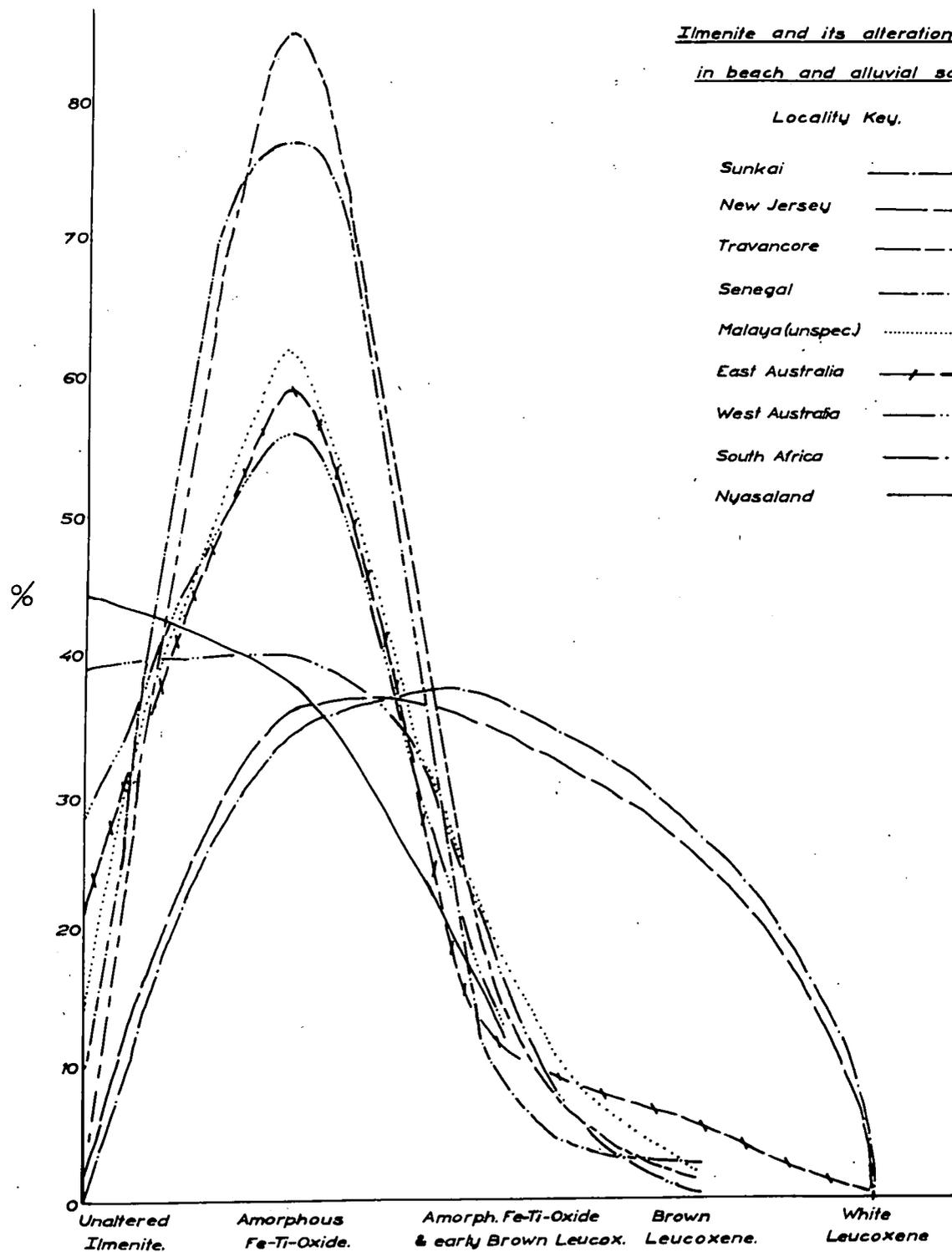
Table V XI Chemical, Xray and episcopic data on various Ilmenite Concentrates

Locality	TiO₂	FeO	Fe₂O₃	No. of lines	X-ray Pattern (Minerals detected)	Mineral detected by X-rays	Episcopy
Sierra Leone	46.4	33.6	19.5	23	Sharp	Ilmenite & trace of magnetite	Fresh angular grains with abundant hematite exsolution lamellae and a little magnetite, slightly martitized
Otanmaki, Finland				33	Sharp	Ilmenite	Fresh angular grains with some hematite and magnetite exsolution lamellae
Storgangen, Norway				21	Sharp	Ilmenite	Fresh angular grains with hematite exsolution lamellae
Nyasaland (Port Herald)	50.2	34.4	15.5	17	Moderately sharp	Ilmenite and a little rutile	Most grains show slight alteration to amorphous Fe-Ti-oxide. Hematite exsolution lamellae and some non-authigenic rutile. Unaltered Ilmenite 44% early alteration + Fe-Ti-oxide 38%. Early leucoxene 14%
South Africa (Umgababa)	51.0	38.6	10.3	25	Sharp	Ilmenite and a slight trace of rutile	Some grains contain hematite exsolution lamellae. Most grains show circumferential development of early leucoxene. Unaltered Ilmenite 39%. Early altered & FeTi Oxide 40% Early leucoxene 1%.
East Australian	54.2	26.5	19.2		N O D A T A		Unaltered Ilmenite 21%. Early alteration + Fe-Ti-oxide 59%. & Fe Ti Oxide 13%. Brown Leucoxene 6% White Leucoxene 1%
Malaya	58.3	31.1	9.7	15	Rather Diffuse	Ilmenite rutile & very weak hematite	Unaltered Ilmenite 14%. Early alteration & Fe-Ti-Oxide 62%. Early Leucoxene & Fe-Ti-Oxide 21%. Brown Leucoxene 3%.
Senegal	58.4	11.0	30.5	11	Diffuse	Ilmenite & rutile	Unaltered Ilmenite 10%. Early alteration & Fe-Ti-oxide 77%. Early leucoxene & Fe-Ti-oxide 11%. Brown Leucoxene 3%.
West Australian	58.9	25.0	15.8	15	Diffuse	Ilmenite & rutile. Possible trace of anatase	Unaltered Ilmenite 28%. Early altered + Fe-Ti-oxide 56%. Early leucoxene 16%

Analyses recalculated to 100% for constituents given

Travancore	60.8	12.7	26.3	18	Rather diffuse	Rutile and some ilmenite	Unaltered Ilmenite 4%. Early alteration + Fe-Ti-Oxide 85%. Early leucoxene and Fe-Ti-oxide 19%. Brown leucoxene 2%.
New Jersey	63.9	0.5	35.6	7	Diffuse	Rutile with a little ilmenite and hematite	Unaltered Ilmenite 2%. Early altered and Fe-Ti-oxide 36%. Early leucoxene and Fe-Ti-oxide 35%. Brown Leucoxene 26%. White leucoxene 1%.
Sunkai	69.2	8.2	22.6	10	Diffuse	Rutile with a little ilmenite	Unaltered Ilmenite 1%. Early altered & Fe-Ti-oxide 34%. Early leucoxene & Fe-Ti-Oxide 37%. Brown leucoxene 28%. White leucoxene 2%.

concentrates abstracted from a beach sand heavy mineral deposit
of the New South Wales seaboard.   They discovered, like Lynd et alia
and Bailey et alia, that the ilmenite varied in its magnetic
susceptibility.   They were able to divide the ilmenite concentrate
into fifteen different fractions, varying in magnetic susceptibility
from $0.32^{x10^{-3}}$ e.m.u. for the least magnetic fraction to $11.0^{x10^{-3}}$ e.m.u.
for the fourth most magnetic.   The three most magnetic fractions
contained free magnetite, detected by x-ray examination, and these
were discarded.   The fraction with the lowest magnetic
susceptibility had a Cr_2O_3 content of 13.0% and by spectrophotographic
analysis was shown to contain small included grains of chromite.

