An overview of titanium deposits in Norway

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Titanium deposits in Norway are of three major types: igneous, metasomatic and metamorphic. The igneous deposits are composed of ilmenite, magnetite and apatite in various proportions and occur in geological provinces of different ages, and some have a metamorphic overprint. The other major Ti ore-type is the rutile-bearing eclogites in western Norway that formed during the Caledonian high-pressure metamorphism of predominantly Proterozoic basic igneous rocks. The third Ti ore-type is the Proterozoic rutile-bearing, scapolitised and albitised rocks in the Bamble region of South Norway.

Norwegian Ti mineral resources are large. The Egersund province in southernmost Norway is by far the most significant. This province includes the Tellnes ilmenite deposit which is in operation, as well as large volumes of other low-grade ilmenite ores. The annual ilmenite production at Tellnes, ~550,000 t. ilmenite, is 6-7 % of the total mine production of Ti minerals in the world, and Tellnes alone has approximately 12 % of the world's resources of ilmenite.

Mineralogy is the overall factor influencing the economic significance of Ti deposits, defining the quality of the Ti mineral product that can be produced. Grainsize, mineral intergrowths and mineral chemistry are a reflection of the geological environment and later conditions of the ore-forming process. Due to significant variation in geological settings, Norwegian Fe-Ti deposits show a large range in mineralogical signatures.

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Introduction

Norway has a long tradition in ilmenite mining, starting as early as 1785 in the Egersund area (Rogaland anorthosite province) in southwestern Norway (Figs. 1 & 2) where ilmenite ore was mined as iron ore. For an excellent overview see Krause et al. (1985). The element Ti was first isolated in 1789, but it was more than a century before it could be utilised on the industrial scale. During the second half of the 19th century, mining of ilmenite ore bodies in the Egersund area, and also farther southeast in the Sokndal area, commenced as iron ore mining, with Blåfjell as the most important deposit. Before the turn of the century the very large ilmenite ore reserves within the Storgangen ilmenite norite body were known (e.g. Vogt 1887, 1892, Kolderup 1896). After about ten years of pioneering research on utilising the Ti contents of the ilmenite, the chemists Drs. P. Farup and G. Jebsen succeeded in 1916 in developing an industrial method for the production of a white TiO_2 pigment, known today as the sulphate process (Jonsson 1992). In order to utilise the new method and the patents taken out for it, the company Titania A/S in 1917 started mining the Storgangen deposit. Mining here continued until 1965 when all the production was transferred to the open-pit operation at the nearby Tellnes deposit where regular mining then had already been going on for five years. At present, Tellnes has an annual production of approximately 550,000 t. ilmenite. The Norwegian Ti slag producer, Tinfos Titanium and Iron (TTI), is producing Ti slag based on ilmenite from Tellnes as well as imported ilmenite.

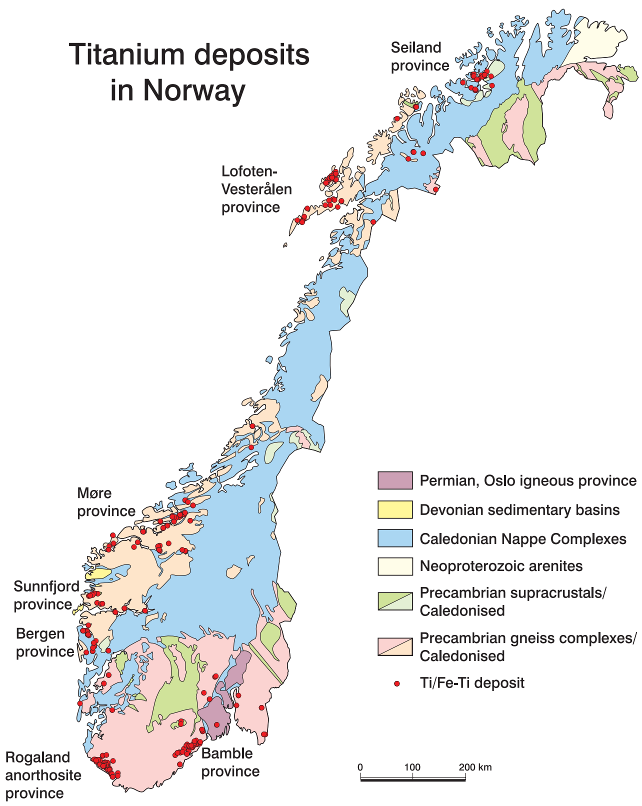

Fig. 1. Simplified geological map of Norway with Ti/Fe-Ti provinces and deposits.

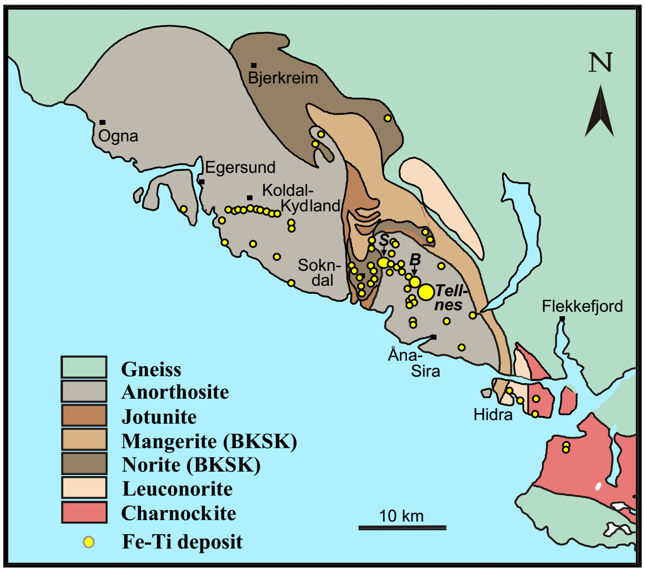

Fig. 2. Simplified geological map and ilmenite ore bodies in the Rogaland anorthosite province. S = Storgangen ilmenite deposit, B = Blåfjell ilmenite deposit. BKSK = rock units belonging to the Bjerkreim-Sokndal intrusion.

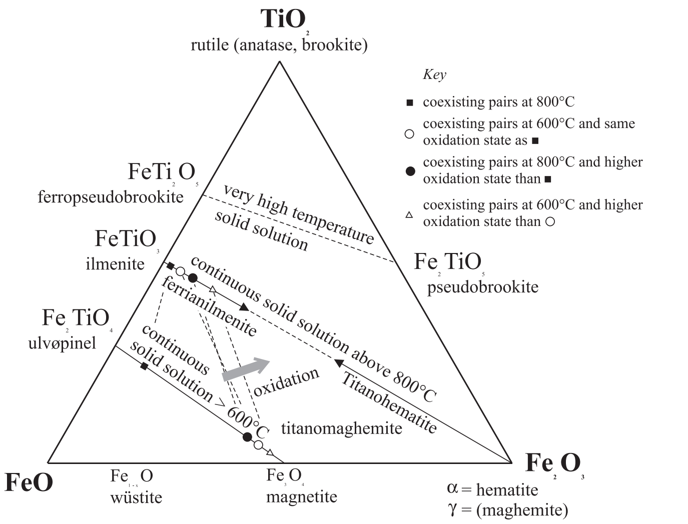

Fig. 3. Composition of oxide minerals in the system FeO - Fe_2O_3 - TiO_2. The dashed lines between ilmenite and magnetite indicate common geological coexistence at relatively low temperatures, in which magnetite commonly contains ilmenite lamellae. Such intergrowths are formed by the oxidation of magnetite - ulvöspinel followed by oxidation-exsolution of ilmenite. Source could not be located.

More than 300 Ti/Fe-Ti deposits and minor occurrences are registered in Norway. Most occur in distinct geological provinces (Fig. 1). It is our opinion that Norway has large resources of Ti that are insufficiently investigated, and that some of these resources might be of sufficient quality for the Ti pigment industry in the future.

The purpose of this paper is to summarise geological information on Ti provinces and individual deposits in Norway. Rutile resources in Norway are reviewed in a companion paper in this volume by Korneliussen et al. (2000).

Titanium raw materials and the titanium industry

Titanium is the ninth most common element in the Earth's crust, averaging 0.9% Ti (Turekian 1977). It is present in rocks as oxide and silicate minerals. Oxide minerals in the system FeO - Fe_2O_3 - TiO_2 are shown in Fig. 3. Ilmenite and rutile are the primary raw materials for Ti in the world. Force (1991) divided Ti deposits into five major classes: igneous, metamorphic, hydrothermal, sedimentary and weathered. At present, the igneous, sedimentary and weathered types are of most economic interest. Australia, South Africa and Canada are the sources of approximately 80% of the total mine production of Ti minerals in the world, while Norway is producing ~5 %, as ilmenite. The world resources of Ti minerals are very large, although the known resources of high-quality ilmenite and rutile are probably limited.

