Rutile in eclogites as a mineral resource in the Sunnfjord Region, western Norway

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The world's resources of the primary titanium raw materials ilmenite and rutile are very large. However, there is a lack of high-grade, high-quality ilmenite deposits as well as good rutile deposits. Particular focus has been given to rutile-bearing eclogites in the Sunnfjord region of western Norway, due to a combination of factors such as high rutile content over significant volumes of rock and favourable rutile grainsize. Eclogites in the Sunnfjord region are found in a number of elongated lenses up to 3-4 km long, surrounded by gneisses of amphibolitic to granitic composition, as well as numerous smaller eclogite bodies and eclogitised mafic layers in gneisses. The eclogites originated by high-pressure and temperature alteration of Proterozoic, Fe-Ti rich, gabbroic rocks, and were strongly deformed under eclogite-facies metamorphism and thereafter variably affected by retrograde processes. Eclogites in which conversation of ilmenite to rutile was complete and in which this mineral assemblage was negligibly affected by subsequent retrograde processes, are those of greatest economic potential. An example of such an eclogite is the Engebøfjellet eclogite on the north side of Førdefjord, Naustdal commune.

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Introduction

The world reserves of economic sources of titanium are estimated to be approximately 300 mill. tons of contained TiO_2, and some 90% of the resource is accounted for by ilmenite. At present, 93 % of the titanium is used to manufacture TiO_2 pigment by either the chloride or the sulphate manufacturing method; the chloride manufacturing process is steadily becoming dominant. Environmental demands and the need to increase capacity at existing plants are driving manufacturers to use increasingly higher and higher grade feedstock, i.e. rutile, Ti-rich slag derived from ilmenite, and synthetic rutile derived from leached ilmenite. High-grade stocks (>85% TiO_2) are forecast to account for 75% of demand in the year 2000, an increase of 29% since 1996. The price of ore will have climbed by 65% from 1985 to 2000, whereas the price of pigment has risen by only 5 % in that period. These economic factors represent a stimulus for the search for alternative types of Ti ore. Despite fluctuations in world economies, TiO_2-pigment use has grown steadily at a rate of 3% per year. Ti-rich slag is produced from both sand ilmenite ores and hard-rock ilmenite such as the Allard lake deposit in Canada and the Tellnes deposit in Norway. Rutile sand ores are limited in volume and are being rapidly depleted and are therefore not forecast to be a major source in the future. At present, there is an adequate supply of high-grade feedstocks but demand is forecast to exceed supply by 2005, resulting in the current focus on the location and evaluation of new TiO_2 resources. In particular, there are inadequate supplies of high-grade (>55% TiO_2) ilmenite sand, a preferred feed to slag and synthetic rutile. Hence, there is a window of opportunity for new, high-grade TiO_2 ores. The rutile-bearing eclogites of western Norway (Korneliussen & Foslie 1985, Korneliussen 1995, Korneliussen et al. 1999) have the potential to supply rutile for the high-grade ore market. Eclogites of economic potential in western Norway are bodies of rock several hundred million tonnes in volume and containing several million tonnes of contained TiO_2 as rutile.

In the 1970-80's, scattered geological investigations were carried out on rutile-bearing eclogites in West Norway by the Norwegian Geological Survey (NGU) and the companies Elkem, Norsk Hydro, and others. In the early 1990's, DuPont, the largest Ti-pigment producer in the world, started an exploration programme in order to evaluate rutile resources in western Norway. A significant number of deposits have been identified and examined. Of these, the Engebøfjellet eclogite body (McLimans et al. 1999, Erambert et al., in prep.), situated on the northern side of Førdefjord in the Sunnfjord region, proved to be a high-quality rutile deposit with a good potential for production in the future. The purpose of this article is to describe the occurrence of rutile in eclogites in the Sunnfjord region of western Norway and address their potential as a major Ti resource.

Eclogites as a rutile resource

Deposits of rutile can be grouped into a variety of igneous, metamorphic, hydrothermal and sedimentary types (Force 1991). Only sedimentary deposits are of economic importance at present. Among the hard-rock rutile deposit types, eclogite deposits probably have the largest potential as a future source of Ti since they are frequently of sizeable volume with adequate ore grades.

With the exception of a relatively small mining operation of rutile in an amphibolitic rock in China, rutile from hard-rock deposits is not currently mined. The main reason for this is that raw-material quality requirements by the TiO_2-pigment industry place strict limitations on the suitability of many deposits for exploitation. Restrictions include the content of CaO in the rutile concentrate, which is due to the presence of calcium-bearing silicates as impurities. In sand deposits, the minerals are separated naturally by weathering, and the CaO in rutile concentrates will not normally be a significant problem. In hard-rock deposits, however, the minerals have to be separated mechanically, which is appreciably less effective than the combined mechanical and chemical forces of nature operating over millions of years.

Although rutile concentrates which meet the specification for chlorination have been produced from hard-rock deposits, the price is a reduction in recovery of rutile. The principal problem is assuring that the CaO content in the concentrate is less than 0.2%, which is not easily obtained since essentially all non-ore minerals in most rock-types, including eclogite, contain CaO. However, it should be emphasised that eclogite rutile concentrates have a clear advantage over sand-type ores as they are essentially free of U and Th. Environmental concerns demand the concentrations of the radioactive elements to be as low as possible.

The only known example of historical rutile mining from eclogite was from the Shubino Village, Russia (Force 1991), although this mining was probably not a regular mining operation. The enormous rutile-bearing eclogite at Pian Paludo, Italy, was studied for Ti-ore potential (Mancini et al. 1979, Clerici et al. 1981). More recently, E. I. duPont conducted detailed studies of this eclogite and its mineralogy (Liou et al. 1998). Although the grade of TiO_2 is as high as 10-12% in parts of the eclogite, the combined effects of small grain size, extensive retrogression, and costly grindability index render it financially unattractive. Furthermore, the fine size of the liberated rutile would require beneficiation by flotation methods, a less desirable method particularly from the environmental view.