The eleven median fractions, on being exposed to x-rays, each
produced a typical ilmenite pattern on photographic emulsions.   They
did not appreciably vary one from the other and apparently showed
no traces of any pattern which could have been attributed to the
presence of other minerals.   Partial chemical analyses were performed
on the different fractions, and it was found that as the magnetic
susceptibility decreased, so the Fe^{111}/Fe^{11} ratio decreased from
0.64 to 0.39 indicating a decreasing oxidation of the iron.   Unfortunately
no mineralogical determinations were carried out so that no exact
correlations between changes in the physical, magnetic and chemical
properties of the various ilmenite fractions can be deduced.   At first
sight these results are totally at variance with those obtained by
Bailey et al. and Lynd et al. and it becomes necessary to attempt
to account for this discrepancy.   Table XII is taken from the
published results of Curnow and Parry's work.

Table V.XII.   Chemical and Magnetic Properties of Various Magnetic
Subfractions of an ilmenite concentrate (Curnow
and Parry 1955).

Fraction	% Wt. Distribution	Vol. Susceptibility e.m.u. $x\ 10^{-3}$	TiO_2	Fe	Wt.% Cr_2O_3	MnO	$\dfrac{Fe^{111}}{Fe^{11}}$
D	2	11.0	46.9	37.0	0.36	2.2	0.64
E	12	8.7			0.15		
F	16	4.3			0.09		
G	7	3.8	49.7	36.8	0.09	2.3	0.51
H	13	2.3			0.097		
I	10	1.4			0.093		
J	4	1.3			0.11		
K	5	0.65	51.8	35.2	0.09	2.6	0.44
L	6	0.62			0.09		
M	11	0.52			0.09		
N	5	0.467	50.1	34.3	0.24	1.6	0.39
O	6	0.32			13.0		

An important fact, which can be seen in the analytical figures,
is that the TiO_2 content of the ilmenites is below the theoretical
figure of 52.66% for pure ilmenite, but there is a consistent
variation in them from 46.9% for the most magnetic fraction richest
in trivalent iron to 51.8% in fraction K, with a slight drop to
50.1% in the least magnetic and most Fe^{11} rich fraction N. Fraction
O is omitted from consideration owing to the small included chromite
bodies in the ilmenite. Thus there appears to be a real variation
in the TiO_2 content of the original ilmenite for, even if the
trivalent iron has been produced by secondary oxidation of divalent
iron, recalculation of the total iron as FeO does not significantly
reduce the 5% difference between the maximum and minimum TiO_2
values. There is no evidence to suggest that the TiO_2 content should
vary as a result of secondary alteration.

The decline in the TiO_2 content of the ilmenite with increasing
Fe_2O_3 content appears to contradict the general findings of Lynd et
al. and Bailey et al. but in fact this may not be the case. TiO_2

and Fe_2O_3 percentages increased as ilmenite became altered to leucoxene but it can be concluded that ilmenite from New South Wales has not been altered to the leucoxene stage of development, because there is no sign of a rutile pattern when it is subjected to x-ray examination. If the variations in TiO_2 and Fe^{111}/Fe^{11} content of the ilmenite are to be attributed to alteration of the ilmenite, then it would seem that these variations occur within Stage I of observed alteration as defined by Bailey. Within this stage of "patchily altered" ilmenites and amorphous iron titanium oxide Bailey et al. found no indication (see Table V.IX) of a mineralogical change detectable by x-ray examination. Reference to the data obtained by experimenting with ilmenite concentrates from North Carolina included in Table V.II. (Lynd et al.) reveals that the mineral fractions of this slightly weathered ore show a similar decline in the Fe^{111}/Fe^{11} ratio with declining magnetic susceptibility. The result is complicated by small amounts of Fe_3O_4 which are present, and admittedly the TiO_2 does not behave as in the case of the Australian ilmenite, but nevertheless a measure of support is provided for the hypothesis that the Australian ilmenite has suffered only incipient alteration and represents perhaps an earlier stage of alteration than that which the North Carolina concentrates have reached.