Some relationships between Ti raw materials and their products are shown in Figs. 4 and 5. The term *ilmenite,* as used by the Ti industry, covers both hard-rock ilmenite, containing variable proportions of exsolved hematite, lowering the TiO_2 content, and sand ilmenite enriched in TiO_2 by weathering processes. Commercial ilmenite contains from 44 to 70% TiO_2, while weathered and heavily altered ilmenite

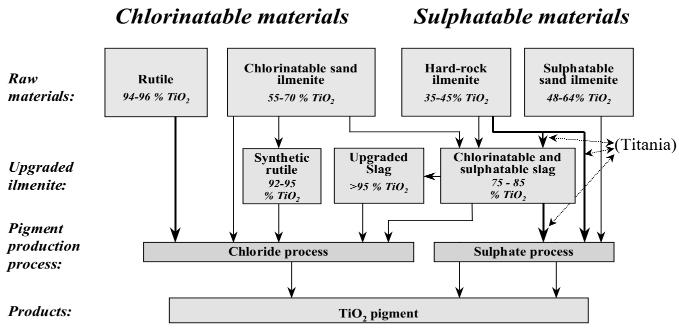

Fig. 4. Paths from titanium raw materials to products (modified from Dormann 1993).

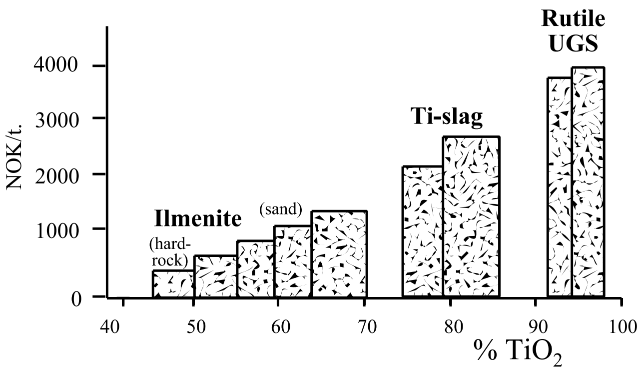

Fig. 5. Schematic plot of the 3 major categories of titanium mineral products; ilmenite, titanium slag and rutile, and their approximate market price. There is a distinct relationship between market price and quality, in this figure illustrated by TiO_2 content. However, a complicated set of quality requirements, as outlined by Dormann (1993), has influence on the raw-material/market price relationships. Iron is an important co-product in titanium slag production. UGS: Upgraded slag (produced by QIT, Canada).

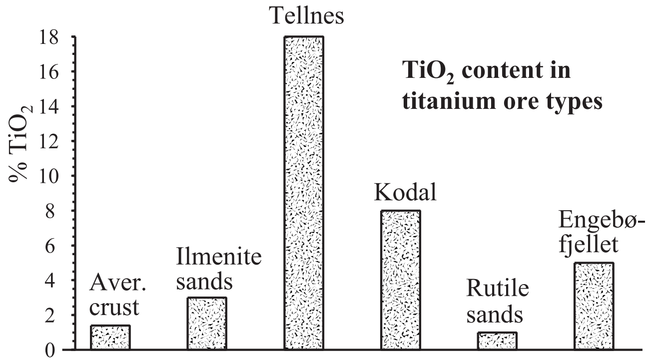

Fig. 6. Comparison of approximate TiO_2 contents in different titanium ore types. The examples used in this diagram are: average crust (1.4% TiO_2; Turekian 1977); ilmenite and rutile sand (Force 1991); Tellnes (Norwegian hard-rock ilmenite mine in operation, Krause et al. 1985); Kodal (Norwegian hard-rock apatite-ilmenite deposit, Lindberg 1985); and Engebøfjellet (Norwegian rutile-bearing eclogite deposit, Korneliussen et al. 2000).

has > 70% TiO_2 and is traded as leucoxene. In comparison, stoichiometric ilmenite contains 52.7 % TiO_2. At present, with the exception of a relatively small rutile hard-rock mining operation in China, rutile is exclusively obtained from sand deposits, while hard-rock ilmenite is actively mined in Canada and Norway. Titanium slag is an intermediate product made from ilmenite, used for Ti pigment production. In the Ti slag production process, the iron oxides are reduced to metallic iron, thereby producing a TiO_2-rich slag and high purity iron.

The sulphate and chloride processes are used in the Ti industry to recover Ti. In the sulphate process, ilmenite and Ti slag are leached with sulphuric acid. In the chloride process, TiO_2 pigment and Ti metal are produced from rutile, Ti slag and some TiO_2-rich sand ilmenites, via a $TiCl_4$ stage at high temperatures. Upgraded ilmenite, in the form of chlorinatable slag and synthetic rutile, has become an attractive raw material for the TiO_2-pigment producers.Ninety-three percent of the world's consumption of Ti is as TiO_2 pigment used mainly in paints, paper and plastics. Other uses of Ti are in welding rods, and for Ti metal in aeroplane construction, heat exchangers and desalination water plants, and a variety of other applications.

Quality requirements impose severe restrictions on the Ti raw materials, as pointed out by Dormann (1993). In general, there is a tendency for ilmenite and Ti slag with low MgO and Cr to be increasingly more attractive relative to raw materials containing high MgO and/or Cr. In TiO_2-pigment production, ilmenite used in the chloride process must have less than 1.5 % MgO. Chromium is a waste problem for the sulphate process, pigment producers; the less Cr in the raw material the better. Similarly, rutile with a low U content (< 10 ppm) is more attractive for the chloride-process, TiO_2-pigment producers. These compositional limitations are due to environmental restrictions.

Mineralogy is essential for the mineability of Ti deposits. In sand deposits the Ti minerals are liberated by nature, and the mining can be done on low-grade sands if the Ti mineral is of a sufficiently high-quality. High quality sands with only 1% rutile are economic and ilmenite sand deposits may be mined at approximately 5% ilmenite. In ilmenite hard-rock deposits, however, the ore has to be mined, crushed and the ilmenite separated out by an expensive separation process; therefore ore-grade requirements will be high. The significant differences between major Ti ore-types in terms of TiO_2 content is illustrated in Fig. 6. For many sand-deposit operations, by-product minerals such as monazite and zircon play an economically significant role.

Titanium resources in Norway

Norwegian Ti resources are summarised in Table 1 and Figs. 7 & 8. The igneous deposits have ilmenite ± magnetite ± apatite in various proportions. These deposits are associated with many types of mafic intrusions in several geological provinces (Fig. 1). The major Norwegian ilmenite province is the Rogaland anorthosite province in southern Norway (Fig. 2). This province contains a large variety of ilmenite-bearing rocks, and deposits ranging from massive ores to large, low-grade mineralisations. The most important deposit in this region is the world-class Tellnes deposit with a yearly production of 550.000 t. ilmenite, which is 6-7% of the total production of ilmenite in the world. The Tellnes ore reserve, with 57 Mt. of contained TiO_2, represents roughly 12 % of the world's reserves of ilmenite. Elsewhere in the Egersund province, large volumes of low-grade ilmenite - apatite - magnetite ores represent a resource that might become of economic importance in the future (Nor. geol. unders., unpublished data), although these deposits still require further investigation.

The Kodal apatite-ilmenite-magnetite deposit in the Permian Oslo Rift (Bergstøl 1972, Lindberg 1985) was investigated by Norsk Hydro in the 1970's as an apatite deposit with ilmenite and magnetite as possible by-products. Proven reserves are 35 Mt. of massive ore with 17 % apatite, 40% titaniferous magnetite and 8% ilmenite. An additional 35 Mt. of disseminated ore is regarded as a reserve in case of open-pit mining (Lindberg 1985).

In the Seiland alkaline province in northernmost Norway, large volumes of ilmenite ± apatite in pyroxenitic rocks (Robins 1985) represent a mineral resource, although poorly investigated. Other deposits of magmatic ilmenite are, with a few exceptions, mainly deposits of titaniferous magnetite with subordinate ilmenite. The magnetite in these deposits is commonly enriched in vanadium, for example in the Rødsand deposit in the Møre region (Sanetra 1985) that was mined from 1891 to 1981 for vanadiferous magnetite with the by-product ilmenite for use in coalseparation. Proven reserves of vanadiferous magnetite-ilmenite ore in the Rødsand area are 11 Mt., with additional resources of 120 Mt. (Korneliussen et al. 1985). However, only approximately 10 % of this tonnage is ilmenite. Another significant vanadiferous magnetite-ilmenite deposit is Selvåg in the Lofoten-Vesterålen province containing an identified resource of 44 Mt. ore with an additional possible ore estimated to be more than 50 Mt. (Priesemann & Krause 1985). Twelve to fourteen percent of this tonnage is ilmenite.

Table 1. Titanium resources in Norway. Reserves are ore in relation to a mine in operation (Tellnes). Identified resources are proven sub-economic ores. Possible resources are identified ores that are poorly investigated.