Proven resources at Engebøfjellet in the Sunnfjord region, an eclogite extensively studied and drilled by DuPont, are 9 million tonnes of rutile recoverable by current processing, with a significant additional tonnage of possible ore reserve. If put into production, a planned 200,000 tonnes p.a. rutile production would make Engebøfjellet one of the largest rutile mining operations in the world. The potential for further resources in the Sunnfjord region, as well as elsewhere in West Norway, is very large, although poorly investigated.

The extraction of rutile from hard rock requires that the rutile be completely liberated, separated, and concentrated by milling and upgrading circuits. In addition, the purity requirements of the chloride manufacturing process (rutile cannot be used in the sulphate process) necessitate a rutile free from impurities such as CaO, Al_2O_3, MgO, etc. which are contained in the silicate minerals in eclogite. Hence, the rutile from eclogite must be completely liberated and the separation circuits should yield a clean rutile product. In the case of the rutile eclogite at Engebøfjellet, the rutile grain size, extent of eclogitisation, and preservation of eclogite facies without pervasive retrogression, are such that feedstock suitable for the chloride process has been produced economically by conventional and non-chemical processing technology.

The eclogite province of western Norway

The prominent feature of the Scandinavian Caledonides is the series of thrust sheets that were transported to the southeast and emplaced onto the Baltoscandian Platform during the Scandian orogenic event in Middle to Late Silurian times. Eclogites and eclogitic rocks are found within several tectonostratigraphic levels including allochthonous units, but are most commonly found in the autochthonous basement, as reviewed by Krogh & Carswell (1995).

Most occurrences of eclogite in the western Gneiss Region (WGR) of South Norway, including the Sunnfjord Region, are revealed as pods and lenses ranging in size from a few metres to several hundred metres in length, apparently representing boudinaged layers within amphibolite- to granulite-facies Proterozoic/sub-Caledonian gneisses. Mafic intrusions showing all stages of transition to eclogite are common in some areas (Gjelsvik 1952, Cuthbert 1985, Mørk 1985). Eclogitisation along fracture- and shear-zones, which probably formed conduits for circulating fluids, triggering the eclogitisation reactions, has been described from the Bergen Arc Nappe Complex (e.g. Austrheim 1987, Boundy et al. 1992). Eclogite bodies in the Sunnfjord region and elsewhere are commonly retrogressed under amphibolite- and greenschist-facies metamorphic conditions along late-orogenic shear zones. These retrograde zones cut the eclogite bodies and, in most cases, form the margins of the bodies.

It is generally agreed that HP/UHP metamorphism in the Scandinavian Caledonides is related to burial in a continental collision zone, whereas exhumation is presumed to relate to orogenic extensional collapse and sub-crustal vertical thinning (e.g. Andersen & Jamtveit 1990). In the WGR, equilibrium temperatures and pressures for the eclogites increase from approximately 550-600°C and 15-17 kb in the Sunnfjord region, which is in accordance with P/T estimates for the Engebøfjell eclogite (Erambert & Braathen, in prep.), to > 700°C and > 20 kb in the northwest (e.g. Griffin et al. 1985, Smith 1988).

Occurrences of eclogite in Sunnfjord

In the Sunnfjord area, eclogites occur as 0.5 to 3-4 km bodies surrounded by gneiss of amphibolitic to granitic composition. Numerous smaller eclogite bodies and eclogitised mafic layers in gneisses are common. In general, eclogites within gneisses are extensively deformed and completely eclogitised without identifiable relics of the protolith rocks. This is the case on both sides of the Førdefjord and in eclogites