The absence of any recognisable mineral other than ilmenite in the x-ray powder photographs, leads to the conclusion that the excess ferric iron must largely be either in solid solution with the ilmenite or in an amorphous state. According to Edwards only 6% of Fe_2O_3 could be accomodated in the ilmenite by the replacement of the Fe^{11} by Fe^{111} ions, so that the remainder must be at the
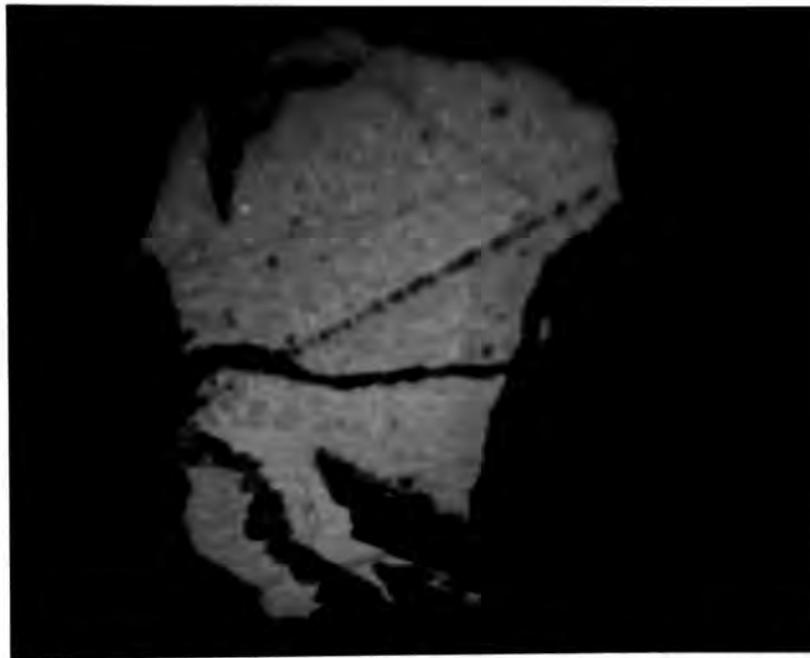
Plate V 19.   Nyasaland xn. x 250.   A composite grain of ilmenite,
containing hematite exsolution discs (speckled grey
area), and rutile (even lighter grey forming 'promontories'
at the edge of the grain).   Concentrates which contain
this type of grain are a snare for the unwary purchaser
because non-authigenic rutile of this type represents
TiO_2 unrecoverable in the usual type of pigment process.
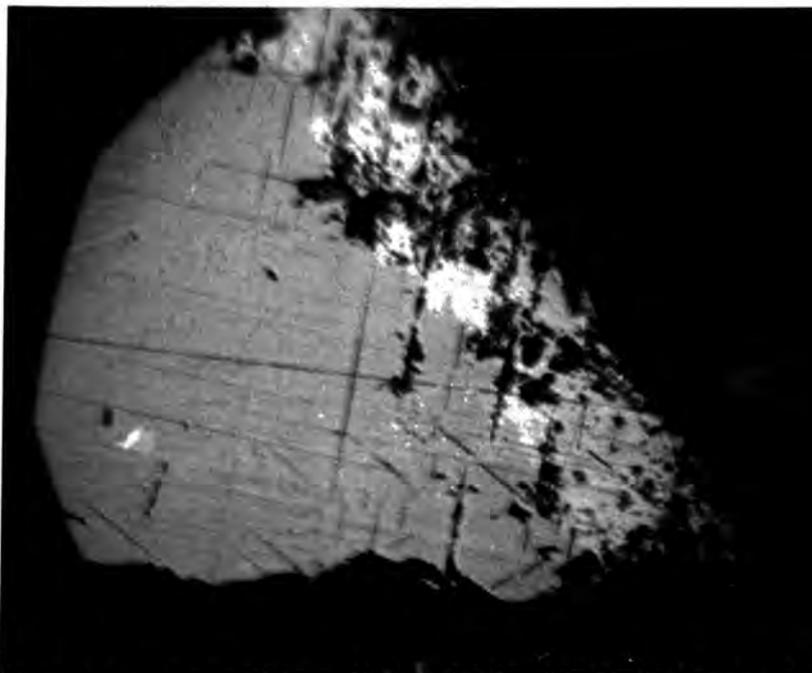
Plate V 20.   Sierra Leone x 200.   Magnetite (grey) in an early
stage of alteration to martite (white).   Spinel
lamellae (black) can be seen in the magnetite.
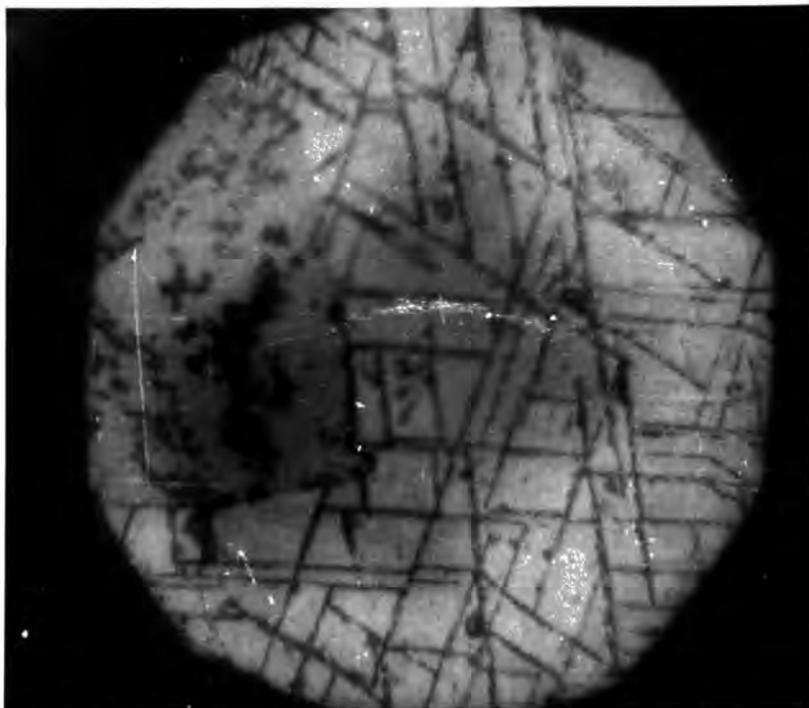
Plate V 21. Aden Protectorate x 900. Magnetite, now martite
and goethite, containing amorphous Ti-Fe-oxide lamellae
(black) formed from ilmenite. The latter have not
taken a polish. An advanced stage of alteration in a
grain in a beachsand derived from locally outcropping
lavas.
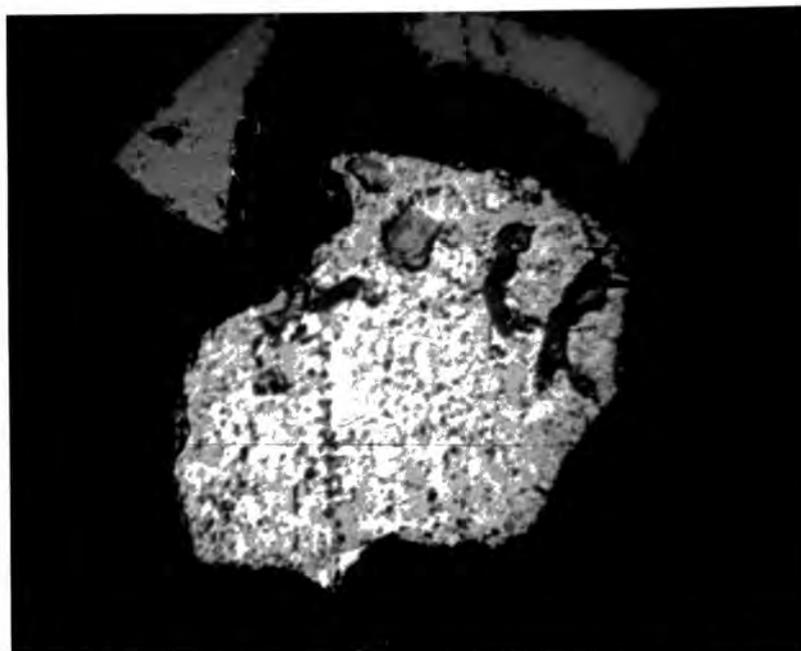
Plate V 22. Burma x 250. An intergrowth of rutile (grey) and
maghemite (light grey) (γ Fe_2O_3). Maghemite is
isotropic but has a higher reflectivity than the
amorphous mixed oxides. This was presumably formed
from either an irregular ilmenite-magnetite
intergrowth or ilmenite.

amorphous iron-titanium stage of alteration. Neither

of these processes alters the ilmenite cell size or produces any

significant difference in the x-ray powder pattern. The cause of the

increase in magnetic susceptibility with increasing Fe_2O_3 content

is difficult to ascertain. Most probably it is due to small

quantities, too small to be detected by x-rays of magnetite

exsolved from some of the ilmenites but obviously without examining

the minerals under the microscope one cannot arrive at any conclusion.

There is a possibility, which would be worth investigating, that

the oxidation in its early stages may give rise to a ferri-ilmenite

of the type described by Chevallier, Bolfa and Mathieu (1955)

and Pouillard and Michel (1949; 1950) (see Chapters II and III).

It might be suggested that the trivalent Fe in the beach sand il-

menites could be combined as γ Fe_2O_3 instead of the α variety. This

is less probable if only because γ Fe_2O_3 has a cubic spinel structure

and $FeTiO_3$ a hexagonal lattice, with the result that they are

naturally less compatible than α Fe_2O_3 and $FeTiO_3$, both of which

have very similar hexagonal lattices. Evidence which bears upon this

point is forthcoming from studies of the Bushveld ores of the

Transvaal which have been made by Frankel and Grainger (1941) and

Strauss amongst others. The titaniferous magnetite in the ore has

been in part oxidised, as far as is known by sub-aerial processes,

to maghemite, or γ Fe_2O_3. There is, therefore, evidence that

Fe_2O_3 can be formed in atmospheric oxidising conditions, so that

its occurrence in beach sand ilmenite would not appear to be

impossible from any reduction – oxidation potential or temperature

considerations. On the other hand the maghemite in the Bushveld ores

occurs only as an alteration product of magnetite, Fe_3O_4, which has a

spinel structure, and not of the ilmenite.