Ti-province / region	Type of deposit		Age	Major deposit	Role of titanium	Resources (mill.t. TiO_2) Reserve	Identified resource	Possible resource	Comments
Bamble - Arendal	Ilm-Mt (V)	igneous	1200 - 1250		co-prod.			5	< 1.5% MgO in ilm
	Rutile	metasomatic	1180	Ødegård	main prod.		0,5	2	>30 ppm U in rutile
Rogaland anrth. prov.	Ilm	igneous	925	Tellnes	main prod.	57	38		3-4% MgO in ilm
	Ilm.	igneous	930	Storgangen	main prod.		5		
	Ilm-Ap-Mt	igneous	932		co-prod.		5	100	< 2.5% MgO in ilm
Bergen	Ilm-Mt	igneous	950		co-prod.				< 1.5 % MgO in ilm
	Rutile	metamorphic	400	Husebø	main prod.		0,5	2	
Sunnfjord	Ilm-Mt	igneous	1200		co-prod.			5	< 1.5% MgO in ilm
	Rutile	metamorphic	400	Engebøfj.	main prod.		16	10	< 1 ppm U in rutile
	Rutile	metamorphic	400		main prod.			20	< 1 ppm U in rutile
Møre	Mt (V)-Ilm	igneous	1700		by-prod.			5	< 1.5% MgO in ilm
	Rutile	metamorphic	400		main prod.			10	< 1 ppm U in rutile
Lofoten - Vesterålen	Mt(V)-Ilm	igneous	1900		by-prod.			3	1.5-3.0% MgO in ilm
Seiland	Ilm-Ap	igneous	500		co-prod.			10	
Other deposits	Ap-Ilm-Mt	igneous	270	Kodal	by-prod.		5		< 1.5% MgO in ilm

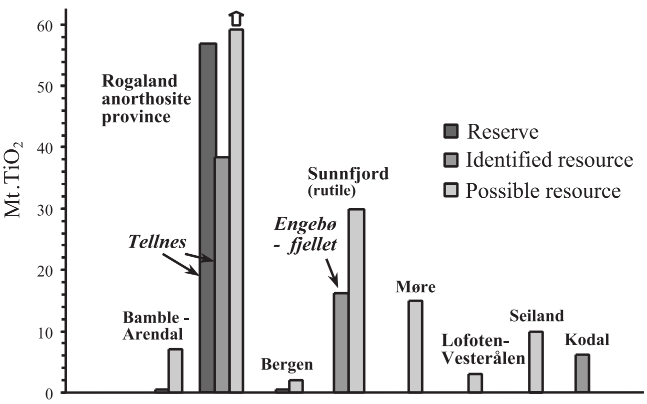

Fig. 7. Titanium reserves and resources in Fe-Ti provinces in Norway.

The other major Ti ore-type in Norway is rutile-bearing eclogite found mainly in West Norway (Fig. 1). Eclogites in the Sunnfjord region have been extensively investigated, leading to the documentation of a world class rutile resource in the Engebøfjell deposit. The identified resource at Engebøfjellet is 400 Mt. of 3-5 % rutile ore (McLimans et al. 1999, Korneliussen et al. 1999, 2000). Additional rutile resources related to Engebøfjellet and other eclogites in the area are significant, though further investigations are needed to fully quantify the rutile ore. The Engebøfjellet deposit represents a large proportion of the world's resources of rutile.

A third deposit category is rutile associated with Proterozoic metasomatised gabbros in the form of rutile-bearing albitites and scapolite rocks in the Bamble-Arendal regions of southern Norway. Of the known rutile deposits in this province, the Ødegård rutile-bearing scapolite-hornblende rock (see Sandøy 1996, and references therein), called ødegårdite by Brøgger (1934), is the largest known deposit in the region. This deposit probably contains more than 50 million tons of ore with 2 - 4 % rutile (Korneliussen & Furuhaug 1993).

Ilmenite and titaniferous magnetite provinces in Norway

The Rogaland anorthosite province, also called the 'Farsund - Egersund igneous province' or the 'South Rogaland igneous province', comprises large massif-type anorthosites and associated noritic, jotunitic, mangeritic and charnockitic intrusions (Duchesne et al. 1987b). It was emplaced in a Middle Proterozoic, migmatised, metamorphic terrane at inter-

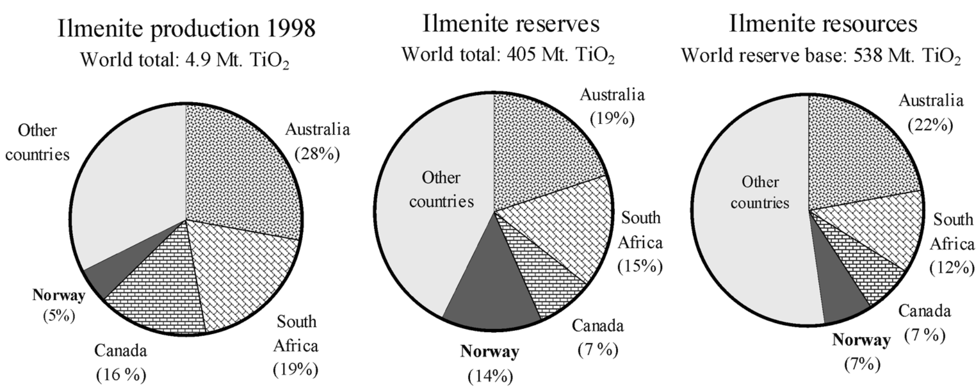

Fig. 8. World ilmenite mine production, reserves and resources, based on J.M. Gambogi, U.S. Geological Survey Mineral Commodity Summaries, Jan. 1999, with modified data for Norway (Tellnes) in accordance with Table 1 and Fig. 7.

mediate crustal levels. Major plutonism, including formation of the anorthosites, took place between 932 and 920 Ma (Schärer et al. 1996). Ti-Fe deposits are widespread in the province, principally as ilmenite-magnetite rich cumulates, or as ilmenite - magnetite rich dykes. There is a wide variety in chemical characteristics and mineral textures in these deposits.

The Bjerkreim-Sokndal intrusive complex (Fig. 2) is a part of the Rogaland anorthosite province with anorthosites, leuconorites, troctolites, norites, gabbronorites, jotunites and mangerites derived through crystallisation from a jotunitic parental magma (Duchesne et al. 1987a, Wilson et al. 1996, Robins et al. 1997). It contains Fe-Ti rich, noritic and gabbronoritic cumulates that have been mined on a small scale at several locations in its southern extension. The oxide compositions vary systematically with host-rock mineralogy (Duchesne 1972, Wilson et al. 1996).

The most prominent deposit is at Tellnes (Fig. 9), which contains more than 300 million tons of ore averaging 18% TiO_2 (Krause et al. 1985). It is related to a post-deformation noritic dyke, having an uncertain genetic relationship with a late jotunitic/mangeritic dyke system (Wilmart et al. 1989). The Blåfjell ilmenite ores are related to noritic pegmatite dykes within the Åna-Sira anorthosite. Several minor ilmenite-rich dykes have been mined on a small scale in the past. The compositions of these dykes generally range from bimineralic plagioclase-ilmenite rocks, to locally oxide-rich norites, to 'pure' ilmenitite dykes. The layered Storgangen intrusion with Fe-Ti rich noritic cumulates was emplaced as a sill in the Åna-Sira anorthosite and was subsequently deformed

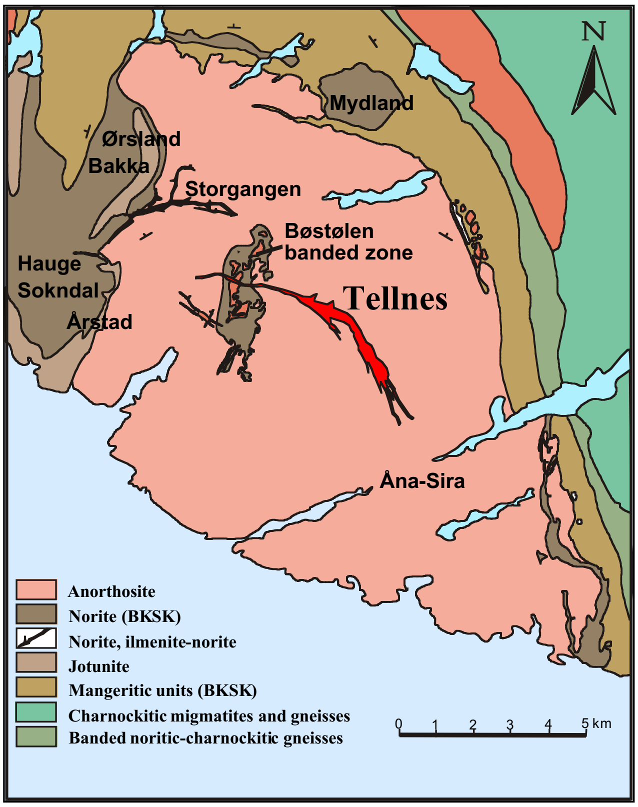

Fig. 9. Geological map of the southeastern part (Sokndal area) of the Rogaland anorthosite province. Modified from Krause & Pedall (1980).

through the relative motions of the anorthosite and the Bjerkreim-Sokndal intrusion (Schiellerup 1996). The Storgangen intrusion was mined from 1916 to 1964. The identified remaining ore reserve is 60 Mt. ore with 17-18% TiO_2 (Krause et al. 1985). Between the Egersund-Ogna and Håland anorthosites there is a zone a few hundred metres wide with leuconoritic orthogneiss and a spectrum of other gneisses. This unit includes several reworked intrusive bodies (Koldal-Kydland area, Fig. 2) between the two massif anorthosites and they were subsequently deformed by their relative movements. Ilmenite deposits in this zone are likely to represent fragmented and reworked oxide-rich cumulates; oxide compositions vary systematically from east to west (Duchesne 1999).