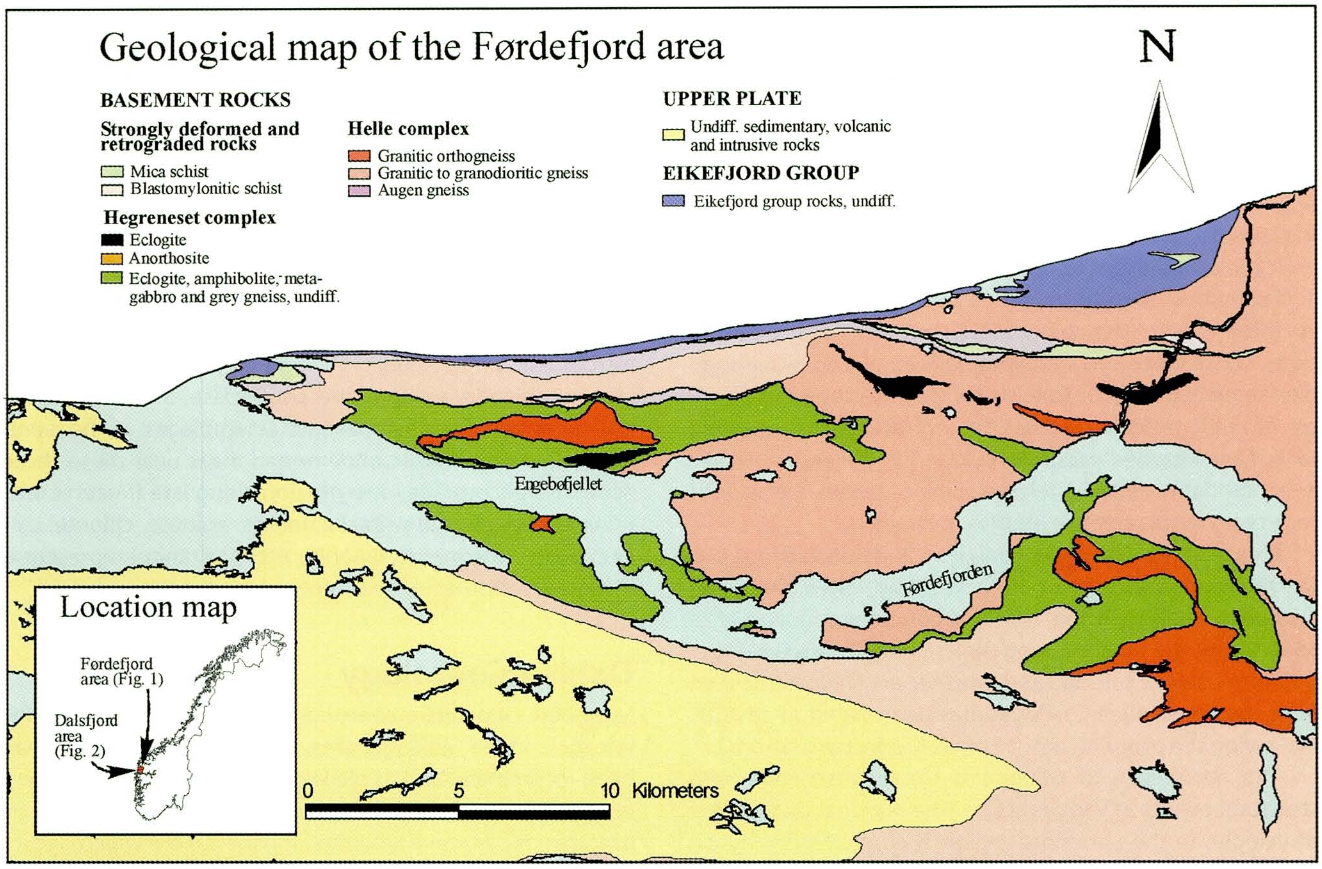

Fig. 1: Geological map of the Førdefjord region. Simplified from Lutro & Ragnhildstveit (1996).

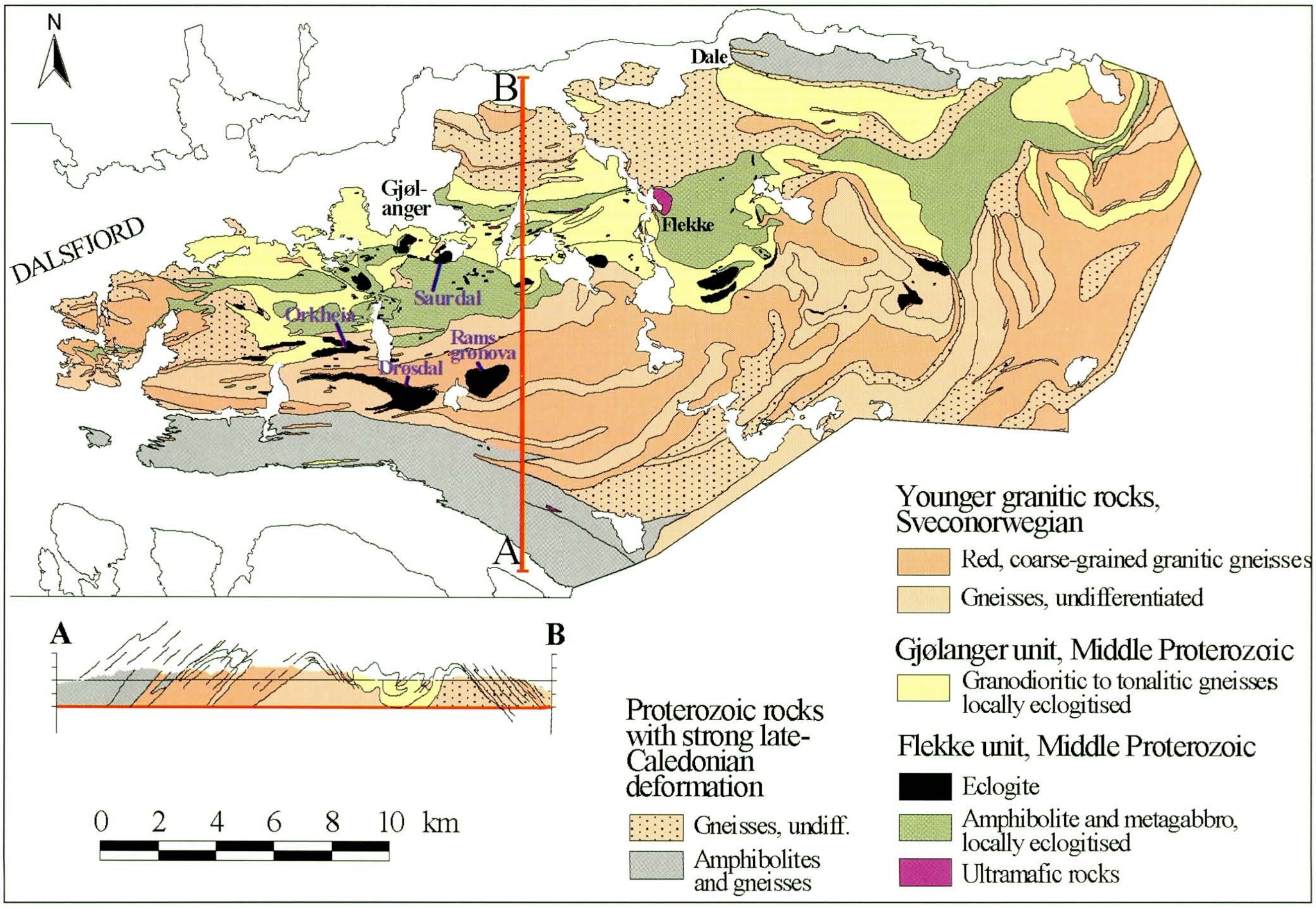

Fig. 2: Geological map of the Dalsfjord region. Simplified from Ragnhildstveit & Nilsen (1998).

along the southern parts of the Dalsfjord region (Figs. 1 & 2). In the Gjølanger-Flekke area, large bodies of mafic rocks, including gabbro and anorthosite, are only partly eclogitised or show no signs of eclogitisation (see Cuthbert 1985, Engvik 1996, Skår 1997.

