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Tittel

Rutile-bearing Eclogites in the Sunnfjord Region of Western Norway

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Rutlførende eklogitter i basalgneis-komplekset i Sunnfjord området i Sogn og Fjordane fylke er potensielle titan reserver, og har vært gjenstand for prospektering i det siste tiåret.
Eklogittene opptrer som linser i prekambriske gneiser og antas å være dannet ved rekrystallisasjon av de basiske eruptivbergarter under kaledonsk høy-trykks metaforfose. Rutilinnholdet er normalt i området 1 - 4 vekt%, men høyere konsentrasjoner kan forekomme lokalt. Omkring 90% av titanet i eklogittene er bundet i rutil. Noen av de større eklogittforekomstene er beregnet å inneholde minst 100 mill. tonn med ca. 3% rutil, som pr idag er uøkonomisk.

Andreas [illegible]

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Rutile-bearing Eclogites in the Sunnfjord Region of Western Norway

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Rutile-bearing eclogites from the basal gneiss-complex of the Sunnfjord region in Sogn og Fjordane fylke are potential titanium reserves, and have been the subject of prospecting activities during the last decade.

The eclogites occur as lenses and pods in Precambrian gneisses and are believed to have been formed by the recrystallization of basic igneous rocks during high-pressure Caledonian metamorphism. They are composed principally of garnet, omphacitic clinopyroxene and barroisitic amphibole. Rutile concentrations are generally in the range 1 to 4 wt.%, although higher concentrations occur locally. About 90% of the titanium in the eclogites is contained in rutile. Some large eclogite bodies are each estimated to contain at least 100 Mt. containing approximately 3% rutile, which is presently uneconomic.

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Introduction

Most of the titanium in the crust of the earth is contained within the major rock-forming minerals biotite and hornblende, and in the common accessory phases sphene, ilmenite and rutile. In all commercial deposits titanium occurs as oxides, mainly ilmenite or rutile. They occur in association with anorthosites and alkaline complexes, as well as in detrital sediments and laterites. Rutile (TiO_2) is a more attractive raw material for titanium dioxide and titanium metal production than the more common ilmenite ($FeTiO_3$). Consequently fairly low-grade rutile deposits are potential economic sources of titanium.

Titanium-bearing silicates, mainly sphene, biotite and hornblende, have restricted stability fields at higher metamorphic grades. The silicates that form in their place contain much smaller amounts of titanium than their precursors, and the excess titanium can form oxides (Force 1976, Blake and Morgan 1976).

Rutile is the characteristic titanium mineral in many eclogites. It crystallises from iron-titanium oxides and titanium-bearing silicates during the metamorphic recrystallization of basic igneous rocks into eclogite. Titanium-rich basic rocks that have been transformed into eclogite are, therefore, potential sources of rutile, and have been the subject of prospecting activities in the Sunnfjord region of Western Norway.

The Sunnfjord eclogites were first described by Kolderup (1928) to be fairly rich in rutile. Based on Kolderups descriptions H.-P. Geis (unpublished report, Elkem A/S) located notable rutile concentrations within the Naustdal eclogite body in 1969 and within the Engebøfjellet eclogite in 1970. The investigation continued between 1978 and 1980 as a cooperative venture involving Elkem A/S and the Norwegian geological survey (NGU). Deposits of commercial interest were, however, not found (Korneliussen 1980, 1981, Foslie 1980). At the present time 4–5% rutile is estimated as an economic grade.

The purpose of this paper is to give a general description of the Sunnfjord eclogites and their significance as sources of rutile.

Eclogites in Western Norway

In Western Norway eclogites occur as pods, lenses and layers in ultramafic rocks in Proterozoic gneisses and Early-Palaeozoic metasediments (Bryhni et al. 1977, Griffin et al. 1984).

The genesis of the eclogites is controversial: One view is that they represent allochthonous mantle fragments that were metamorphosed at very great depths (Eskola 1921, O'Hara & Mercy 1963, Lappin & Smith 1978); The other that they were formed by in situ metamorphism of basic igneous rocks (Gjelsvik 1952, Bryhni et al. 1977, Krogh 1980 a and b, 1982, Griffin et al. 1985). A third possibility is that eclogitic rocks within ultramafic bodies represent mantle fragments while the eclogites within gneisses formed in situ (Carswell 1974, Bryhni et al. 1977).