The effect of atmospheric oxidation on titaniferous magnetite in beach sands is, as yet, an uninvestigated problem. The processes of breakdown of magnetite, containing titanium both in solid solution and as exsolution lamellae, are not yet fully understood and there is little data available on the relative rates of decay of titaniferous and non-titaniferous varieties. The writer would suggest that the greater stability of ilmenite may be due to a sort of "cementing" effect caused by the presence of the stable TiO_2 molecule, which holds the mixture of hydrated ferric oxides together in a manner of which the original ferric iron in magnetite is incapable. The lack, or at least low content, of magnetite in the heavy mineral concentrates of tropical and sub-tropical beaches, where derived other than directly from igneous or metamorphic rocks is evidence strongly in support of the theory that magnetite is less stable than ilmenite in atmospheric conditions. A beach sand from the south Arabian coast which the writer has examined contains evidence supporting this conclusion. Natural heavy concentrates formed from the sand contain up to 35% opaque minerals of which about 15% are strongly ferromagnetic magnetite and the remainder, apart from a few percent of ilmenite, are hydrated ferric oxide containing exsolution lamellae of ilmenite, some of which are now rutile. The magnetite in the sand has been derived from locally outcropping lavas. Thus, despite the close proximity of the source rock, the ratio of altered to unaltered magnetite is as high as 6:1.

This is not to suggest that magnetite, or at least titaniferous magnetite, is a _very_ unstable mineral in such an environment. The high concentrations and enormous tonnages of the mineral on the west coast beaches of North Island, New Zealand confound any such
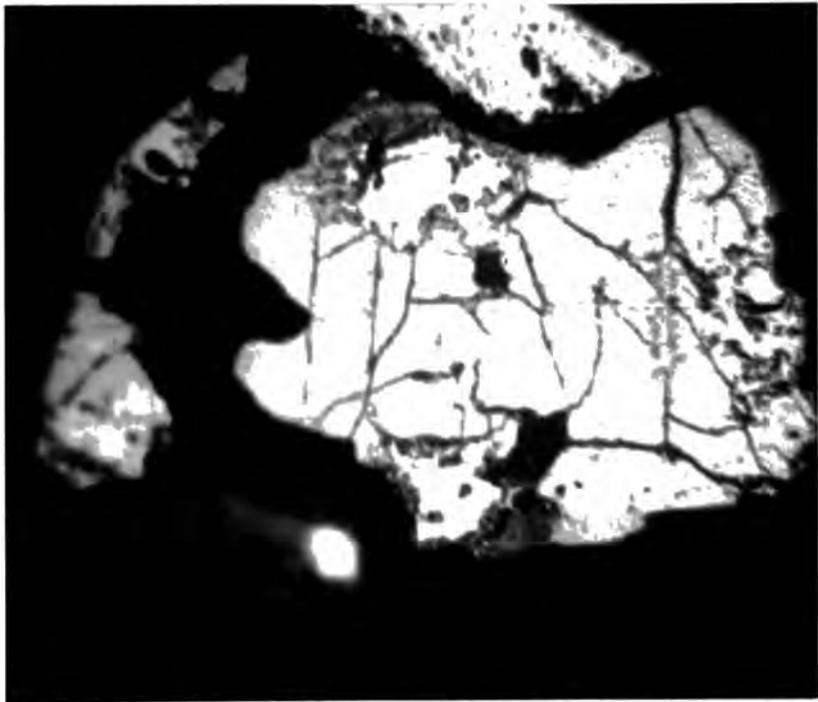
Plate V 23.   Burma x 250. The light grey-white areas consist of a
fine rutile-maghemite intergrowth, which is not visible
on the photograph, enclosed by replaced ilmenite.
Small root-like relictual areas of ilmenite (even grey)
are just visible among the slighter darker, finely
pitted early leucoxene-amorphous Fe-Ti-oxide intergrowth.
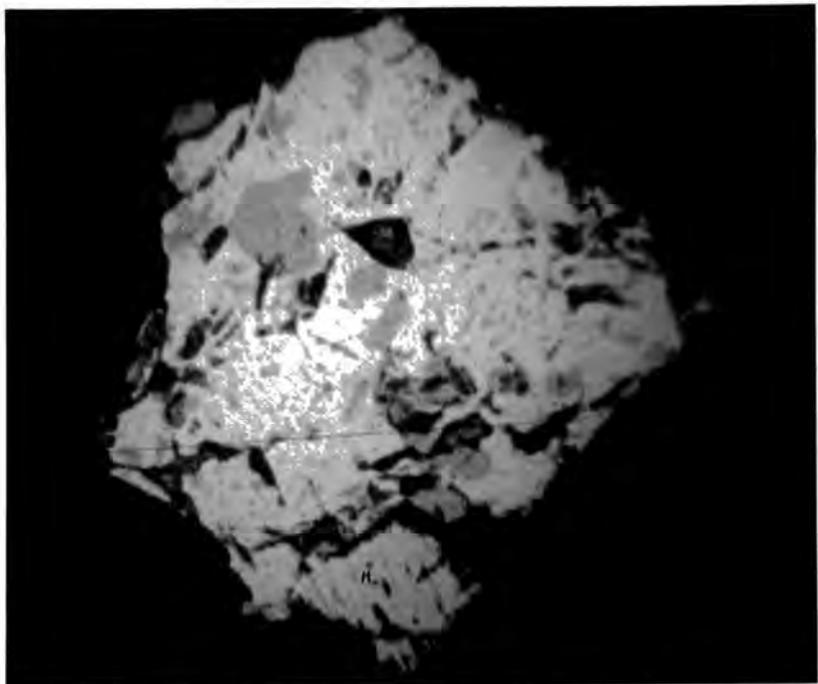
Plate V 24.   Burma x 200.   Grey-white maghemite enclosing relictual
areas of grey magnetite. The marginal area marked H is
hematite containing exsolution blades of ilmenite.

hypothesis.   The accumulations of opaque minerals on the North Island beaches differ genetically in a most significant manner from the ilmenite-rutile deposits earlier described.   Although no detailed studies have been carried out it is clear that the titaniferous magnetite has been derived directly from effusive volcanic rocks of Tertiary or younger age.   No intermediate stage of lateritic weathering or re-deposition has intervened between the removal of the minerals from their source rock and their deposition on the ocean beaches.   The result of this rapid transit is a general limitation to the amount of oxidation of the ferrous iron that has occurred.

Conclusions

From the evidence presented in the preceding section the following general conclusions can be stated concerning the nature and behaviour of iron-titanium oxide minerals in secondary deposits.

<u>Arizonite</u> is a discredited mineral species.

<u>Leucoxene</u> is not a mineral species but is usually a mixture of cryptocrystalline rutile or anatase.   It may be cryptocrystalline brookite or sphene, although the latter cannot occur as an alteration product of ilmenite in secondary deposits.   Leucoxene is most commonly an authigenic mineral but it may in some cases be detrital. The name leucoxene is worth retaining provided that it is appreciated that it is a general term applicable to the alteration products of titaniferous minerals.

<u>The nature of ilmenite</u> in beach sands is dependent upon the length of time during which the mineral has been subjected to conditions of atmospheric weathering.   It may vary from unaltered ilmenite through amorphous iron-titanium oxide to cryptocrystalline leucoxene,

which may be almost pure TiO_2. The soft end products of the alteration process do not form a large proportion of the ilmenite concentrates in beach sands because these are rapidly abraded. They are common in alluvial deposits.

The process of alteration. The first stage of alteration involves the oxidation of ferrous iron to the ferric state. The ilmenite remains apparently homogenous but has an abnormally high ferric iron content and suffers loss of anisotropy. The second stage which is divisable into a number of substages involves further oxidation of the ferrous iron until the ilmenite lattice is destroyed and a mixture of amorphous iron oxides and titanium oxide results. During the third stage, the iron content of the mixture is gradually leached out, leaving a cryptocrystalline mass of titanium dioxide.