The eclogites occurring in the Førdefjord and Dalsfjord regions represent eclogitisation of a variety of Proterozoic mafic rocks. Some of these eclogites, particularly the Fe-Ti-enriched eclogites at Engebøfjellet and Naustdal, Førdefjord, and at Orkheia, Ramsgrønova and Saurdal south of Dalsfjord, are interpreted to derive from Fe-Ti-enriched gabbroic intrusions. These intrusions were originally emplaced into a complex sequence of mafic to felsic rocks, now present as a variety of mafic to felsic gneisses. In contrast to this, granitoid rocks have intruded gabbroic rocks in the Gjølanger - Flekke area, although detailed relationships between the various rock-types in this area are poorly constrained.

A gabbro from the Flekke unit (Fig. 2) yielded an intrusive Sm-Nd whole-rock age of 1522 ± 55 Ma (Skår 1997), and Cuthbert (1985) reported a U-Pb zircon minimum age of ca 1500 Ma for the neighbouring Gjølanger unit. The Gjølanger unit rocks have a calc-alkaline, volcanic arc character. Zircon from the Engebøfjellet eclogite has been dated at ca 1500 Ma, giving the protolith age (Thomas Krogh, pers. comm.).

The occurrence of eclogite is closely associated with structural events at various scales. The regional distribution of eclogite in the Sunnfjord region is controlled by major, late-Caledonian deformation processes (Andersen & Jamtveit 1990, Andersen et al. 1994). These authors advocate that a Caledonian orogenic root experienced vertical constrictional strain, then vertical shortening during eclogitisation. The subsequent decompression resulted in retrograde processes. Erambert and Braathen (in prep.) describe structural and metamorphic relationships that are not entirely consistent with the above-mentioned processes, and indicate that the proposed deformation processes in the lower crust are hypothetical rather than proven.

Eclogite petrography and structure

Eclogite assemblages form from dynamic, prograde metamorphic reactions, where the deformation process basically is controlled by availability of fluids (eg., Jamtveit et al. 1990). The deformation guiding these reactions is displayed as foliations and various shear-related quartz-bearing veins (Jamtveit et al.1990, Boundy et al. 1992, Andersen et al. 1994). Most eclogite bodies show a single prominent foliation. Some large bodies reveal two eclogite-facies fabrics, for example the Engebøfjellet eclogite. Here, an earlier banding with preferred mineral orientation is obliterated in certain shearzones (Erambert & Braathen, in prep.). These foliations were partly rejuvenated and retrograded during superimposed amphibolite-facies, simple-shear deformation, a common feature throughout the eclogite regions of western Norway (e.g., Andersen & Jamtveit 1990).

Eclogite parageneses comprise garnet, omphacite, amphibole, phengite, clinozoisite, quartz, dolomite and rutile. Accessory minerals include pyrite, apatite, allanite and zircon. Titanium is mainly present as rutile, mostly as grains occupying the matrix. A lesser occurrence is as numerous but tiny inclusions within silicates. Fluid-rock interaction has been frequent during the eclogite-facies metamorphism, particularly at Engebøfjellet where variations in eclogite petrology have been studied in detail (Erambert & Braathen, in prep.).

Retrogression of the eclogites is dependent on both deformation and fluid infiltration that occurred predominantly along internal shear zones and at the margins of bodies. Garnet amphibolites typically represent the first stage of retrogression. Amphibolites within major shear zones contain hornblende, epidote and plagioclase. Static retrogression of eclogites to symplectitic assemblages of the same minerals is observed in undeformed areas near these shear zones. Local coronitic retrogression along late fractures and mineral filling in the veins (actinolite, epidote, chlorite, calcite, quartz, magnetite, ilmenite and/or titanite) represent a late greenschist-facies overprint.

Oxide mineralogy

Magnetite - ilmenite ores are commonly found in metagabbroic rocks in the Gjølanger area, where the eclogitisation has been incomplete, and in places also in eclogite, where they represent relics of the eclogite protolith. Fig. 3 shows an example of a massive ilmenite - magnetite ore which occurs as dm-thick bands within amphibolitised and partly chloritised eclogite at Saurdal. This ore was subject to a small-scale mining operation for iron early in the 20th century.

The character of the Fe-Ti ore was significantly changed by metamorphism. In metagabbro/amphibolites that have not reached the stage of eclogitisation, hemo-ilmenite (Fig.

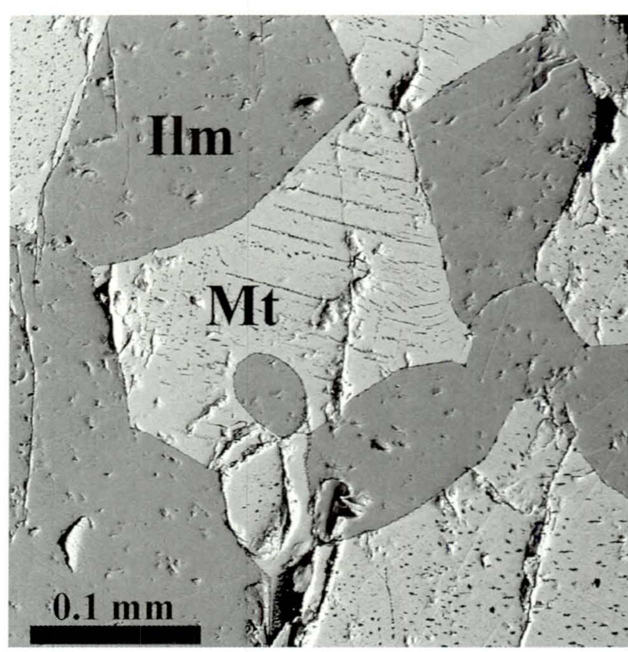

Fig. 3: Back-scattered electron image of ilmenite-magnetite ore (protolith relics) associated with the Saurdal eclogite. The magnetite contains numerous, tiny, exsolution blebs of spinel. Sample 618.78.