A considerable amount of data now suggests that the gneisses of Western Norway have been subjected to high-pressure metamorphism, with increasing P and T towards the coast (10 to 20 Kb and 500 to 800° C). The metamorphism has been attributed to a continent/continent collision in which the leading edge of the Baltic shield underthrust a N. American plate (Krogh 1977, Cuthbert et al. 1983, Griffin et al. 1985). Infolded Caledonian metasediments containing eclogites that are believed to have been formed by in situ metamorphism (Krill 1980, 1985), and Caledonian Sm-Nd ages for eclogite minerals (approx. 425 Ma., Griffin & Brueckner 1980), indicate a Caledonian age for the regional eclogite-facies metamorphism.

THE BASAL GNEISSES IN THE SUNNFJORD REGION

The so-called 'Basal gneisses' of the Sunnfjord region, Western Norway (Fig. 1), are separated by Bryhni (1966) into a relatively homogeneous complex (The Jostedal Complex) and a heterogeneous complex (The Fjordane Complex). The latter was subdivided by Skjerlie & Pringle (1978) into the Holsen Gneiss complex, containing mainly quartz-rich paragneisses and augen-gneisses, and the overlying Vevring complex of various gneisses, amphibolites, eclogites, anorthosites, gabbros and ultramafic rocks.

Rb-Sr whole-rock isochrons for gneisses from the Jostedal complex give ages from 1700 to 1800 Ma. (Skjerlie & Pringle 1978, Brueckner 1972, while gneisses from the Holsen Gneiss complex (Skjerlie & Pringle 1978) give a Rb-Sr whole-rock isochron age of 1225 ± 100 Ma. (Brueckner 1972). These authors also reported Rb-Sr biotite ages of 390 to 400 Ma. for the same gneisses. These mineral ages result from recrystallization during Caledonian tectonometamorphic events, while the whole-rock ages are thought to represent the time of igneous crystallisation in the Proterozoic.

The Sunnfjord eclogites

The eclogites occur as pods, lenses and high-strain zones in gneiss, mainly within the Vevring complex, although eclogites also occur within the Jostedal complex between Naustdal and Førde and near Gjølanger (Fig. 1). Their size varies from a few dm^2 to 3–4 km^2.

The eclogites are generally fine grained, especially those in the Førdefjord area. They tend to be amphibolitized in border zones and along fractures and veins. Internal banding is generally parallel to the fabric of the surrounding gneiss. Eclogites in the north-eastern part of the Førdefjord area have been described by Binns (1967), Krogh (1980 b), and Krogh & Brunfelt (1981). Kolderup & Rosenquist (1950) and Kolderup (1960) have described eclogites from Gjølanger. In the same area leucotroctolites and gabbros show the arrested development of reaction coronas, complete reaction having produced eclogites (Cuthbert, in prep.).

MINERALOGY

Garnet, barroisitic amphibole, and omphacitic clinopyroxene are the main minerals of the eclogites. White mica (paragonite, phengite), quartz, rutile, ilmenite, apatite and pyrite occur in minor amounts. Eclogites south of Vilnesfjord (Dalsfjord) are zoisite- and kyanite-bearing.

During retrogression, omphacite is altered to aggregates of diopsidic clinopyroxene and plagioclase which, with more advanced retro-