The Bamble - Arendal Fe-Ti province, also called the Bamble Sector of the Baltic Shield, contains rocks that have been affected by both the Gothian (c. 1500 - 1750 Ma) and the Sveconorwegian (990 - 1250 Ma) orogenies (e.g., Starmer 1991, Kullerud & Dahlgren 1993). Deposits of ilmenite and V-rich magnetite are found as bands and lenses in the metagabbros and amphibolites that are possibly related to magmatism early in the Sveconorwegian orogeny. This magmatism was followed by a period with extensive hydrothermal activity that caused the metasomatic alteration of basic rocks into scapolite rocks and albitites. At Ødegården, gabbros and amphibolites were metasomatically altered to a rutile-bearing scapolite-hornblende rock called ødegårdite by Brøgger (1934). During this process, Cl-rich fluids leached iron from ilmenite while Ti, which is fairly immobile, was incorporated into rutile. The classic ødegårdite locality is a 1.5 km-long and 100-150 m-wide zone surrounded by metagabbro/amphibolite (Brøgger 1934, Lieftink et al. 1993, Korneliussen & Furuhaug 1993, Sandøy 1996). The ødegårdite was altered to albitite along fractures by later metasomatic fluids. Many occurrences of rutile-bearing albitites are known in the Ødegården - Kragerø region (Brøgger 1934, Green 1956, Bugge 1965).

The Bergen Fe-Ti province. The Bergen district contains a tectonostratigraphic unit comprising Precambrian anorthositic, jotunitic and mangeritic rocks with a variety of ilmenite - magnetite deposits. Parts of the region experienced Caledonian high-pressure metamorphism and eclogitisation, such as the Husebø locality at Holsnøy which contains 2-5 % rutile (Korneliussen et al. 1991).

The Sunnfjord Fe-Ti province is a part of the Western Gneiss Region, composed of Proterozoic mafic and felsic igneous rocks that were strongly affected by the Caledonian orogeny (see Korneliussen et al. 2000). Two types of Ti deposits occur in this region: magmatic ilmenite-magnetite deposits associated with Proterozoic mafic intrusions, and rutile-bearing Caledonian eclogitic rocks. The rutile-bearing eclogites are Proterozoic basic rocks that were transformed into eclogite during Caledonian high-pressure metamorphism at approximately 400 Ma. During this process, ilmenite in the protolith broke down, with the Fe entering garnet and Ti into rutile. In this process, large volumes of ilmenite-bearing mafic rocks were transformed into rutile-bearing eclogitic rocks with the same TiO_2 content, but of much more economic interest since the price of rutile is much higher than that of ilmenite. From a mineral resource perspective, the ilmenite deposits in the region are of only minor interest, while the rutile-bearing eclogites represent a major mineral resource, particularly the Engebøfjell deposit.

The Møre Fe-Ti province is, like the Sunnfjord province, a part of the Western Gneiss Region of southern Norway, with a large variety of Proterozoic rocks affected by the Caledonian orogeny. Magnetite - ilmenite ores (Geis 1971) are found in certain suites of metagabbro and amphibolite. Rutile-bearing eclogites are common in parts of this province. The Rødsand deposits (Sanetra 1985) were a major source of Fe-Ti-V ore in Norway for 80 years, until mining ceased in 1981.

The Lofoten - Vesterålen Fe-Ti province. Massive and disseminated Fe-Ti deposits occur in gabbros and anorthosites that belong to a 1900 Ma suite of intrusions emplaced into Early Proterozoic supracrustals and Archaean gneisses. A major Fe-Ti deposit is the layered Selvåg gabbroic intrusion (Priesemann & Krause 1985). This intrusion contains cumulate layers of magnetite - ilmenite. An overview of the geology of this province has been given by Griffin et al. (1978).

The Seiland Fe-Ti province. The Seiland Igneous Province in northern Norway consists of very large volumes of mafic and ultramafic rocks. The province contains large, low-grade deposits of Fe-Ti oxides within intrusions of gabbronorite, olivine gabbro and hornblende clinopyroxenite (Robins 1985). Recent results of isotopic data suggest that much of the magmatism took place in connection with Riphean to Middle Cambrian intracontinental rifting (Robins 1996).

Isolated deposits. Scattered occurrences of Fe-Ti deposits occur outside the main Fe-Ti geological provinces. Most of these are of Proterozoic age, an exception being the Kodal deposit (Lindberg 1985) in the Permian Oslo Igneous Province. This ore is believed to have formed either from a Fe-Ti oxide and apatite-rich magma generated by liquid immiscibility (Bergstøl 1972) or by cumulus processes related to a monzonitic magma (Lindberg 1985).

Oxide mineralogy

General oxide mineralogy

The main Ti-bearing minerals of interest, ilmenite ($FeTiO_3$), hemo-ilmenite ($FeTiO_3$ with extensive Fe_2O_3 solid solution, now ilmenite with hematite exsolution lamellae), rutile (TiO_2) and titanomagnetite (Fe_2TiO_4-Fe_3O_4), are all in the system FeO-Fe_2O_3-TiO_2 (Fig. 3). There is a large compositional range in ilmenites in intrusive igneous rocks, because ilmenite is formed either by direct crystallisation from a melt, or as a product of oxidation-exsolution from titanomagnetite (Frost & Lindsley 1991). At low temperatures and under strongly oxidising conditions ilmenite alters to rutile plus hematite. Ilmenite and magnetite occur widely in low- to high-grade metamorphic rocks. Rutile occurs most commonly in three metamorphic settings, in all of which FeO available for the formation of ilmenite is lacking: (a) in rocks dominated by sulphides or hematite. (b) in rocks that are low in FeO due to hydrothermal alteration, such as in the Bamble area of South Norway. (c) in high-pressure metamorphic rocks where FeO is strongly fractionated into silicates, such as in the eclogite province of West Norway.

In Norway, ilmenite is found in both igneous and metamorphic settings as illustrated by the examples shown in Fig.10. The selected samples represent a variety of geographic locations and petrogenetic histories and highlight the variation in oxide mineralogy. The largest hemo-ilmenite and ilmenite ± magnetite deposits are those associated with anorthosite bodies in the Rogaland region. More detailed descriptions of ilmenite from Tellnes, as well as elsewhere in the Rogaland region, are presented in a companion paper in this volume (McEnroe et al. 2000) and in Duchesne (1972, 1999). The magmatic ores in this region vary in their average ilmenite, hemo-ilmenite and magnetite contents and show significant textural variations.

The Tellnes deposit in Rogaland, southern Norway, contains hemo-ilmenite and minor magnetite. The ilmenite host has abundant hematite exsolution lamellae parallel to {0001} as shown in Fig. 10a. Multiple generations of hematite exsolution down to the micron scale are observed, and, based on measured magnetic properties (McEnroe et al. 1996, McEnroe 1997), it appears that generation of exsolution lamellae continued down to the nanometre scale (Harrison et al. 1998). Minor aluminous spinels are common exsolution products. Directly surrounding the spinel there is a zone free of hematite exsolution. When hemo-ilmenite and magnetite are in contact (Fig. 10b), a symplectite of magnetite, ilmenite and spinel is formed by re-equilibration during cooling in which Fe^{3+} in the ilmenite was exchanged for Fe^{2+} in the magnetite. The portion of the ilmenite grain that is in direct contact with magnetite is free of hematite exsolution due to the diffusional loss of Fe^{3+}. In the magnetite-rich cumulate rocks from other localities in the Sokndal region the magnetite generally has {111} oxidation-exsolution lamellae of ilmenite as well as lamellae of spinel. Spinel-magnetite-ilmenite symplectites are common where ilmenite-magnetite grains are in contact (Fig. 10b). Discrete ilmenite grains in the magnetite-rich rocks are free of hematite lamellae. Fig. 10c shows a typical titanomagnetite from the Kodal deposit in larvikite of the Permian Oslo rift. This deposit is rich in magnetite, ilmenite and apatite. The titanomagnetite commonly has {111} lamellae of ilmenite and minute spinel parallel to {100}. Discrete ilmenite and euhedral apatite crystals are present in most samples.

In the Lofoten - Vesterålen province the Proterozoic Eidet-Hovden layered mafic intrusion hosts the Selvåg Fe-Ti-V deposit (Priesemann & Krause 1985). The titanomagnetite grains commonly have {111} oxidation- exsolution lamellae of ilmenite (Fig 10d). The first generation of ilmenite lamellae commonly enclose spinel. Multiple generations of spinel exsolution parallel to {100} are also present throughout the titanomagnetite grains. The variety of microstructures reported from the deposit, trellis, sandwich and composite lamellae, and lit-par-lit textures may well be indicative of variations in the oxidation and cooling history in the layered intrusion.