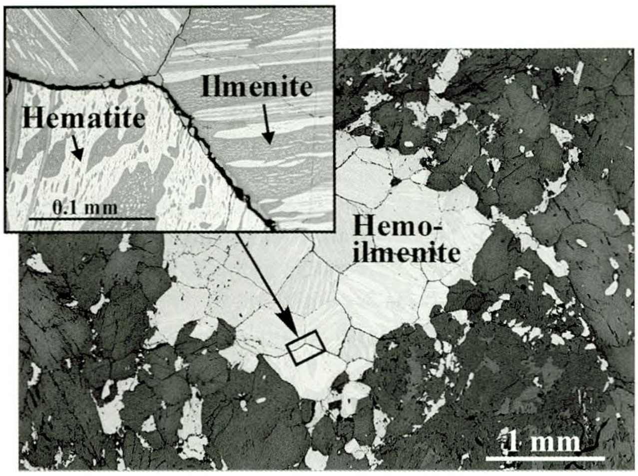

Fig. 4: Photomicrograph of hemo-ilmenite in garnet-amphibolite from the Saurdal area. Sample 941018. Reflected light, oil immersion.

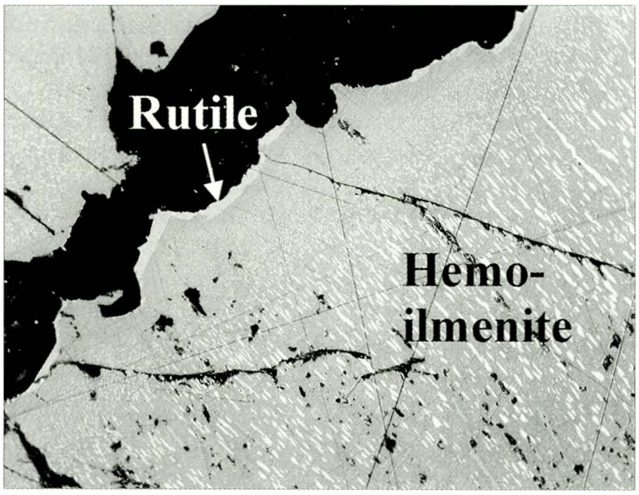

Fig. 5: Photomicrograph of rutile rimming hemo-ilmenite in garnet-amphibolite from the Saurdal area, sample K222A.94. Reflected light, oil immersion. With of photo, 0,3 mm.

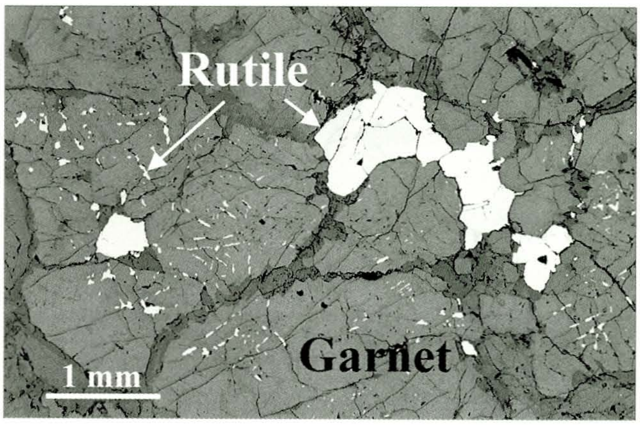

Fig. 6: Photomicrograph of rutile in coarse-grained, garnet-rich eclogite from Saurdal. Sample 941017. Reflected light, oil immersion.

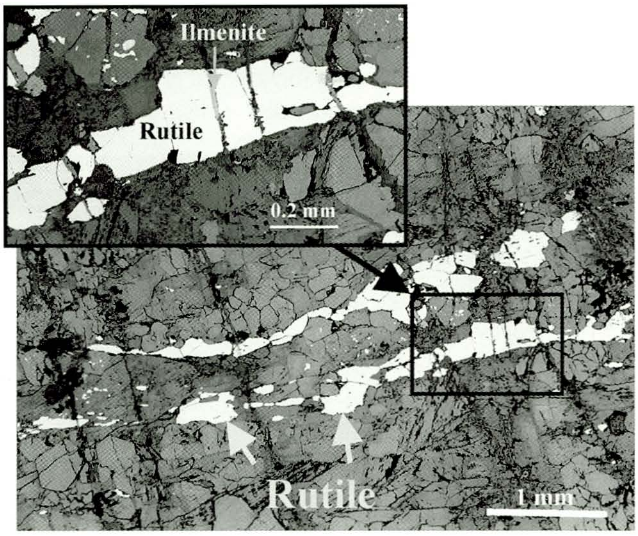

Fig. 7: Photomicrographs of thin-section K153A.93 from Orkheia (reflected light, oil immersion). This rock is a garnet-rich eclogite with elongated trains of rutile (light grey) due to an early eclogite-facies deformation. The rutile is cut by fractures (dark grey to black), that served to channel fluids that triggered an amphibolite-facies retrogression along the fractures.