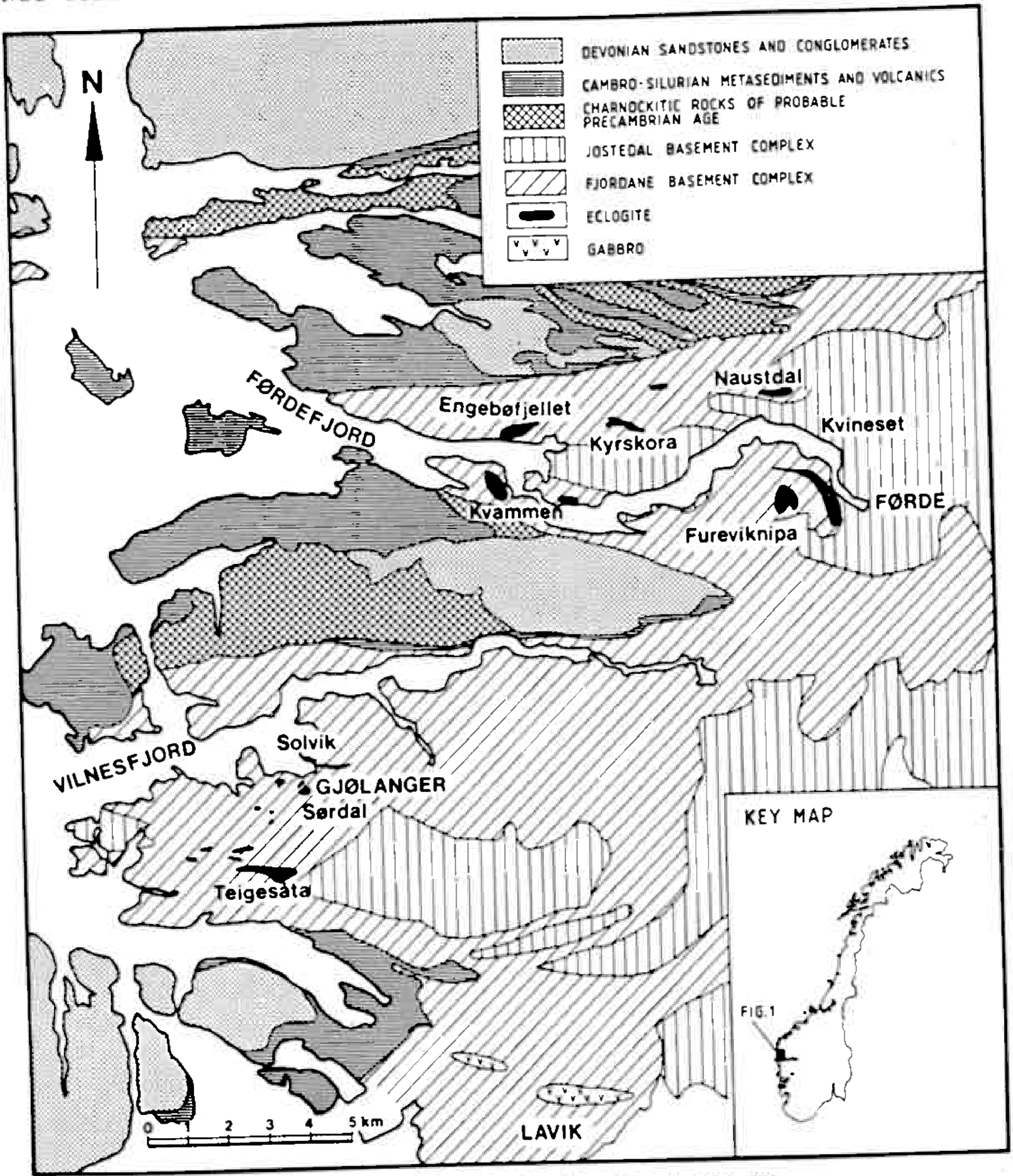

Fig. 1. Generalised geological map of the Sunnfjord region (based on Sigmond Kildal 1970).

gression, is replaced by hornblende. Barroisitic amphibole is altered to hornblende, and rutile to ilmenite. Garnet is relatively stable and is altered with intense retrogression to an aggregate of hornblende + magnetite ± epidote ± biotite. The latest event during retrogression is chloritization accompanied by the formation of magnetite. Eclogite minerals and their alteration products have been described in detail by Binns (1967) and Krogh (1980 b) for eclogites in the Naustdal–Førde area and by Cuthbert (in prep.) for the eclogites at Gjølanger.

Rutile occurs as anhedral grains varying from 0.01 to 1.0 mm in diameter (Fig. 2 a). Grain sizes from 0.1 to 0.2 mm are typical.