Magnetite and titaniferous magnetite are oxidised to amorphous and hydrated ferric oxide more rapidly than ilmenite. The effect of titanium in solid solution in the magnetite on the rate of alteration is not known but is probably small. Fine lamellae of ilmenite in magnetite, if sufficiently numerous do, however, exert a cementing effect on grains prolonging their existence in secondary deposits.

CHAPTER VI

THE GENESIS OF THE BATHOLITHIC ANORTHOSITES AND THEIR RELATED TITANIFEROUS ORES

The large batholithic anorthosite massifs of the world occur in Pre-Cambrian regions of the crust.   They are associated spatially with syenitic and granitic gneisses of charnockitic affinities, and usually enclose small areas of gabbro-norite rocks often containing high proportions of iron and titanium oxide minerals frequently in sufficient quantity to constitute ore bodies.

In a consideration of possible modes of origin for rock masses of the size of the anorthosite 'batholiths', it is necessary to find a source material which is both widely distributed in the crust and present in very large amounts.   The anorthosites occur in such large quantity in their locales that there are only three possible source materials sediments, granite and basalt.

Sediments

Sediments provide a problem of such complexity and so much guesswork is necessary to arrive at basic assumptions for compositions that they are not fully discussed here.   There is so little agreement as to the composition of the average sedimentary rock that it is almost impossible to arrive at a starting point for a genetic hypothesis.   If the average for continental sediments, supposedly typical of a geosyncline, given by Sujowski (1952) is accepted certain particularly difficult problems immediately arise.   Their lime content is abnormally high, high enough to be an embarrassment even for the derivation of a high lime-bearing rock such as anorthosite,

Average Continental Sediment (Sujowski 1952)

SiO_2	59.46		MgO	1.96
TiO_2	0.60		CaO	15.60
Al_2O_3	10.90		BaO	0.06
Cr_2O_3	0.04		SrO	0.03
Fe_2O_3	3.10		K_2O	3.07
FeO	1.74		Na_2O	2.27
NiO	0.002		P_2O_3	0.20
MnO	0.06		Cl	0.45
			Others	0.36

and their alumina content is very low. As a result it is suggested that anorthosite is not derived directly from geosynclinal sediments although they may have played a modifying role during the genetic processes.

Granite

Provided that a large primary assumption is made granite is a possible parent magma from which anorthosite could be derived. The high calcium content of anorthosite demands that the granitic parent be at least five times as abundant as the anorthosite derivative.

	Average Plutonic Granite (Daly)	Residue of Granite x5 reduced to %	Average S.W. Norway Anorthosite (Barth)
SiO_2	70.18	74.0	54.8
TiO_2	0.39	0.16	1.3
Al_2O_3	14.47	11.8	25.2
Fe_2O_3	1.57	1.7	1.1
FeO	1.78	1.7	2.1
MnO	0.12	0.15	-
MgO	0.88	0.85	1.0
CaO	1.99	0.3	8.7
Na_2O	3.48	3.0	5.4
K_2O	4.11	4.95	0.7
H_2O	0.84	1.05	-
P_2O_5	0.19	0.21	0.1

From the central column of the above table it can be seen that the residue from an average granite after the abstraction of one

fifth by weight of anorthosite has a rather distinctive composition; the calcium value is abnormally low while the $K_2O:Na_2O$ ratio is moderately high.   Alumina is also low.   There is a similarity between the analysis and analyses of potassic granites and true charnockites.

	Charnockite, Madras (Washington 1916)	Biotite granite, Alexandria type. Adirondack Mts. (Buddington 1939 Average of four analyses)
SiO_2	77.47	74.22
TiO_2	0.26	0.31
Al_2O_3	11.00	12.78
Fe_2O_3	1.04	1.52
FeO	2.02	1.03
MnO	-	0.04
MgO	0.43	0.34
CaO	1.02	0.54
Na_2O	2.86	3.49
K_2O	4.14	5.20
H_2O	0.25	0.29
P_2O_5	-	0.08

It follows from this that if granite is the parent magma of anorthosite there should be large areas of granite with a high potash and low alumina content associated with the anorthosites.   In all the anorthosite regions there are large areas of granite exposed which in Norway are somewhat charnockitic in character but, except in small areas,they are neither potassic nor sub-aluminous. Many of the leucocratic rocks are syenitic and monzonitic with low SiO_2 contents.

In the Adirondack region the rock types occur in the following relative proportions:- anorthosite 16.5%, gabbro 3%, quartz syenite 40%, granite 40.5%.   The average rock would be an alkaline quartz-monzonite.   To derive such a rock from a granitic source implies

the separation of silica and potash from the original source, and
its injection into the country rocks.   There is no special evidence
of widespread metasomatism of the regional sediments and in Norway
at least, most of the metasomatic effects have been attributed to
endomigmatitization (Michot.).-

The difficulties inherent in a granite hypothesis are increased
by the dissociation in time of the Adirondack granite intrusives
from the anorthosite and its more mafic associates.   Buddington
(1939) is quite definite in his view that the granite intrusions are
in no way connected with the anorthosite.   If this is the case
the average Adirondack anorthositic rock becomes a per-aluminous
quartz-diorite or quartz-monzonite.

	Average Adirondack igneous rock excluding granite	Average of S.W. Norway igneous rock possibly comagmatic
SiO_2	62.2.	62.7
TiO_2	0.7	1.1
Al_2O_3	18.1	19.0
Fe_2O_3	1.3	1.4
FeO	3.0	2.3
MgO	1.1	0.8
CaO	4.7	5.4
Na_2O	4.4	4.2
K_2O	3.9	2.9
H_2O	0.4	-
P_2O_5	0.2	0.2

The similarity of compositions between the European and North
American averages is quite striking and a strong endorsement for
Buddington's conclusions.   Accepting his views, the derivation of
an intermediate magma from granite is required which re-introduces
the problems of silica and potash removal, enumerated above, in an
aggravated form.

It would probably be theoretically possible to devise a mechanism whereby a magma of anorthositic composition could be derived from granite but such a method would require differentiation at a very critical stage. The work of Bowen and Tuttle and Chayes has shown that in a melt of granitic composition a stage may be reached where crystals of labradoritic composition are in equilibrium with a liquid of orthoclase-albite composition. These crystals would tend to sink and could accumulate to form an anorthosite. Whether, at the same time, noritic and gabbroic differentiates could form seems less likely.

The association of titaniferous ores with anorthosite is a further factor which militates against the existence of a genetic connection between granite and anorthosite. Granite generally has a low titanium content. Nowhere are titanium ores associated with granitic rocks except in the case of certain rare peralkaline rock provinces. Even allowing for local conditions of a special character in which the titanium might be accumulated, there is a fundamental dissociation of titanium from magmatic granitic terranes which is hard to reconcile to the facts.

Basalts

In all the classical theories of anorthosite genesis a magma of gabbroic or basaltic composition has always been the parent which has given birth to a leucocratic offspring. During the last century Winchell, in reference to the Duluth gabbro, expressed the opinion that anorthosite had separated from gabbro under the influence of gravity which had moved the feldspathic pole upwards. Bowen in 1917 considered that anorthosite could not exist as a

magma, and that anorthosites were gravitational differentiates of gabbroic magma from which the more mafic constituents had settled out.   The plagioclase was supposed to sink leaving a granitic residium.   Loewinson-Lessing (1923) in a criticism of Bowen's work, pointed out that the plagioclase crystals should have floated. Vogt, however, was in favour of gravity settling _and_ an anorthosite magma which was supposed to have formed palingenetically by anatexis.