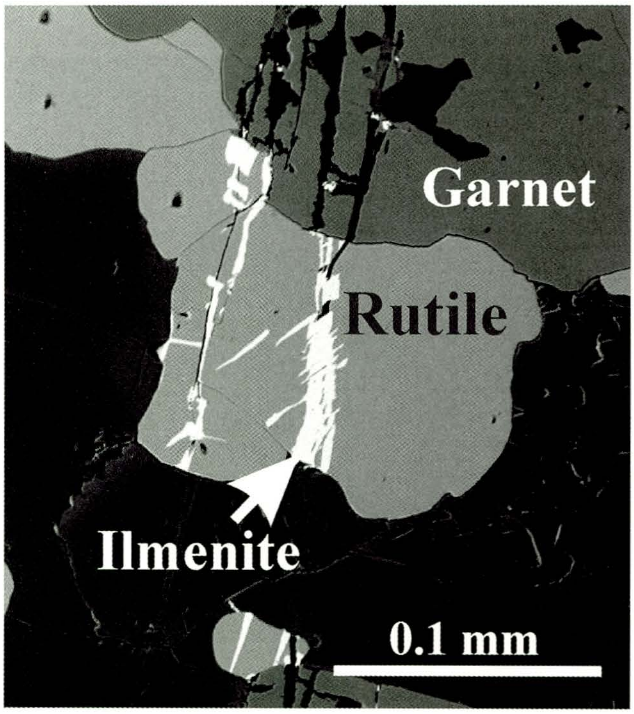

Fig. 8: Back-scattered electron picture showing alteration of rutile to ilmenite along fractures under amphibolite-facies conditions. Sample S2/2, Saurdal.

4) is the stable oxide. In some garnet amphibolites, rutile has begun to form as a rim surrounding hemo-ilmenite (Fig. 5). Hematite exsolutions in the hemo-ilmenite disappear towards the rutile contact which is believed to be an effect of solid-state diffusion.

During eclogitisation, the remaining Ti will form rutile, whereas Fe from ilmenite enters garnet. In completely eclogitised basic rocks, rutile occurs as large grains or aggregates mimicking the occurrence of Fe-Ti oxides in the protolith. Large rutile grains (Fig. 6) probably formed after large ilmenite grains, while scattered smaller rutile grains, mainly present as inclusions in garnet, presumably formed from Ti derived from the breakdown of titanomagnetite. A characteristic occurrence of rutile in many eclogites is as clusters or aggregates of rutile (Fig. 6). Another common occurrence of rutile is in stretched-out rutile aggregates (Fig. 7) formed during the early eclogite-facies deformation of the rock.

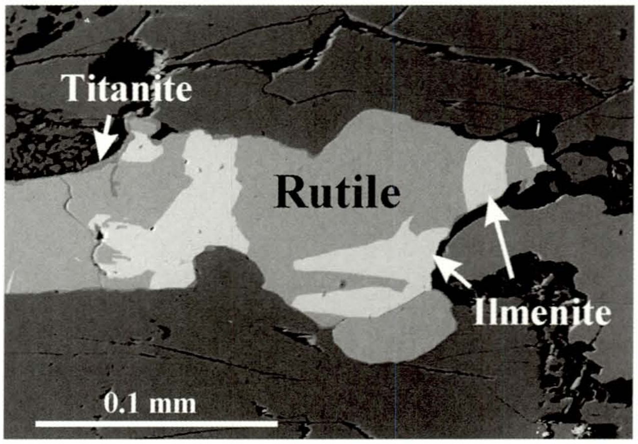

Fig. 9: Back-scattered electron image showing rutile-ilmenite intergrowths rimmed by titanite. This type of rutile/ilmenite intergrowth is typical of eclogites that have experienced pervasive amphibolite-facies retrogression (stage 3, see the text). The very narrow titanite rim indicates retrogression under lower –amphibolite- to greenschist-facies conditions (stage 4). Sample S2/23.0, Saurdal.

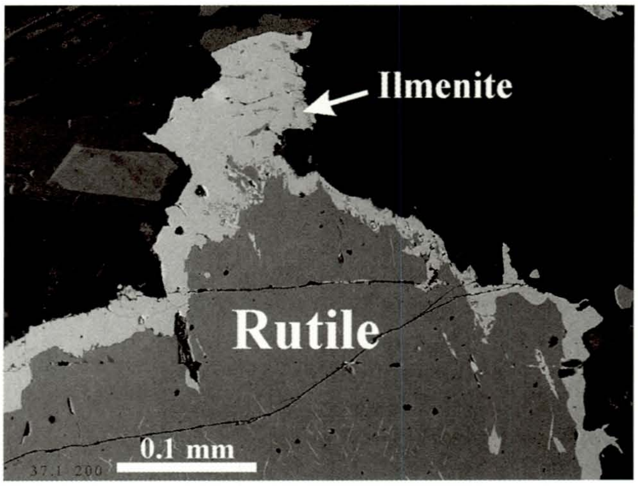

Fig. 10: Back-scattered electron picture of a large, second-generation rutile from a quartz - white mica - omphacite vein in eclogite. Tiny, needle-shaped hematite exsolutions occur in the rutile. Alteration to ilmenite is distinct at the margin of the rutile crystal. Sample E214/337.7, Engebøfjellet.

Also typical for many eclogites is a distinctive pattern of cracks/fractures (Fig. 7) that have channelled the influx of fluids under retrograde, low-grade, amphibolite-facies transitional to greenschist-facies conditions, leading to amphibolitisation along cracks. Such amphibolite-facies veining is found in eclogites all over the region, although the intensity varies. Fig. 8 is an example of amphibolite-facies alteration of rutile to ilmenite along such fractures. At conditions of more pervasive amphibolitisation, which is generally found along metre-wide shearzones and at the margins of the eclogite bodies, all the rutile in the rock is affected. This can be seen as an ilmenite rim around rutile and, more commonly, rutile/ilmenite intergrowths, as shown in Fig. 9. When retrogressed at greenschist-facies conditions, rutile and ilmenite alter to titanite.

Rutile in eclogite-facies quartz-omphacite-white mica veins which are cutting an early eclogite-facies foliation in several eclogite bodies, occurs as crystals up to several centimetres in size. These coarse rutile grains, which represent a second generation of rutile formation, tend to have numerous hematite exsolutions (Fig. 10) and are in places distinctly altered to ilmenite at their margins due to amphibolite-facies retrogression.