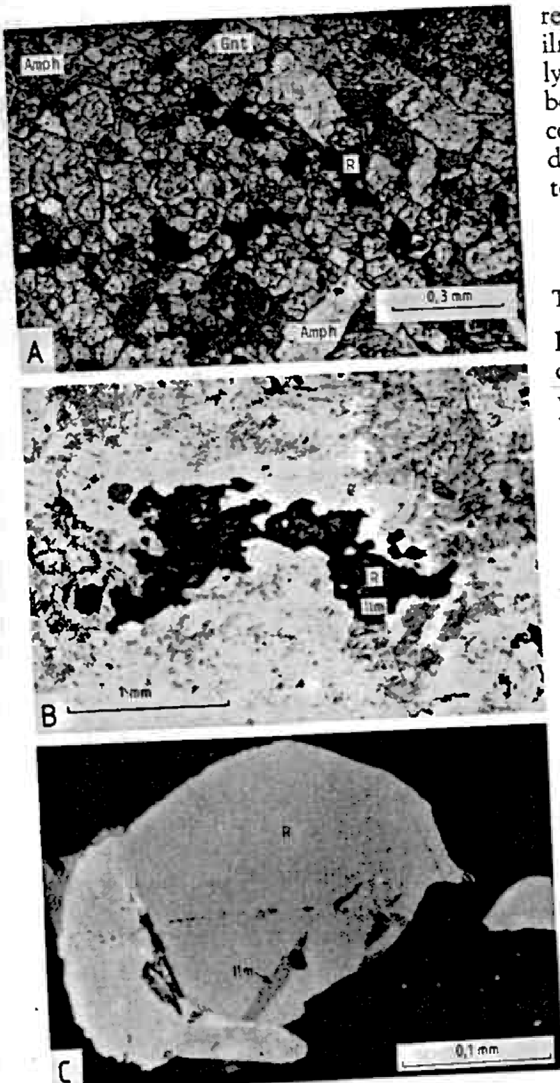

Fig. 2 a. Rutile (R) and silicate minerals (Gnt-garnet, Amph-amphibole)
b. Rutile (R) with rim of ilmenite (Ilm)
c. Rutile (R) with ilmenite (Ilm) inclusions.

Inclusions of rutile are particularly common in amphiboles and garnets. Ilmenite occurs intergrown with rutile (Fig. 2 c), and as reaction rims around rutile in retrograded eclogite (Fig. 2 b). The amount of ilmenite is relatively minor in unretrograded eclogite, except in some exceptionally iron-rich eclogite varieties where it becomes a significant component.

Ilmenite is an important factor in the economic evaluation of eclogite, for the following reasons: (1) Intergrowths of the less-valuable ilmenite will lower the purity, and accordingly the value of the rutile concentrate that can be produced; (2) An increase in the ilmenite content in eclogite will lead to a correspondingly smaller amount of titanium available to form rutile.

THE FORMATION OF RUTILE

Field and textural evidence shows that concentrations of TiO_2 in the eclogite protoliths were ilmenite- and titano-magnetite-rich bands and pods in modally layered gabbroic and troctolitic intrusions. In non-coronitic, foliated eclogites ilmenite is found as inclusions in the cores of garnets, together with amphibole, epidote and magnetite. Outer zones of garnets contain inclusions of omphacite, barroisite and rutile, which are also found in the matrix. Thus ilmenite in a pre-existing amphibolite-facies assemblage is transformed into rutile in eclogite. This has been well described by Krogh (1980 b, 1982).

Two modes of rutile formation are observed in coronitic metagabbros in the Gjølanger area (S. Cuthbert, pers. comm.): (1) Formation of garnet coronas around euhedral grains of ilmenite and/or titano-magnetite, probably by reaction with plagioclase or its breakdown product zoisite, produces angular, idiomorphic patches of rutile mimicking ilmenite, within the coronas. (2) Breakdown of cumulus Ti-augite causes exsolution of very fine, dusty ilmenite. As the pyroxene becomes more omphacitic the ilmenite is transformed into rutile, which segregates into anhedral clots within aggregates of coarse omphacite.

SAMPLING AND ANALYSES

The purpose of the sampling has been to estimate the rutile content of the eclogite bodies. Samples were collected systematically along profiles across well-exposed eclogites and less systematically in areas of poor exposure. Samples were approximately 1 kg in size for XRF analysis. Dust samples have also been drilled for TiO_2 analysis in the field

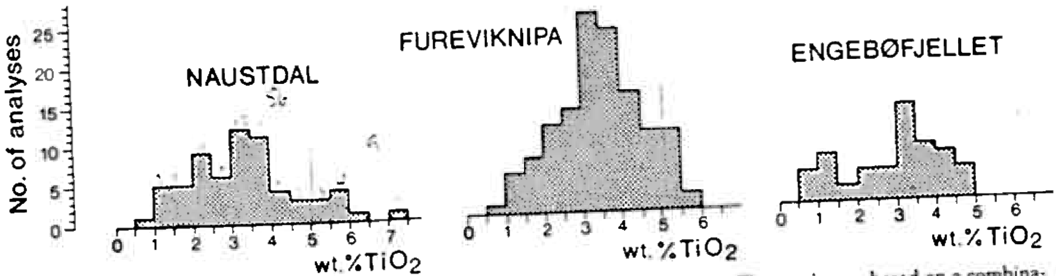

Fig. 3. TiO₂ distributions for Naustdal, Fureviknipa and Engebøfjellet eclogites. The results are based on a combination of XRF analyses of dust and rock samples carried out in the field, and XRF laboratory analyses.

with a portable XRF instrument. This instrument has also been used directly on rocks and provided semi-quantitative results. These results are included in Table 1 and Fig. 3 in addition to the laboratory analyses.