The classical accounts have, in general, ignored the special features of the anorthosite batholiths and did not clearly differentiate between them and anorthosite of much more local occurrence in gravity stratified basic intrusions, in which also the plagioclase is more calcic.   As a result their hypotheses are not very satisfactory.   More recent evidence has encouraged the present writer to put forward the rather different hypothesis here set out.   It is suggested that basalt of tholeitic composition, derived from the top of the sima where it may have become contaminated with a limited amount of sialic material, is the parent magma. Basalt of tholeitic composition and andesite are common in continental regions where the anorthosite batholiths are found.

A pure anorthosite magma of labradoritic composition would require a temperature of about $1350^{\circ}C$ for it to remain in a molten condition.   There are no metamorphic effects adjacent to the anorthosite batholiths to substantiate such a high intrusion temperature.   From the work of Yoder and Tilley (1956) it appears to be unnecessary to require a temperature in excess of $815^{\circ}C$ to derive a liquid of feldspathic composition (probably andesine-labradorite) from a tholeitic basalt melt, provided that the system is at a water

vapour pressure of 5,000 bars.   At this temperature and pressure
a basalt magma consists of amphibole, sphene and a liquid of
feldspathic composition.   If the applied pressure was anything but
purely hydrostatic this liquid might separate from the melt and
be injected into the surrounding or overlying crust.   The anorthosites
are essentially phenomena of a plutonic synorogenic phase in the
history of a geosyncline, probably earlier than the migmatic and
magmatic granite phases produced, in part at least, by
endomigmatitization of sediments.   In such an environment where
many constituents are in a semi-mobile state of anatexis a magma,
or migma, of andesine-labradorite composition would tend to rise,
even through sialic rocks of a geosyncline.   The temperature of
intrusion, between 800-850°C, would be only 70°-100°C above that
suggested for the granulite facies by Turner and Verhoogen so that
metamorphic effects would be negligable.   During its intrusive rise
the volatile portion of the magma would gradually be lost resulting
in partial crystallization, with the development of the granulated
textures which are typical of the anorthosites.   The origin of
the water which plays such an important part in the melting up process
of basalt is obscure, but it is suggested that it may be derived
from the relatively water rich sediments of a geosyncline which might
have been depressed in the crust to such an extent that the
distance between them and the top of the basalt layer was relatively
small.   It must be emphasised here that the occurrence of batholithic
anorthosites in the Pre-Cambrian is probably very significant
petrogenetically.   It is not improbable that the crust was affected
to a much greater depth during the intense Pre-Cambrian than it was
in the Post Cambrian orogenies.

At a period either during or after the separation and intrusion of the anorthosite magma, most of the volatiles escaped from the affected areas of basalt and anorthosite, probably in connection with continuing earth movements which may have produced channelways for the upward migration of highly mobile constituents. With increasing temperature and continuing high pressures in the partial or complete absence of water vapour some of the mineral phases became unstable.

The anorthosite which crystallized from a magma probably showed many magmatic features of texture which are so obviously lacking in the exposed rocks. The extraordinary size of many phenocrysts, and the total absence of zoning together with their typically porphyroblastic habit indicates complete reworking of the original rock. Reconstitution to homogeneity would have been carried out by solid diffusion, a process which has been shown (Ramberg 1949; Backlund 1948) to be sufficiently effective over limited distances to satisfy the requirements in this example.

The effects of increasing temperature and decreasing water vapour content in the de-feldspathised basalt was more complex. All hydrous silicates and sphene recrystallized as pyroxenes and possibly olivines. Yoder and Tilley (1956) found that pyroxene commenced to crystallise at the expense of amphibole even in the presence of excess water vapour at 5,000 bars, at $975^{\circ}C$. Wittels (1952) found that monoclinic amphiboles, in atmospheric pressure conditions between $900^{\circ}C$ and $1100^{\circ}C$, recrystallised to monoclinic pyroxenes, cristobalite, hematite, magnetite, olivine, plagioclase and water. At high pressures in a dry atmosphere the reaction would take place at a lower temperature. The work of

Eugster (1956) demonstrates that annite breaks down, at 2,000 bars pressure, at 800°C or less. The products of the reaction vary with temperature and, very critically, with partial pressure of oxygen, but they may in certain conditions be magnetite and quartz. In the presence of quartz the reaction can occur at 600°C.

Ramberg, approaching the problem from a totally different standpoint, has described the breakdown of amphiboles, biotite, and sphene in the granulite facies from rocks collected in the field. The significant reactions are as follows:-

1. $NaCa_2(MgFe)_4Al_3Si_6O_{22}(OH)_2 + 4SiO_2 \rightleftharpoons NaCaAl_3Si_5O_{16} +$
    (Hornblende)   (Plagioclase An:Ab,50:50)

    $3(MgFe)SiO_3 + Ca(MgFe)Si_2O_6 + H_2O$.
    (Hypersthene)   (Diopside)

2. $K(MgFe)_3AlSi_3O_{10}(OH)_2 + 3SiO_2 \rightleftharpoons KAlSi_3O_8 + 3(MgFe)SiO_3 + H_2O$.
    (Biotite)   (potash   (Hypersthene)
                                                  feldspar)

If garnet is formed in the basalt recrystallised in hydrous conditions, and it enters into the reactions on the left hand side, the products of reaction differ only in the quantity of the constituents.

The rocks which Ramberg studied were charnockite gneisses with a high quartz content, under which conditions normal amphiboles with an Fe:Mg ratio of 50:50 or 40-60 were found to be unstable. It is important that although excess SiO_2 appears to be a pre-requisite for the reaction (according to Ramberg) the factor controlling the P.T. at which the reaction hornblende $\longrightarrow$ pyroxene occurs is the Ca/Na ratio of the system. In rocks with a plagioclase of composition

An 35 the reaction takes place if the Fe:Mg ratio falls below 50:50.
With a more sodic plagioclase even hornblendes with a high Fe:Mg
ratio are altered.

In the system under consideration, a defeldspathised basalt,
the Ca:Na ratio is high so that a higher temperature and pressure
than that necessary for dissociation of hornblende in an acid
facies is required. Ramberg found that in the basic rocks which he
encountered hornblendes with FeTi:Mg ratios of 23:77 could exist.
He attributes this to the higher degree of metamorphism necessary
to produce the following reaction.

3. $2NaCa_2(MgFe)_4Al_3Si_6O_{22}(OH)_2 + 6(MgFe)SiO$ (hypersthene)

$$+ 2(MgFe)_3Al_2Si_3O_{12} \rightleftharpoons 2NaCa_2Al_5Si_7O_{24}$$
(Labradorite)

$$+ 10(MgFe)_2SiO_4 + 2H_2O.$$
(Olivine)
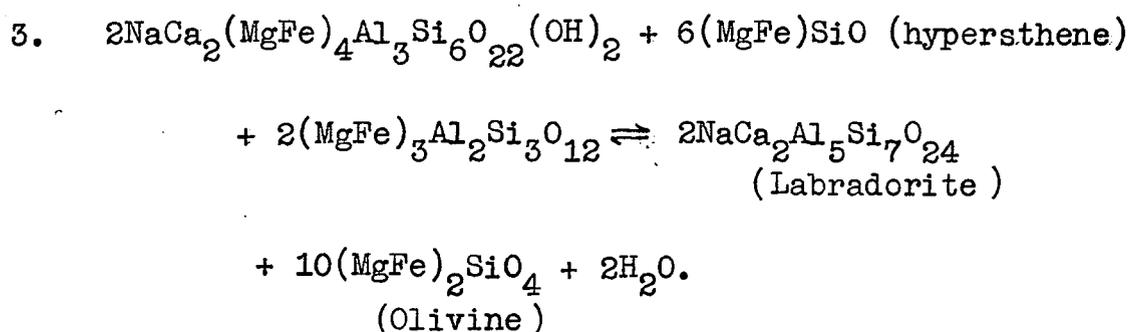
Thus a higher temperature and pressure than that which caused
hornblende dissociation in the rocks examined by Ramberg appears
to be necessary in this case, unless a soda-silica metasomatism of
the amphibolite is invoked in which case the amphibole reacts
according to equation 1 above. In the absence of a soda-silica
metasomatism the temperature and pressure at which the reaction
occurs might be, by comparison with the figures for biotite (Eugster),
approximately $800^{\circ}C$.