Two examples of metamorphosed Fe-Ti ore deposits are shown in Fig. 10. The Rødsand ore, hosted by an amphibolite

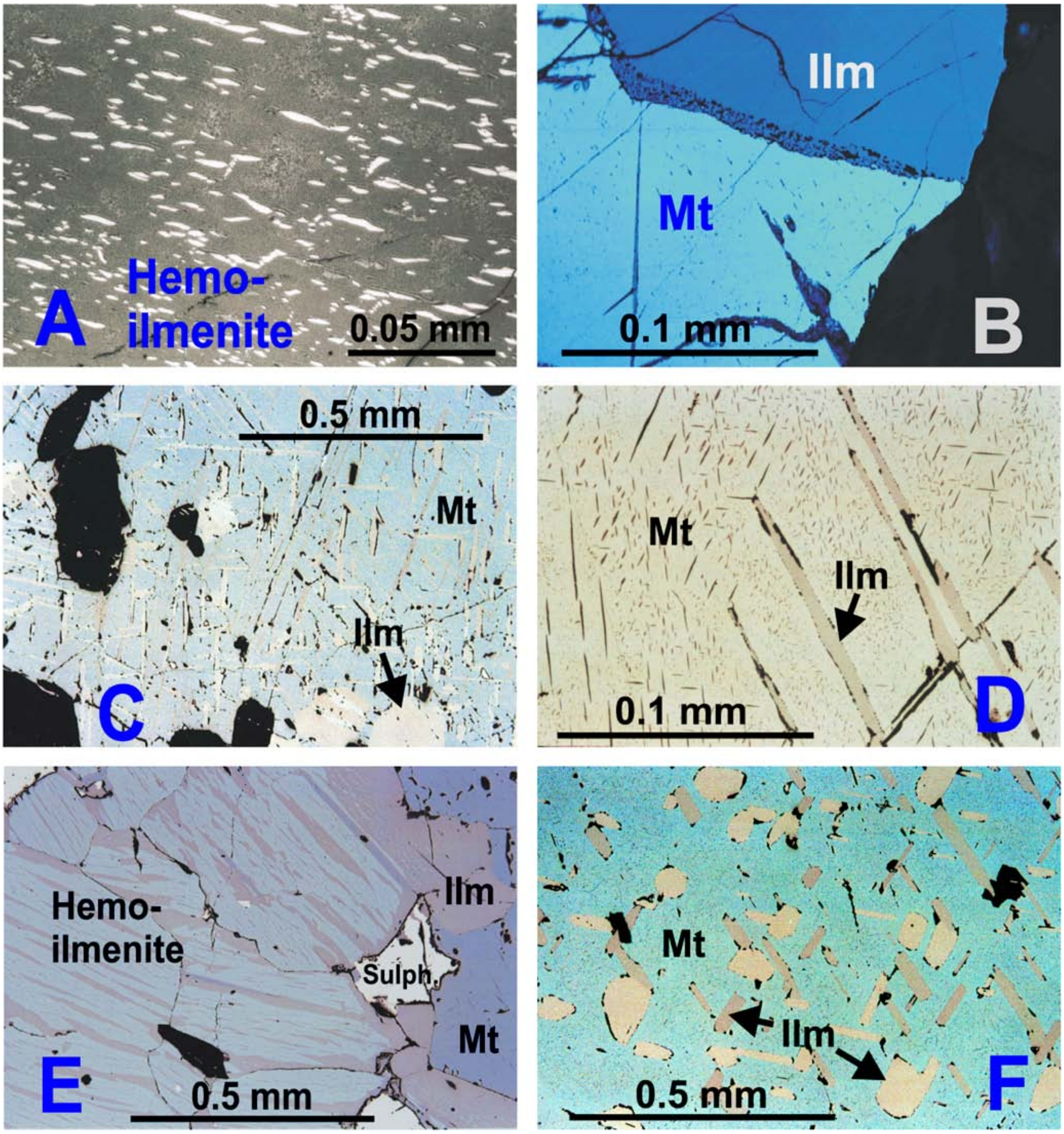

Fig. 10. (A) Ilmenite (dark brown) with very fine hematite exsolution lamellae (light grey). Tellnes ilmenite norite ore. (B) Ilmenite with spinel symplectite at the magnetite contact, and magnetite with lamellae of ilmenite and spinel. Ilmenite-magnetite bearing norite from the Sokndal area. (C) Titanomagnetite (light grey) with closely spaced ilmenite lamellae and abundant euhedral apatite (dark grey) crystals. Kodal larvikite (monzonite) hosted ap-mt-ilm / P-Fe-Ti deposit in the Permian alkaline Oslo Rift. (D) Titanomagnetite (light grey) with several generations of fine and very fine spinel exsolution lamellae (black) plus broader ilmenite lamellae, all following crystallographic directions in the host magnetite. Selvåg Fe-Ti-V deposit in the Proterozoic, Eidet-Hovden, layered mafic intrusion, Lofoten-Vesterålen Fe - Ti province. (E) Typical Rødsand ore: magnetite (grey) with minute spinel exsolution lamellae (right), abundant sulphides (white) and hemo-ilmenite gradually passing into ilmeno-hematite away from the magnetite contact. Rødsand titanomagnetite-ilmenite deposit, hosted in a strongly deformed and amphibolitised Palaeoproterozoic gabbro, Møre Fe -Ti province. (F) Prismatic inclusions of ilmenite in magnetite. Røra magnetite-ilmenite occurrence, hosted in a basic complex west of Porsgrunn, Bamble - Arendal Fe - Ti province (Kongsberg-Bamble, Mid Proterozoic, high-grade shear belt). The ore is among the most vanadium rich in Norway with up to 1.5 wt. % V_2O_3 in magnetite.

Table 2. Electron microprobe analyses (average values) of magnetite and ilmenite in some Fe-Ti deposits in Norway. The analyses were done by a focused electron beam scanning an area of the mineral grains to average out the effect of inhomogeneities, such as hematite exolutions in ilmenite. n is the number of analyses pr. deposit.