Lists of all analyses that have been used in the preparation of the figures and tables can be obtained from the authors on request.

Table 1 – Average TiO_2 contents (wt.%) of some eclogite bodies

Eclogite locality	Average (% TiO_2)	Lowest–highest value (% TiO_2)	No. of analyses
Kvammen	1.79	0.5– 4.8	117
Engebøfjellet	2.99	0.5– 9.3	73
Kyrskora	1.62	0.6– 3.6	122
Langevatn	1.30	0.8– 2.4	9
Naustdal	3.36	0.6–14.7	77
Fureviknipa	3.40	0.6– 5.6	149
Solvik	3.96	1.6– 7.6	12
Sørdal	2.20	0.6– 4.5	8
Teigesåta	1.40	0.4– 4.6	114

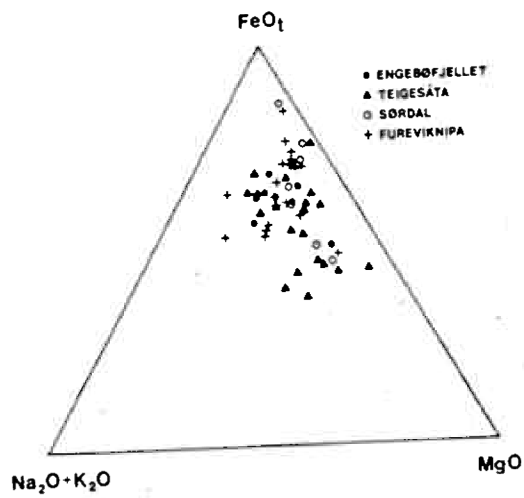

Fig. 4. (Na_2O+K_2O) – FeO(t) – MgO (wt.% oxides) diagram showing the compositional variations within four major eclogite bodies.

TITANIUM IN MINERALS

The average titanium contents of the silicate minerals garnet, clinopyroxene (omphacite), primary amphibole (barroisite) and white mica (paragonite, phengite), based on electron microprobe analyses, is 0.07%, 0.06%, 0.27% and 0.51% respectively (Fig. 6). Considering that garnet, clinopyroxene, primary amphibole and white mica constitute 30, 15, 40 and 5 wt.% of the rock respectively, the contribution from these minerals is 0.16% TiO_2 ($(0.07\times30 + 0.06\times15 + 0.27\times40 + 0.51\times5)/100 = 0.164$). For the purpose of rutile exploration this value can be assumed to be constant; the excess titanium in the rock forms oxides.

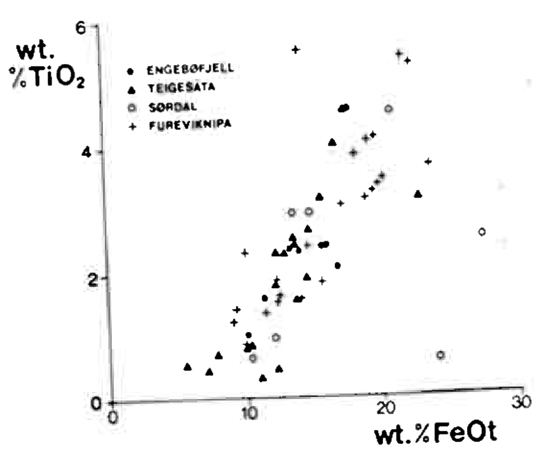

Fig. 5. TiO_2 vs. FeO(t) for eclogites.