Due to variable retrogression, the proportion of Ti as rutile varies between eclogite masses as well as within individual bodies. At Orkheia and Engebøfjellet, 90-95 % of the Ti occurs as rutile. Individual samples from Engebøfjellet that plot well below the line rutile/TiO_2 = unity in Fig. 11 represent significantly retrograded eclogite, in which much of the rutile is altered to ilmenite. The Fureviknipa and Saurdal eclogites are distinctly more retrograded than Orkheia and Engebøfjellet, and their samples tend to plot well below the line.

Rutile from eclogite deposits normally has a very low content of uranium (< 2 ppm U) compared with rutile from other types of deposits which commonly contain 50-100 ppm U (Korneliussen et al. 2000). Normal contents of some other minor or trace elements in eclogitic rutile are 0.4-0.8 % V_2O_5, < 0.1 % MgO, 0.2-0.6% FeO, < 0.1% MnO and < 0.2% Cr_2O_3.

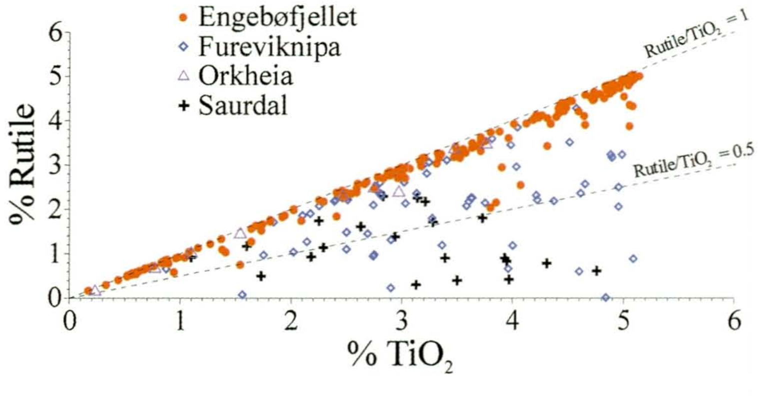

Fig. 11: Scattergram plot of rutile vs. TiO_2. The data are from the Engebøfjell, Fureviknipa, Orkheia and Saurdal eclogites.

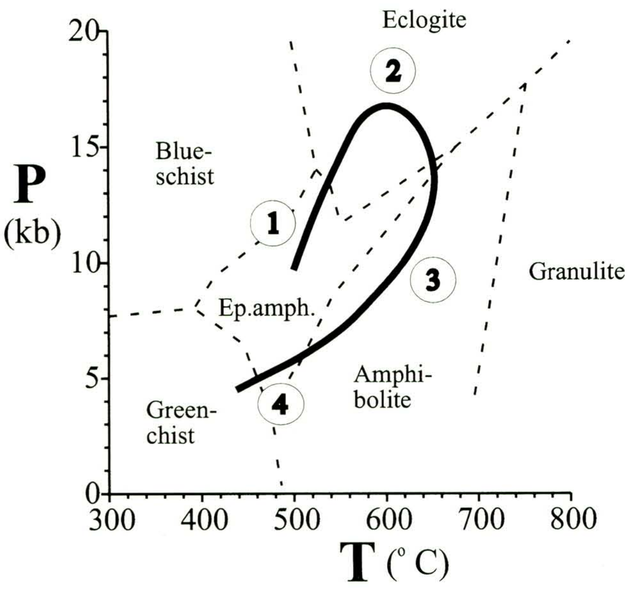

Fig. 12: Generalised P-T evolution path for the Sunnfjord eclogites exemplified by the Naustdal eclogite (based on Krogh & Carswell 1995). The following stages are discussed in the text: (1) Protolith stage, (2) Eclogite-facies metamorphism with the breakdown of igneous Fe-Ti oxides and the formation of rutile. (3) Amphibolite-facies retrogression along fractures and shearzones. (4) Lower amphibolite- to greenschist-facies retrogression with alteration of rutile and ilmenite to titanite.

Oxide mineralogy in relation to metamorphic history

The changes in oxide mineralogy with metamorphism can be related to the P-T evolution for the Sunnfjord eclogites, as exemplified by the P-T trend for the Naustdal eclogite (Krogh 1980). In this evolution, four metamorphic stages, numbered 1 to 4 in Fig. 12, have a major effect on the oxide mineralogy: (1) At the protolith stage, represented by Proterozoic Fe-Ti oxide-bearing metagabbroic rocks, ilmenite and magnetite are the stable oxides (Fig. 3); in some metagabbro/garnet-amphibolites, hemo-ilmenite is the stable oxide with magnetite absent (Fig. 4). (2) During eclogitisation, when the Proterozoic rocks were metamorphosed at high pressures in the Caledonian subduction regime, rutile (Fig. 6) was the stable Ti mineral. The eclogitisation period was dynamic in terms of deformation, fluid activity and associated metasomatic processes, leading to formation of typical garnet-omphacite eclogite, and a variety of metasomatic, rutile-bearing, quartz-omphacite-garnet-mica rocks and quartz-omphacite veins. Relatively late in the eclogite-facies metamorphic period, a second generation of rutile (Fig. 10) was formed in quartz-rich veins. (3) During uplift, fractures and shearzones opened for an influx of fluids which triggered amphibolite-facies retrograde reactions in which rutile altered to ilmenite, as shown in Fig. 8. (4) The final metamorphic stage, with a distinct influence on the oxides, is the alteration of rutile and ilmenite to titanite (Fig. 9). This latest event occurred under greenschist-facies conditions. Thus, retrogression is assumed to have been active over a long P-T interval.