Deposit		n	TiO_2	V_2O_3	FeOt	MnO	MgO	Cr_2O_3	Deposit		n	TiO_2	V_2O_3	FeOt	MnO	MgO	Cr_2O_3
Bamble - Arendal Fe-Ti province																	
Barmen	Ilm	8	48,63	0,19	47,44	0,90	1,48	0,01	Myrestø	Ilm	3	49,08	0,16	47,89	0,63	1,03	0,01
Barmen	Mt	3	1,24	0,63	89,21	0,49	0,38	0,06	Myrestø	Mt	2	1,07	1,19	89,81	0,36	0,30	0,02
Dobbe	Ilm	4	46,35	0,26	46,78	0,73	1,11	0,01	Røra	Ilm	3	49,27	0,30	46,84	0,93	1,62	0,00
Dobbe	Mt	2	0,01	1,21	86,81	0,39	0,06	0,01	Røra	Mt	2	0,05	1,48	91,34	0,38	0,11	0,03
Gumøy	Mt	5	0,00	0,24	91,25	0,26	0,03	0,00	Selåsfjellet	Ilm	3	47,14	0,10	45,53	0,73	0,80	0,01
Gundersbo	Ilm	6	48,31	0,01	42,39	4,28	0,25	0,00	Selåsfjellet	Mt	3	0,33	1,00	86,94	0,25	0,11	0,02
Gundersbo	Mt	10	0,04	0,14	89,80	0,28	0,07	0,02	Skredderhagen	hemoilm.	1	9,30	1,57	72,61	0,01	0,28	0,03
Herre	Ilm	11	48,76	0,16	48,27	0,78	0,34	0,01	Skredderhagen	Ilm	5	40,12	0,50	46,74	0,13	2,55	0,02
Herre	Mt	5	6,87	1,13	85,53	0,27	0,20	0,04	Skredderhagen	Mt	6	4,17	0,34	82,27	0,32	0,08	0,02
Langøy	Ilm	7	47,57	0,21	49,69	0,93	0,21	0,00	Ståltjern	Ilm	10	42,17	0,27	50,61	0,75	0,72	0,02
Langøy	Mt	3	0,16	0,86	91,79	0,31	0,03	0,03	Ståltjern	Mt	6	0,08	0,91	88,00	0,26	0,09	0,26
Bergen Fe-Ti province																	
Baugstø	Ilm	9	49,12	0,11	47,80	1,19	0,13	0,00	Seifall	hemoilm.	6	30,96	0,26	60,28	0,43	0,51	0,01
Baugstø	Mt	2	1,74	0,70	91,28	0,15	0,00	0,02	Seifall	Ilm	6	46,14	0,12	50,59	0,89	0,21	0,01
Espeland	hemoilm.	1	9,97	0,90	80,68	0,44	0,30	0,07	Seifall	Mt	6	1,83	0,19	90,62	0,28	0,05	0,01
Espeland	Ilm	2	48,26	0,35	46,87	0,81	2,67	0,01	Seifall	rutil	2	82,50	0,26	10,35	0,01	0,00	0,01
Espeland	Mt	1	0,00	0,73	92,08	0,00	0,24	0,13	Soltveit	hemoilm.	4	15,00	0,63	73,27	0,12	0,28	0,07
Gymmeland	hemoilm.	2	12,82	0,51	79,09	0,30	0,14	0,00	Soltveit	Ilm	6	43,47	0,22	49,91	0,32	1,01	0,02
Gymmeland	Ilm	3	47,23	0,07	49,70	1,47	0,57	0,00	Soltveit	Mt	1	0,00	0,32	90,26	0,28	0,07	0,04
Gymmeland	Mt	2	0,45	0,34	92,59	0,46	0,08	0,01	Tveitøy	hemoilm.	2	15,86	0,58	73,57	0,09	0,45	0,04
Lyseknappen	hemoilm.	3	14,74	0,63	77,19	0,45	0,31	0,01	Tveitøy	Ilm	4	45,38	0,14	47,81	0,41	1,33	0,01
Lyseknappen	Ilm	4	45,61	0,21	51,03	0,33	1,20	0,00	Tveitøy	Mt	1	0,25	0,23	88,94	0,63	0,06	0,06
Egersund Fe-Ti province																	
Bakka	Mt	4	2,60	0,79	88,99	0,28	0,21	0,02	Storgangen	Ilm	9	46,04	0,27	46,87	0,47	3,51	0,01
Blåfjell	Ilm	4	47,72	0,14	47,41	2,10	0,07	0,00	Storgangen	Mt	5	0,00	0,72	91,80	0,33	0,30	0,08
Blåfjell	Mt	2	0,06	0,24	90,32	0,19	0,07	0,01	Tellnes	Ilm		48,67	0,16	47,38	0,28	3,46	0,08
Bøstølen	Ilm	5	49,49	0,24	47,34	0,58	1,80	0,01	Tellnes	Mt		0,30	0,66	91,00	0,01	0,30	0,70
Bøstølen	Mt	5	0,96	0,63	96,48	0,07	0,18	0,03	Ålgård	Ilm	2	47,60	0,16	46,65	0,49	3,87	0,13
Mydland	Ilm	11	45,88	0,23	51,25	0,52	1,07	0,01	Årsland	Ilm	2	48,70	0,20	46,46	0,43	3,49	0,07
Mydland	Mt	6	0,97	0,32	94,84	0,27	0,08	0,07	Årsland	Mt	1	0,05	0,69	90,16	0,01	0,22	1,81
Deposits outside the Fe-Ti provinces																	
Bjørnvatn	Ilm	6	49,02	0,24	47,70	0,85	0,61	0,00	Linde	Ilm	4	42,87	0,25	50,52	0,86	0,72	0,01
Bjørnvatn	Mt	3	0,73	1,70	89,59	0,43	0,07	0,10	Linde	Mt	7	0,01	0,40	90,26	0,29	0,06	0,04
Frøn	hemoilm.	3	32,95	0,34	48,69	0,36	0,47	0,02	Nomme	Ilm	2	42,59	0,12	46,13	2,54	1,65	0,01
Frøn	Ilm	3	33,64	0,22	48,14	0,42	0,44	0,01	Nomme	Mt	3	0,65	0,16	85,85	0,04	0,13	0,00
Frøn	Mt	4	0,00	0,72	78,72	0,22	0,06	0,06	Pesedalen	Ilm	6	37,59	0,19	40,97	0,34	2,42	0,08
Gladsøy	Ilm	8	47,09	0,22	47,27	1,12	0,34	0,01	Rimmo	hemoilm.	3	13,88	0,52	78,11	0,18	0,23	0,05
Gladsøy	Mt	3	0,15	0,85	88,87	0,19	0,04	0,03	Rimmo	Ilm	3	43,42	0,26	52,63	0,46	1,29	0,02
Hattavarre	Ilm	3	50,35	0,07	39,02	0,90	4,39	0,00	Spissholt	Ilm	6	43,86	0,01	40,41	1,24	0,69	0,01
Hattavarre	Mt	3	2,41	0,52	83,90	0,13	0,75	0,05	Spissholt	Mt	2	3,11	0,19	76,52	0,34	0,15	0,04
Hitra	hemoilm.	3	10,86	0,03	75,03	0,18	0,01	0,01	Svalnes	Ilm	4	46,33	0,35	46,76	0,41	4,00	0,02
Hitra	Ilm	3	44,74	0,03	47,24	1,42	0,10	0,01	Vikeby	Ilm	2	47,99	0,42	42,62	1,47	2,09	0,02
Kaneset	Mt	4	0,00	0,11	90,31	0,71	0,02	0,00	Vikeby	Mt	2	0,31	1,25	86,06	0,03	0,11	0,23
Kirkehaugene	hemoilm.	2	15,89	0,88	73,06	0,45	0,23	0,17	Åletødne	Ilm	7	45,11	0,16	45,98	1,59	0,13	0,01
Kirkehaugene	Ilm	4	45,31	0,19	49,17	0,99	0,32	0,04	Åletødne	Mt	4	0,13	0,72	86,05	0,21	0,04	0,03
Kirkehaugene	Mt	2	0,00	0,53	89,94	0,63	0,10	0,33	Årdal	hemoilm.	1	8,41	0,25	81,52	0,40	0,40	0,07
Kodal	Ilm	9	48,11	0,14	43,29	5,58	0,85	0,00	Årdal	Ilm	2	49,19	0,16	43,17	0,13	5,53	0,01
Kodal	Mt	7	4,52	0,15	85,29	1,07	0,86	0,00	Årdal	Mt	3	2,99	0,14	89,29	0,14	0,27	0,04
Linde	hemoilm.	6	37,11	0,28	56,10	0,82	0,42	0,02	Årdal	rutil	3	96,20	0,18	1,07	0,03	0,05	0,00
Møre Fe-Ti province																	
Bergsøy	Ilm	3	51,10	0,17	42,26	0,73	4,54	0,00	Meisingset	Ilm	4	44,23	0,20	51,26	1,99	0,29	0,08
Bergsøy	Mt	2	0,26	0,59	89,97	0,03	0,46	0,07	Meisingset	Mt	2	0,07	0,31	92,38	0,23	0,19	0,31
Bersås	Ilm	2	48,76	0,32	46,86	0,93	0,40	0,01	Norvik	Ilm	7	40,96	0,14	41,91	0,53	0,52	0,01
Bersås	Mt	1	0,16	0,72	89,88	0,00	0,03	0,02	Norvik	Mt	5	0,40	0,59	77,02	0,35	0,03	0,01
Bæverfjord	Ilm	9	38,56	0,17	40,51	1,08	0,24	0,01	Oppdøl	Ilm	20	46,59	0,17	43,65	2,80	0,15	0,01
Bæverfjord	hemoilm.	3	0,05	0,54	77,06	0,20	0,17	0,02	Oppdøl	Mt	13	0,13	0,52	87,20	0,28	0,02	0,01
Bårdsetøya	Ilm	4	51,96	0,07	44,08	0,39	1,29	0,03	Raudsand	hemoilm.	9	16,54	0,90	73,75	0,37	0,37	0,04
Bårdsetøya	Mt	3	7,00	0,77	78,94	0,08	0,49	0,04	Raudsand	Ilm	32	44,74	0,27	49,94	1,07	0,74	0,01
Fiskå	Ilm	6	46,84	0,21	47,29	0,35	1,44	0,03	Raudsand	Mt	24	0,07	0,65	90,82	0,29	0,10	0,02
Fiskå	Mt	4	0,16	0,67	89,52	0,00	0,09	0,30	Seljeset	Ilm	4	52,26	0,06	44,03	0,75	0,63	0,00
Gruvlia	Ilm	11	47,70	0,29	47,54	0,64	0,52	0,06	Sjøholt	Ilm	4	51,48	0,20	46,41	0,43	0,78	0,00
Gruvlia	Mt	9	0,26	0,99	88,10	0,18	0,10	1,18	Sjøholt	Mt	4	0,09	0,96	89,09	0,01	0,07	0,01
Gussiås	Ilm	6	49,40	0,27	45,63	3,22	0,08	0,01	Solnørdal	Ilm	23	47,50	0,23	49,07	0,89	0,66	0,01
Gussiås	Mt	2	0,05	1,07	90,77	0,05	0,04	0,20	Solnørdal	Mt	21	0,14	0,68	91,55	0,33	0,07	0,03
Heindalen	hemoilm.	12	25,04	0,38	64,02	0,45	0,25	0,01	Strømme	Ilm	3	47,78	0,26	49,80	0,50	0,70	0,00
Heindalen	Ilm	5	43,95	0,22	48,87	0,70	0,41	0,00	Strømme	Mt	4	0,12	0,83	91,16	0,00	0,08	0,01
Heindalen	Mt	2	0,00	0,80	87,87	0,14	0,00	0,10	Tafjord	Ilm	4	37,71	0,17	42,10	0,74	0,65	0,08
Hustadneset	Ilm	4	52,20	0,02	45,15	1,09	0,06	0,01	Tafjord	Mt	1	0,14	0,53	74,71	0,38	0,47	0,90
Lesja	hemoilm.	1	13,35	1,07	76,14	0,56	0,25	0,69	Vågsæternes	Ilm	3	49,46	0,39	47,46	0,81	0,46	0,02
Lesja	Ilm	3	46,76	0,26	49,11	0,56	1,31	0,13	Vågsæternes	Mt	4	0,08	1,04	90,18	0,01	0,05	0,03
Lesja	Mt	2	0,09	1,02	87,09	0,22	0,13	2,27	Øyna	Ilm	9	45,49	0,15	43,99	1,08	0,47	0,01
									Øyna	Mt	7	0,40	0,71	88,23	0,07	0,03	0,13
Sunnfjord Fe-Ti province																	
Løland	Ilm	12	40,25	0,19	51,86	0,90	0,50	0,19	Råsberg	Ilm	4	47,30	0,11	47,63	0,76	1,22	0,01
Løland	Mt	7	6,58	0,47	82,50	0,39	0,14	0,60	Råsberg	Mt	4	0,16	0,67	90,47	0,23	0,10	0,02
Lofoten - Vesterålen Fe-Ti province																	
Andopen	Ilm	2	50,55	0,12	42,36	0,79	3,02	0,01	Klubbskjæret	Ilm	2	49,77	0,02	42,99	3,67	0,50	0,00
Andopen	Mt	1	0,27	0,75	89,96	0,01	0,34	1,24	Klubbskjæret	Mt	1	1,81	0,07	87,75	0,30	0,04	0,03
Barkestad	Ilm	2	49,54	0,16	43,64	0,90	2,64	0,01	Kudalen	Ilm	1	47,50	0,05	45,33	2,10	1,21	0,01
Barkestad	Mt	1	0,34	0,72	88,28	0,01	0,21	0,08	Kudalen	Mt	2	6,01	0,17	84,48	0,11	0,09	0,07
Finberget	Mt	2	0,01		89,44	0,06	0,05	0,00	Kvitheia	Mt	1	0,03	0,01	89,15	0,75	0,50	0,00
Fiskefjellet	Ilm	2	49,54	0,07	45,36	0,88	1,61	0,01	Naustvika	Mt	1	0,07		89,87	0,00	0,03	0,02
Fiskefjellet	Mt	1	0,61	0,64	89,32	0,04	0,13	0,21	Skjerfjorden	Ilm	1	47,82	0,09	48,07	0,23	0,85	0,01
Gustad	Ilm	2	51,49	0,05	41,86	0,80	2,86	0,01	Skjerfjorden	Mt	2	0,05	0,07	90,48	0,03	0,10	0,01
Gustad	Mt	2	1,60	0,44	89,14	0,09	0,11	0,06	Sunnan	Ilm	2	46,17	0,24	47,40	0,56	2,46	0,00
Hjellsand	Ilm	13	51,41	0,07	38,45	0,87	4,76	0,00	Sunnan	Mt	1	0,57	0,75	89,48	0,02	0,22	0,04
Hjellsand	Mt	5	1,45	0,70	87,06	0,11	0,52	0,07	Vinjeneset	Ilm	2	48,48	0,16	47,12	0,70	1,60	0,00
Hysjorda	Ilm	1	51,41	0,07	41,62	1,08	2,83	0,02	Vinjeneset	Mt	1	0,40	0,59	89,63	0,02	0,14	0,08
Hysjorda	Mt	1	0,23	0,82	89,32	0,01	0,13	0,88	Øksnesheia	Ilm	4	50,70	0,08	40,84	4,39	0,62	0,00
Klubbneset	Ilm	3	47,22	0,11	45,40	1,03	1,82	0,01	Øksnesheia	Mt	5	3,56	0,28	86,16	0,07	0,24	0,00
Klubbneset	Mt	1	0,23	0,49	89,35	0,01	0,09	0,32	Åsand	Ilm	2	46,70	0,05	46,89	1,21	1,31	0,00
									Åsand	Mt	5	8,13	0,10	82,11	0,09	0,16	0,00