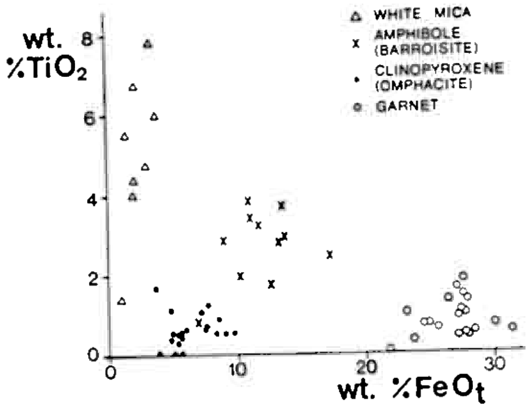

Fig. 6. TiO2 vs. FeO(t) for eclogite silicate minerals.

The average composition of rutile based on electron microprobe analyses from several eclogite localities (Table 2), is 99.09% TiO_2 0.37% Fe_2O_3 and 0.54% V_2O_5 (corrected for interference from titanium). No significant amount of other elements was detected. Relationships between rutile composition, degree of eclogite alteration, locality, and rock composition, have not been observed. Ilmenite, which contains 52.7% stoichiometric TiO_2, has not been analysed.

Table 2 – Electron microprobe analyses of rutile in eclogite. Average values (wt. %). The V_2O_5-values are corrected for titanium interference. n = number of point analyses

	Solvik eclogite (n = 4)	Kvammen eclogite (n = 8)
TiO_2	99.02	99.13
FeO	0.28	0.34
V_2O_5	0.71	0.54

	Sørdal eclogite (n = 3)	Engebøfjellet eclogite (n = 6)
TiO_2	99.45	99.10
FeO	0.17	0.39
V_2O_5	0.38	0.52

	Teigesåta eclogite (n = 9)	Naustdal eclogite (n = 3)
TiO_2	98.90	99.26
FeO	0.51	0.34
V_2O_5	0.59	0.40

RUTILE CONTRIBUTION TO THE TOTAL TITANIUM

The titanium that is not contained in the silicates forms rutile and ilmenite. For most eclogites the ilmenite content varies from 5% to about 15% of the total oxides, with 10% as an estimated average ((ilm × 100)/(ilm + rutile) = 10). Consequently, for an eclogite with 4 wt.% TiO_2 of which 0.16 wt.% TiO_2 is contained in the silicates and 3.84 wt.% as oxides, rutile contributes 3.65 wt.% TiO_2 and ilmenite 0.19 wt.% TiO_2.

RUTILE GRADES AND RESERVES

Rutile is irregularly distributed on a cm to dm scale, but is fairly evenly distributed on a 10 m to 100 m scale, usually in grades of 1 to 3% rutile and 3 to 4% in rutile-rich parts of eclogites bodies. On a meter scale the rutile grade may reach 4 to 5%. Rutile tends to be enriched in garnet-rich bands and aggregates.

As shown in Table 1 the average TiO_2 contents of the eclogite bodies, based on surface sampling, range from 1.30 to 3.96% TiO_2. The Engebøfjellet, Fureviknipa, Naustdal and Solvik eclogites clearly have the highest TiO_2-grades, in the range 3–4%. Solvik is of relatively limited size, while the others contain at least 100 Mt. of eclogite each. Estimating that 90% of the titanium occurs as rutile, gives average grades of 2.7, 3.0 and 3.1% rutile for Engebøfjellet, Naustdal and Fureviknipa respectively. Thus the amounts of rutile contained in these eclogite bodies are considerable.

There is a possibility of significant deposits with more than 3.5% rutile in parts of the larger eclogites, especially within the Engebøfjellet, Naustdal and Fureviknipa bodies. Drilling would be necessary to give a more exact picture of the mineralization. The possibility of a deposit which in grade and size is comparable to the Pian Paludo eclogite in Northern Italy, which contains 150 Mt. of ore with 4.8% rutile (Mancini et al. 1979) seems, however, unlikely. The Pian Paludo deposit is subeconomic at present.

Conclusion

Rutile grades within the Sunnfjord eclogites are generally in the range 1–4%. An average value of about 3% rutile is estimated for a few large bodies containing at least 100 Mt. of eclogite. It seems likely that concentrations containing on average 3.5% rutile or more for several Mt. of ore might exist within the Engebøfjellet, Naustdal, Fureviknipa and Solvik eclogite bodies. Confirmation of this, however, would involve extensive drilling. In addition, a detailed economic evaluation must be based on extensive benefication tests that include floatation. At the present state of knowledge the economic significance of the rutile-bearing eclogites in the Sunnfjord region i uncertain.

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