By drawing upon many sources from the literature Ramberg shows
that hornblendes from charnockitic rocks contain a high
percentage of TiO_2. An average figure is 25% TiO_2 with a maximum of

4.2%. Pyroxenes, taken from similar rocks and in some examples quoted taken from the same specimen as the hornblendes, contain much lower percentages of TiO_2. For example in a charnockitic gneiss from Greenland the TiO_2 content of the mafic minerals is hornblende 2.48%, hypersthene 0.37%, diopside 0.38%. Allowing four molecules of pyroxene for every one of amphibole (equation 1) there is a quantity of TiO_2 which cannot have entered the pyroxene lattice. Ferric iron behaves in a similar manner so that free ferric iron and titanium can be expected in any titaniferous amphibolite recrystallised under granulite facies conditions. Analyses of minerals from a pyroxene-granulite from Saxony (Philipsborn 1930) provide further evidence of the inability of titanium to enter pyroxene lattices in quantity. In a rock containing 4.35% ilmenite, hypersthene contained 0.54% TiO_2, augite 0.65-0.69% and plagioclase 0.0%. Rajagopalan (1946) analysing minerals from a charnockite granite found that the hornblende contained 3.27% TiO_2, but the pyroxene only a trace. The stability relations of biotite are very similar to those of amphibole and a similar release of ferric iron and titanium occurs. If garnet forms instead of hypersthene no ferric iron will be released but a larger quantity of titanium can be expected since the titanium content of analysed garnets in the granulite facies quoted by Ramberg never rises above 0.24%. The titanium content of East Greenland biotites lies between 5% and 6%. Derin (1954) has analysed biotites containing 6% TiO_2. Buddington (1950) found that garnets from anorthosite contained between 0.13 and 1.62% TiO_2. Angel and Schaider (1950) investigating garnet in eclogite arrived at a figure of 1.26% for the TiO_2 content.

Sphene, which was present in the amphibolite obtained from basalt by Yoder and Tilley, is more unstable than amphibole at high P.T. At 5,000 bars with excess water vapour it melts at 875°. In dry conditions it is not unlikely that it becomes unstable at a lower temperature with release of TiO_2, the calcium entering into lime silicates.

There is considerable evidence in both the Adirondack region (Gillson) and the Egersund-Sogndal area that the sequence of events following the crystallisation of the anorthosite was the introduction of 1) NaO resulting in andesinesation of labradorite; 2) Mg'' + Fe'' causing the formation of ferromagnesian minerals and 3) $Fe''_{\sim}$, Ti'''', Cl, P, F, forming ore bodies.

The soda metasomatism may have arisen by the breakdown of hornblende in the defeldspathised basalt without excess silica being present as in the charnockites, so that sodic plagioclase was prevented from forming. Alternatively a soda-silica front rising from a lower crustal level to hasten the decomposition of the amphiboles and extending up into the anorthosite zone is a possible alternative. A deficiency in alumina would prevent the formation of feldspar. At the greater depths from which the $Na-SiO_2$ front would have originated eclogite facies conditions control mineral crystallization and silica would be a free phase in a rock of basaltic composition and would tend to migrate upwards either by solid diffusion or as a pore fluid (Misch 1949; Perrin and Roubault 1949). A deficiency of alumina during the recrystallization of the amphibole would be produced if garnet crystallized instead of feldspar and pyroxene.

$$NaCa_2(MgFe)_4\ Al_3Si_6O_{22}(OH)_2 = 3\ (MgFe)\ (SiO_3)FeCa_2Al_2Si_3O_{12} + H_2O + MgO + NaO.$$
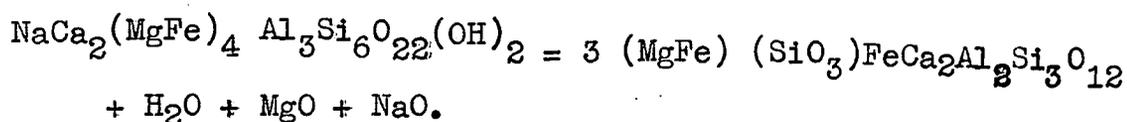
This would result in the release of soda and magnesia.

While the upward diffusion of the sodium ion is readily explained, and generally accepted, it is usually considered that Mg, Fe + Ti should migrate downwards - a "diffusion à double sens". Yet in this case the heavier ions have migrated upwards after being released from the silicate lattices, which indicates that some other process other than straightforward solid diffusion must have been operative. It is suggested that phosphorus, chlorine and fluorine, together with the (OH) ions released from the reconstituted amphibole played a very important part in the upward transfer of the metal ions. In the Virginia titanium ore field there is some evidence to suggest that titanium was introduced first in the ore depositing phase, possibly being carried as TiF_4 vapour and that ferric iron followed it probably as a liquid. In the Adirondack and Norwegian regions no such evidence is available and iron and titanium appear to have been introduced together although there is some indication in individual ore bodies that the latest minerals to crystallize were free from titanium. The presence of scapolite and apatite in association with the ore bodies affords evidence for the introduction of halogens and phosphorus. The anorthosite massif would probably have behaved as a rigid core in an area undergoing plastic deformation and as such may have tended to relieve applied pressure by shearing and faulting, thereby producing low pressure areas into which the constituent ions of the ore would have tended to migrate. Particularly in Virginia (Ross 1941) the ore bodies are related to sheared zones.

The ilmenite-magnetite ore minerals in the anorthosite massifs

are not confined to bodies with high ore concentrations and relatively low silicate content because ilmenite norite-gabbro ore bodies are of equally frequent occurrence. The sharp contacts of, for example, the Tellnes and Storgangen orebodies in S.W. Norway seems to rule out a metasomatic in situ origin in their case. The interpretation of these ores as late stage residual liquid injections of an anorthosite magma is not a happy solution of the problem either, since it brings with it problems of the method of reinjection into the anorthosite, and great difficulties stemming from the paragenetic crystallization of the minerals which is agpaitic. The ore content of these gabbro norites is also altogether too high to permit such a simple explanation for their origin.

A likely method of derivation is a combination of the two methods. The titanium-ferric iron "emanations" instead of being immediately injected high into the anorthosite may have collected locally at its base in sufficient quantity to reproduce the earlier wet stage in the paragenesis. This would cause melting of feldspar and in fact a palingenetic magma would result which, on intrusion into the anorthosite, would crystallize as an amphibole-rich rock, later recrystallizing in granulite facies conditions to a norite.

APPENDIX I

DATA ON THE USE OF A COOK ISODYNAMIC SEPARATOR WITH MINERALS
IN BEACHSANDS

The specimen which has been relected to illustrate the behaviour of the minerals is a natural heavy mineral concentrate formed by wave action on the coast of the Aden Protectorate.