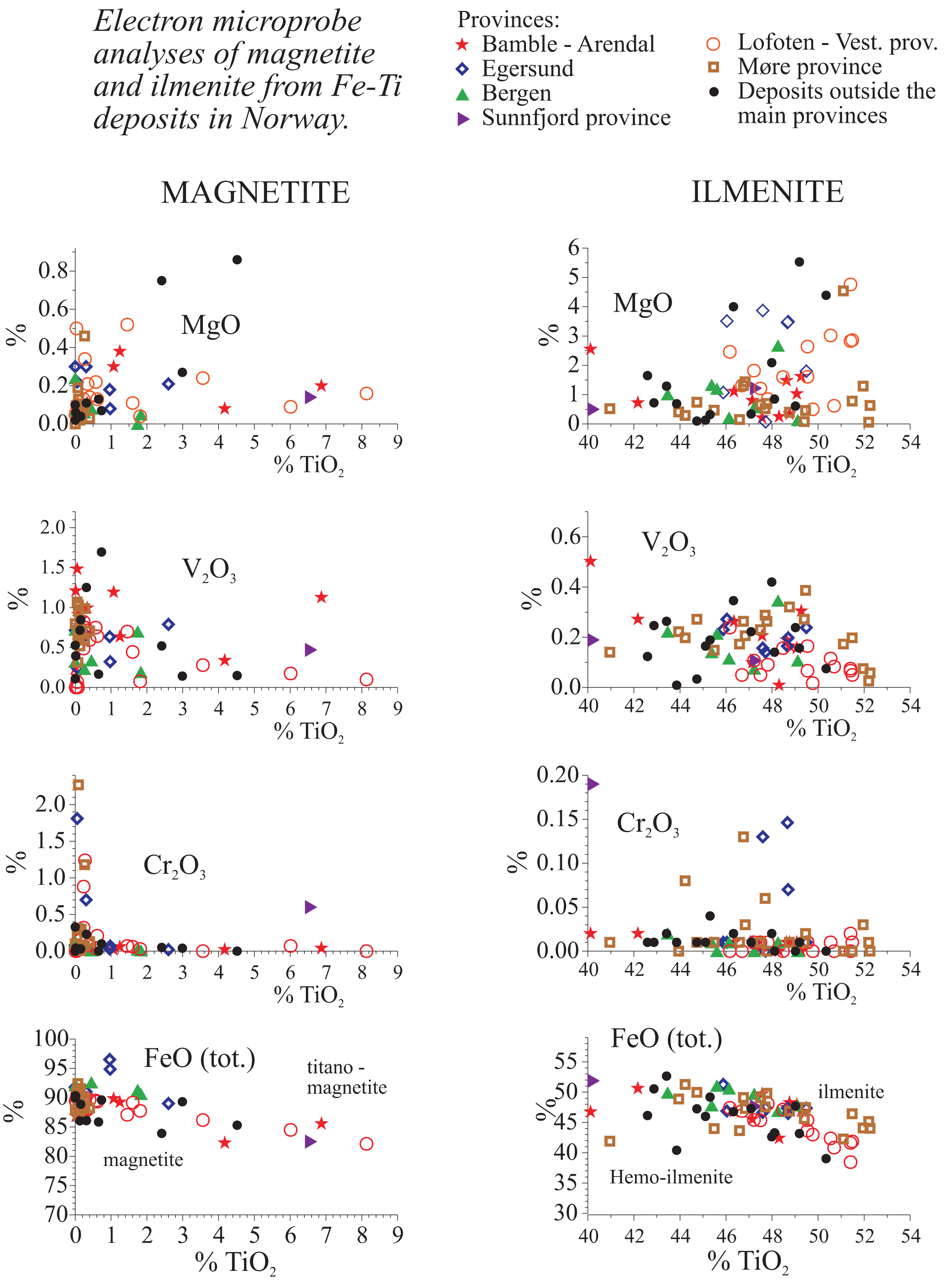

Fig. 11. TiO_2 vs. FeO (tot), MgO, Cr_2O_3, and V_2O_3 in oxide minerals from Norwegian Fe-Ti desposits, based on electron microprobe analyses given in Table 2.