Discussion

The main goal of both DuPont and NGU has been to localise economic rutile ores in West Norway and the Engebøfjell eclogite is promising in this respect. However, only by a combination of many favourable circumstances would it be possible to open a mine on a rutile/eclogite deposit. The natural geological circumstances must be favourable for large volumes of rutile-bearing eclogite with sufficiently and consistently high grade and quality. At an early stage in the rutile exploration in West Norway, reconnaissance investigations showed a large compositional and size variation in the eclogite occurrences, formed from a variety of protolith rocks such as basic volcanic rocks, mafic dykes and minor intrusions, and gabbro-anorthositic plutons. During the Caledonian orogeny these rocks were eclogitised, deformed, and commonly fragmented into boudins/lenses a few metres to several km in size. Only those eclogites that were derived from Ti-rich protoliths are of economic interest. Particularly the gabbro and gabbro-anorthositic association, when eclogitised, show sufficient enrichments of rutile across large enough rock volumes to represent a significant resource. Among the various eclogite regions in western Norway, the Sunnfjord region was found to have the best potential for economic rutile deposits.

Although a high rutile content is a necessity to obtain a sufficiently high ore value, this alone is not enough. The mineralogy of the eclogite is more than equally important. Eclogites in West Norway show a significant variation in mineralogical characteristics, including grain size, mineral intergrowths, modal variations, and differences in the degree of retrograde mineral alterations. These factors have a considerable influence on the ease of mineral processing and on the purity of the rutile product. Amphibolite-facies retrograde alteration of rutile to ilmenite not only reduces the value of the ore, since ilmenite is a much less valuable mineral than rutile, but also complicates the mineral processing scheme.

The alteration of rutile to titanite under lower amphibolite- to greenschist-facies metamorphic conditions will lead to titanite contamination of the rutile concentrate. This is detrimental to the ore quality, since in Ti-pigment production, only very small amounts of calcium (up to 0.2 % CaO) are acceptable. Fortunately, many of the Sunnfjord eclogites, such as Engebøfjellet, Orkheia and Ramsgrønova, are relatively well preserved, and rutile concentrates of sufficiently high quality can be produced. In other eclogites, for example Saurdal and Fureviknipa, the effects of retrogression are severe. These variations can be related to regional, but also local, variations in the structural evolution and progress during uplift, since deformation controlled the channelling of fluids that triggered retrograde mineral reactions.

One possibility is that, on a larger scale, comparing eclogite regions, differences in the degree of retrogression might reflect differences in emplacement and unroofing histories. If valid, eclogite provinces that have experienced relatively fast uplift may have well-preserved eclogites, but this hypothesis remains to be tested.

In eclogites from other eclogite provinces in the world, for example the Piampaludo eclogite in northern Italy (Liou et al. 1998), the Ti content can be higher than in Norwegian eclogites; however, the mineralogy in this case is less favourable. In the Pampaludo eclogite, the alteration of rutile to titanite is extensive, which, among other factors, presently makes the deposit less attractive for mining. On the other hand, Piampaludo is a very large Ti-rich rutile resource that could be exploited in the future, if sufficient advances can be made either in the beneficiation methods or in the chlorination process used.

The rutile grainsize is of considerable importance, since grain size controls the recovery rate in the mineral processing; the larger the grains the more rutile can be recovered. In many of the Sunnfjord eclogites, rutile occurs in aggregates with a grainsize in the range 0.05 - 0.3 mm, and a recovery of 50% and higher can be obtained. Such rutile aggregates are to some extent pseudomorphs after coarse ilmenite in the protolith. Consequently, a protolith with relatively coarse-grained ilmenite, such as gabbro, is needed to form a rutile-bearing eclogite with sufficiently large rutile grains. Titanium contained in other minerals such as magnetite and pyroxenes, when eclogitised, tend to crystallise as small rutile grains, generally as inclusions in garnet; this rutile is not recoverable.

The geographic location must also be favourable, i.e. ideally, new rutile deposits should be situated in areas of low or relatively scattered population, and within reasonably short distance to shipping facilities. In order to minimise harmful environmental consequences during mining, the geography must allow for good waste disposal. All in all, these are reasonably favourable in western Norway although local variations are significant.

Rutile-rich eclogites normally contain 30-40% garnet. Garnet is a possible by-product in rutile production from eclogite, if it can be produced with an optimum grain size. In general, garnet used for sandblasting in the shipping and steel industry, which is the main market in terms of volume, requires grain sizes in the range 0.2-0.7 mm. For some eclogites, for example Engebøfjellet, the overall garnet grain size is 0.05 - 0.2 mm, i.e. it is too fine. In other eclogites, such as Saurdal, Orkheia and Ramsgrønova, the garnet grain size is larger, and garnet from those deposits could become a significant by-product of rutile mining. It is even possible that small-scale mining of garnet alone can be carried out at certain localities with particularly high-quality garnet.

The market for rutile is a key for further exploration in a new type of rutile mineral resource, i.e. eclogites. This is totally dependent on the market outlook in the years to come. The importance of having DuPont as a major actor in rutile exploration in Norway cannot be underestimated, since DuPont in this case also represents the market.

Conclusions

Rutile hard-rock deposits, due to a shortage of high-grade, high-quality, mineral sand deposits, are expected to become an important ore resource in the future. In this perspective, the rutile-bearing eclogites in western Norway represent a new type of rutile deposit. Unfavourable circumstances, such as extensive retrogression and the formation of titanite, are apparently less significant in the Norwegian eclogite province than elsewhere, although this is a subject that requires further investigation. Favourable circumstances in the Sunnfjord region of West Norway are: (1) a high degree of conversion to rutile during eclogitisation, (2) extensive volumes of rutile-bearing eclogites, (3) adequate rutile grain size, (4) favourable grinding test results, (5) good preservation of rutile, (6) good geological exposure, (7) favourable geographical situation with a short distance to fjord and shipping facilities, (8) good infrastructure and (9) good waste deposition possibilities. The best known of the Sunnfjord deposits is the Engebøfjellet eclogite (McLimans et al. 1999; Erambert et al., in prep.); it contains more than 9 million tonnes of recoverable rutile, making it one of the largest known rutile resources in the world.

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