Examination Procedure.- The sand was washed, dried and cursorily examined under a binocular microscope to discover the degree to which the grains had been sorted. Since it was well sorted and did not require sizing the material was fed direct to a Cook separator operating at amperages from 0.0–2.5 amps and longitudinal and latitudinal slopes of 15°. Each fraction was repassed through the separator at least three times. Fractions were taken at 0.05, 0.2, 0.4, 0.6, 0.8, 1.2, 1.6, 2.5 amps and a diamagnetic fraction was also obtained at a setting of 10° long. and 2° lat. slope with a current of 2.0 amps.

Each fraction was weighed, subjected to the action of dilute HCl and weighed again to determine the carbonate content of the specimen.

Each fraction was then studied microscopically and the constituent minerals identified by standard opical methods. The mineral proportions of each fraction were determined by a point counting technique so that the percentages quoted below are not accurate values by weight since they were obtained by a combination of weight and volume methods.

X-ray powder photographs were taken of the fractions separated in the Cook instrument at 0.4 and 0.6 amps. These confirmed that the bulk of the fractions consisted of a mixture of ilmenite and hydrated iron oxides and martite formed from magnetite.

These could not be distinguished from each other under a binocular microscope and it was necessary to polish each fraction to identify the grains with certainty. Many of them proved to be intergrowths of ilmenite and completely or partially altered magnetite and as a result they have been recorded together in tables A.I.1, 2 and 3. In rough figures the ratio of altered magnetite to ilmenite in each fraction was 2:1.

Each fraction was also tested under a delicate Geiger counter and high counts were obtained for the 1.2 and 1.6 amp. concentrates

Table A.I.1   Mineral Content of Mukalla beachsand

	%	
Ilmenite and altered magnetite	29	
Zircon	16	Also traces of garnet (red),
Rutile	4	kyanite and spinel.
Magnetite	6	
Monazite	1	
Tourmaline	1	
Spessartite	1.5	
Diopside	1	
Green pyroxene	7	
Calcite	14	
Quartz, chert and miscellaneous rock fragments	20	
	100%	

confirming the presence of monazite in these. The 0.8 amp. concentrate which did not produce any reaction in the radiation counter must presumably contain a thorium-poor monazite.

In the following tables 1 and 2 the results of the separations are set out. In table 3 the distribution of the minerals through the various magnetic concentrates, arrived at by a recalculation of the results in table 2, is recorded.

Table AI 2   RESULTS OF MAGNETIC SEPARATION

Content of Concentrate %

Wt. of Conc. in grms.	Concentrate in amps.	Magnetite	Ilmenite & Hydrated Fe & oxides	Pyroxene (green)	Diopside	Spessartite	Red garnet	Monazite	Tourmaline	Rutile	Zircon	Calcite	Quartz
2.9	0.05	96		3									1
1.9	0.2		93	6		1							
5.9	0.4		88	4		3	3						2
0.1	0.6		71	15	3	6							5
3.1	0.8		52	19	3	1		1	6		Tr	3	
1.9	1.2			64	2	1		6	7	6	Tr	Tr	14
0.4	1.6				6			3	3	9	7	24	48
0.5	2.5				6				1	11	30	40	13
3.0	Strongly Diamag.										13	20	67
3.3	Weakly Diamag.										25	24	51
14.5	Paramag. Residue								1	11	37	30	22

TABLE AI 3 DISTRIBUTION OF MINERALS IN MAGNETIC FRACTIONS

Concentrate in amps.	Magnetite	Ilmenite and Hydrated Fe oxides	Pyroxene green	Diopside	Spessartite	Monazite	Tourmaline	Rutile	Zircon	Calcite	Quartz including chert
0.05	100%										
0.2		13%	3%		3%						
0.4		41%	24%	1	30%						
0.6		34%	7%	50%	61%						
0.8		12%	30%	25%	3%	16%	48%	1%	1%	1%	
1.2			20%	10%	3%	75%	33%	6%		2%	
1.6			36%	7%		90%	4%	2%	2%	2%	
2.5				8%			2%	3%	3%	3%	
Strongly Diamag.									6%	10%	Cherty Quartz
Weakly Diamag.									12%	13%	Clear Quartz
Paramag. Residue							13%	89%	80%	72%	

APPENDIX II

THE OCCURRENCE OF SIEGENITE (Ni_3S_4) AT OTANMAKI

In Chapter IV the occurrence of the nickel sulphide siegenite together with very small quantities of an unidentified nickeliferous mineral, possibly millerite, was mentioned. The specimen containing it was taken from a narrow late sulphide vein with cross-cutting relationships to the ilmenite-magnetite orebodies. It is suggested that it is genetically associated with the red gneissose granite which outcrops to the north of the Otanmaki orezone.

The siegenite occurs in an intergrowth with hematite which appears to fill cracks, arranged to form a poorly developed cubic or rhombohedral pattern in the siegnenite. It is not definitely suggested that the intergrowth originated by exsolution but the possibility is not to be ignored. The siegenite-hematite intergrowth form rounded masses in a matrix consisting of pyrite, a pyrite-marcasite intergrowth and a little goethite.

An X-ray powder photograph was taken, using a 9 cm camera, of the intergrowth minerals. The material was obtained by removal from a polished specimen while under the microscope by means of a dentists drill. Contamination was thereby avoided. The data are given in the following table.

X-ray Powder Photographs of Siegenite

d-spacing	Intensity	Identification
3.342	W	S
2.852	VS	S
2.691	S	H
2.512	S	H
2.360	S	S
1.823	W	S
1.695	W	H
1.670	M	S

W = Weak   M = Medium   S = Strong   VS = Very strong   H = Hematite
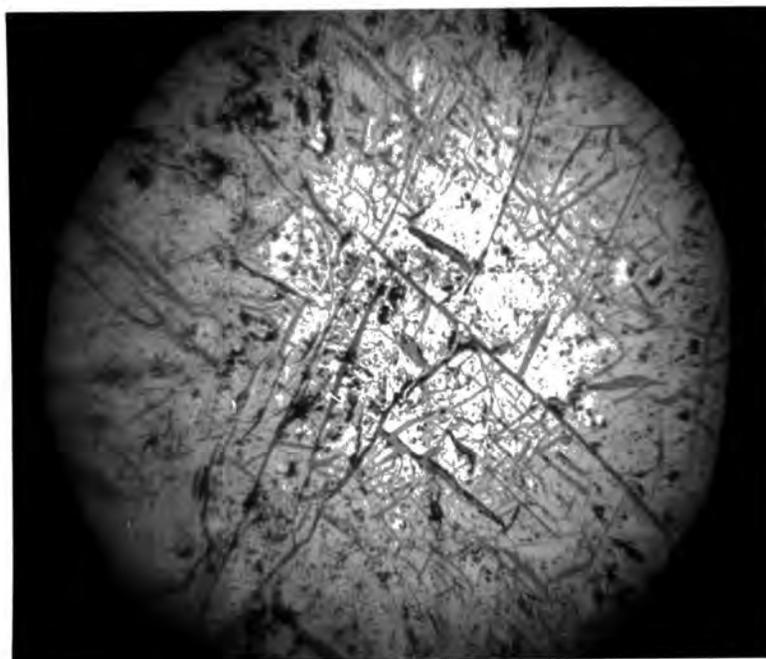S = Siegenite

Plate A 1.   Siegenite with narrow veins of hematite (and a little
              goethite), which are darker than the siegenite.   From
              a late sulphide-ilmenite vein at Otanmaki.

The three strongest lines of the siegenite pattern are in complete agreement with the A.S.T.M.data.

The optical properties in reflected light are in agreement with those given by Uytenbogaardt, a precise measurement of reflectivity was not obtained. The hematite of the intergrowth has in part been altered to goethite.