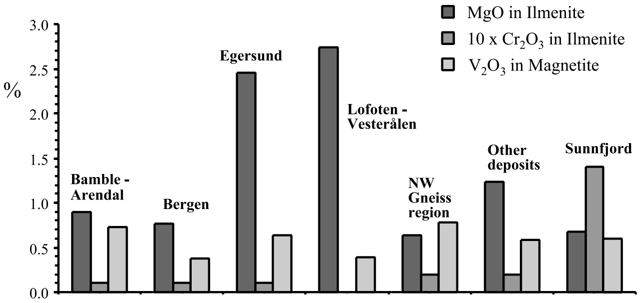

Fig. 12. Average content of V_2O_3 in magnetite and MgO and Cr_2O_3 in ilmenite in Fe-Ti provinces, based on electron microprobe analyses given in Table 2.

in the Western Gneiss Region of western Norway, is rich in titanohematite, ilmeno-hematite and magnetite. Fig. 10e shows a typical section containing titanohematite with ilmenite exsolution and ferrian-ilmenite with hematite exsolution. The hematite host has ilmenite exsolution lamellae parallel to {0001}, and the ilmenite lamellae contain later hematite exsolution parallel to {0001}. Multiple generations of ilmenite and hematite exsolved occur within the titanohematite host phase. Inclusions of sulphides and spinel are common in the titanohematite grains. The coexisting magnetite grains contain {100} spinel exsolution and only rarely ilmenite lamellae. Many other Fe-Ti deposits are in metamorphic settings. An example from one of the high-grade magnetite-ilmenite-apatite deposits in the Bamble-Arendal province in southern Norway is shown in Fig. 10f.

Ilmenite and magnetite compositions

Ilmenite and magnetite from a variety of Ti/Fe-Ti deposits have been analysed by electron microprobe in order to investigate the variations in chemical composition within individual deposits as well as within and between Fe-Ti provinces. Average contents of MgO and Cr_2O_3 in ilmenite, and V_2O_3 in magnetite, from representative samples are given in Table 2. The average MgO and Cr_2O_3 in ilmenite and V_2O_3 in magnetite show distinct variations between the Fe-Ti provinces, although the variation within each province is also significant. Compositional variations can be large within individual deposits. Shown in Fig. 11 are plots of electron microprobe analyses of TiO_2 vs. FeO, Cr_2O_3, V_2O_3 and MgO in ilmenites and magnetites. In these plots each deposit is represented by an average value for magnetite, hemo-ilmenite and ilmenite. From deposits that show distinct compositional variations, the average value given in Table 2 is regarded as representative for the deposit. For other deposits, where fewer samples have been analysed, the average value given in Table 2 may not be representative for the deposit.

The overall MgO content in ilmenite is higher in the Egersund and Lofoten - Vesterålen provinces than elsewhere (Fig. 12), although local variations occur as shown in Table 2 and Fig. 10. For example, ilmenite from Mydland and Bøstølen in the Egersund province averages 1.07 % and 1.80 % MgO in ilmenite, while Ålgård, Årsland and Tellnes average 3.87, 3.49 and 3.46 % MgO, respectively (Table 2). Similarly, the average MgO in ilmenite from deposits in the Lofoten - Vesterålen province varies from approximately 1 % MgO to 3 % MgO, with one deposit (Hjellsand) having 4.76 % MgO in ilmenite. Ores with a high MgO content in ilmenite are Bergsøy (4.54 % MgO) in the Møre province, and the isolated deposits Hattavarre (4.39% MgO), Svalnes (4.00% MgO) and Årdal (5.53% MgO).

In co-existing magnetite and ilmenite, Cr is partitioned into magnetite. In most of the Fe-Ti deposits the amount of magnetite is significant, taking up most of the Cr in the rock with only a small amount partitioned into ilmenite. Consequently, the Cr_2O_3 content in ilmenite is low (< 0.03%) in many deposits. The highest Cr_2O_3 contents in ilmenite are found in deposits in the Sunnfjord region. High Cr_2O_3 contents in ilmenite are also found in some deposits in the Egersund province, with Ålgård, Åsland and Tellnes containing 0.13, 0.07 and 0.08 % Cr_2O_3 in ilmenite, respectively. Particularly Cr_2O_3-rich ilmenites in the Møre region are found in the Lesja (0.13% Cr_2O_3) and Meisingset (0.08% Cr_2O_3) deposits. The variation in Cr_2O_3 content in ilmenite may be considerable within the same deposit. In igneous ilmenites, McEnroe et al. (1996, 2000) found a strong correlation between the hematite lamellae in the ilmenite and Cr concentration.

Vanadium tends to be preferentially partitioned into magnetite. Deposits with more than 1% V_2O_3 in magnetite are found mainly in the Bamble - Arendal and Møre provinces. In addition, a few scattered deposits, e.g., Bjørnvatn and Vikeby, outside the main provinces have particularly V_2O_3-rich magnetites, with 1.70 % and 1.25 % V_2O_3 respectively. The deposits with the highest V_2O_3 content in magnetite within the Bamble - Arendal and Møre provinces are Røra (1.48 % V_2O_3) and Lesja (1.07 % V_2O_3), respectively.

Trace elements in rutile

Elements such as U, Nb, W, Cr and V tend to be enriched in rutile if they were available in sufficient amounts during the original, rutile-forming geological process. Table 3 gives trace-element data for rutile separates from a variety of Norwegian rutile deposits. As an example, the U content is very low (< 2 ppm) in Caledonian eclogite deposits such as Husebø (Bergen province) and Vassbotn (Møre province), because the U content in the original mafic igneous protolith of the eclogite was low. In comparison, examples of U enrichment include rutile from the Lindvikkollen rutile-bearing albitite (100 ppm U) and the Ødegården rutile-bearing scapolite-hornblende rock (61 ppm U). A high Zr content for some of the analyses of rutile separates is caused by zircon inclusions in rutile, which cannot be removed by normal mineral separation techniques. The detailed relationships between the trace-element content in rutile and the character of the deposit need to be further investigated.

Conclusions

The primary source of Ti in the Earth's crust is mafic to intermediate igneous rocks (see Force 1991) in which ilmenite usually is the stable Ti-oxide mineral. Rutile, which is less common than ilmenite, is formed by hydrothermal, metaso-

Table 3. Trace elements in rutile separates from some rutile deposit types in Norway. U, Nb and W are analysed by INA and Zr, Cr and V by XRF. All values in ppm.

Locality	Sample	Region	Host-rock	U	Nb	Zr	W	Cr	V
Lindvikkollen	KB11.91	Bamble - Arendal	albitite	100.0	149	930	300	920	8866
Gruvetjønn	KB6F.91	Bamble - Arendal	amphibolite	48.8	936	580	51	276	1518
Fone	KB5F.91	Bamble - Arendal	amphibolite	42.0	1775	1854	30	46	843
Haukåsen	KB9.91	Bamble - Arendal	pegmatite	93.2	815	2454	72	2323	3072
Ødegård	1Ø66/79	Bamble - Arendal	scapolite-h.bl.	61.4	326	6143	85	207	15635
Husebø-B	Husebø-B	Bergen	eclogite	0.3	84	399	0	184	2512
Vassbotn	VB1A.91	Møre	eclogite	1.9	113	389	0	92	4409
Saurdal	Sørdal-A	Sunnfjord	eclogite	0.9	39	228	7	161	3765

matic or high-pressure metamorphic processes in which ilmenite is broken down. Iron is transported away by hydrothermal fluids, as in the metasomatic deposits, or enters other minerals, as in eclogites. A fundamental difference between the metasomatic and the eclogite rutile deposits is that rutile from eclogites usually has lower amounts of trace elements, particularly uranium which is undesirable in the TiO_2 pigment industry. The low U content is one reason why rutile from eclogite deposits might become an attractive raw material for the Ti industry (see Korneliussen et al. 2000). Another factor in favour of eclogite deposits is their generally large size, particularly those in the Sunnfjord region of western Norway.

In terms of TiO_2 content, the Rogaland anorthosite province is by far the most significant in Norway, representing a considerable potential for future ilmenite production. Large resources exist within the Bjerkreim – Sokndal layered intrusion of ilmenite, vanadiferous titanomagnetite, and apatite-rich noritic rocks. The rocks commonly have 10-20 % ilmenite (containing 0.5-2.0 % MgO), 5-20% titanomagnetite (containing 0.4-1.2 % V_2O_3), and 5-10% apatite.

The other major Ti province in Norway is the Sunnfjord eclogite province of western Norway. Here, the Ti concentration is appreciably lower, but it is contained in rutile, which is a more valuable mineral than ilmenite. The Ti content in rutile-rich eclogites such as the Engebøfjell deposit (McLimans et al. 1999, Korneliussen et al. 2000) is 3-5 % TiO_2.

Overall, the mineralogy defines the mineability of a Ti deposit. Mineralogy is a function of the geological evolution of the deposit, which is often very complex, involving a magmatic evolution, a subsolidus re-equilibrium, and in some instances, a metamorphic overprint. Proterozoic to Permian Ti deposits in Norway occur within a variety of geological provinces and show a large spectrum in chemistry, composition and textural relationships.

The major task in continued investigations of Ti mineral deposits in Norway is not only to identify Ti-rich deposits, but also to identify those deposits that have ore-mineral qualities that can meet the future requirements of the Ti pigment industry. In the near future, focus will be on ore-types occurring in large volumes, such as the ilmenite, vanadiferous titanomagnetite and apatite-bearing noritic rocks within the Bjerkreim-Sokndal intrusion in the Egersund province, particularly those parts which have less than 1.0 % MgO in the ilmenite. Equally, rutile-bearing eclogites in the Sunnfjord province will be the focus of considerable attention.

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