Granåsen, a dolomite-brucite deposit with potential for industrial development

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Øvereng, O. 2000: Granåsen, a dolomite-brucite deposit with potential for industrial development. *Norges geologiske undersøkelse Bulletin 436*, 75-84.

Granåsen, situated close to Mosjøen in northern Norway, is a deposit containing several million tonnes of dolomite and brucite. The deposit has been investigated and characterised in preparation for future development and exploitation. The ore consists of dolomite and brucite. Brucite has formed as a result of hydrothermal alteration associated with intrusion of gabbro. Tests have been carried out to evaluate the commercial value of the dolomite resources. A variety of different beneficiation methods were investigated to achieve commercial concentrates of brucite. The most successful result was obtained by selective flocculation, which up-grades the ore to a maximum grade of 95.5 % brucite, with a recovery of 80 %. As an alternative, or by-product of brucite concentrate production, the deposit could also be worked for dolomite.

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Introduction

Since the beginning of the 1970s, the Geological Survey of Norway (NGU) has investigated a large number of industrial mineral occurrences. In the early stage of this programme, a large deposit of high-quality dolomite marble was found some 13 km north of the town Mosjøen, in Nordland county (Fig. 1). The deposit has a favourable location, as it is situated only 3 km from Vefsnfjord, with railway and good harbour facilities, and is close to a well-developed infrastructure at Mosjøen. The location is also favourable from an environmental point of view. This paper reviews the exploration history of the Granåsen dolomite-brucite deposit.

History of investigations

The Granåsen dolomite marble deposit was first described by Øvereng (1972). Since then, much work has been carried out with the primary goal of obtaining reliable information about the size, geometry and quality of the deposit. In 1974, the central part was mapped at a scale of 1:5,000, and several short drillholes were financed by Norcem A/S to test the quality of the ore (Øvereng 1974). Norcem A/S signed royalty agreements with the landowners.

In 1975 a co-operative project between NGU and SINTEF was initiated to evaluate technical aspects for use of Norwegian dolomite marble in production of basic refractory products. Dolomite marbles from a number of localities were tested for this purpose (Seltveit et al. 1977). The dolomite from Granåsen gave excellent results. Material was also sent to Dolomitwerke GmbH, Wülfrath, Germany, one of the leading producers of refractory bricks. The tests gave results comparable to those obtained at SINTEF and encouraged NGU to continue core drilling at Granåsen in 1978. Additional testing of these cores confirmed the earlier results (Øvereng 1978). In 1979, the mineral brucite ($Mg(OH)_2$) was discovered in parts of the Granåsen dolomite marble (Faye & Øvereng 1979). Extensive mineralogical and geological investigations, including diamond drilling, were carried out in 1979 and 1980 (Øvereng 1981), and confirmed the interpretation that the brucite mineralisation is related to the contact-metamorphic effects of the Mosjøen gabbro. During this programme, a variety of different tests were carried out to estimate the likely commercial value of the deposit (Øvereng 1995). Similar brucite-dolomite deposits are described from Canada, e.g. by Goudge (1957) and Ambrose (1943), and from the USA (Burnham 1959).

Brucite is an industrial mineral with a far higher content of MgO (69.1 wt. %) or elemental Mg (41.6 wt. %) than any other naturally occurring magnesium compound, except the rather rare mineral periclase (MgO). In comparison, the main currently exploited sources of Mg-compounds, magnesite, magnesium chloride and dolomite, contain 28.8, 25.5 and 12.6 wt. % Mg, respectively. Brucite is therefore a mineral of considerable interest as an alternative raw material for production of MgO and elemental Mg.

Geological setting

The Granåsen area is located in the Elsfjord–Mosjøen tectonostratigraphic unit (Riis & Ramberg 1979) in the Helgeland region of Nordland. The rocks of the area belong to the eastern part of the Helgeland Nappe Complex (HNC), the uppermost unit of a series of nappes in the Central Scandinavian Caledonides and ascribed to the Uppermost Allochthon (Gee & Zachrisson 1979). The Uppermost Allochthon in this region consists of three tectonic complexes, the HNC, the Beiarn Nappe and the Rödingfjället Nappe Complex. These complexes broadly consist of comparable lithologies: mica schists, calcareous mica schists, marbles, amphibolites, serpentinites, gneisses and granitoid intrusions (Gavelin & Kulling 1955, Ramberg 1965, 1967, Gustavson 1981).

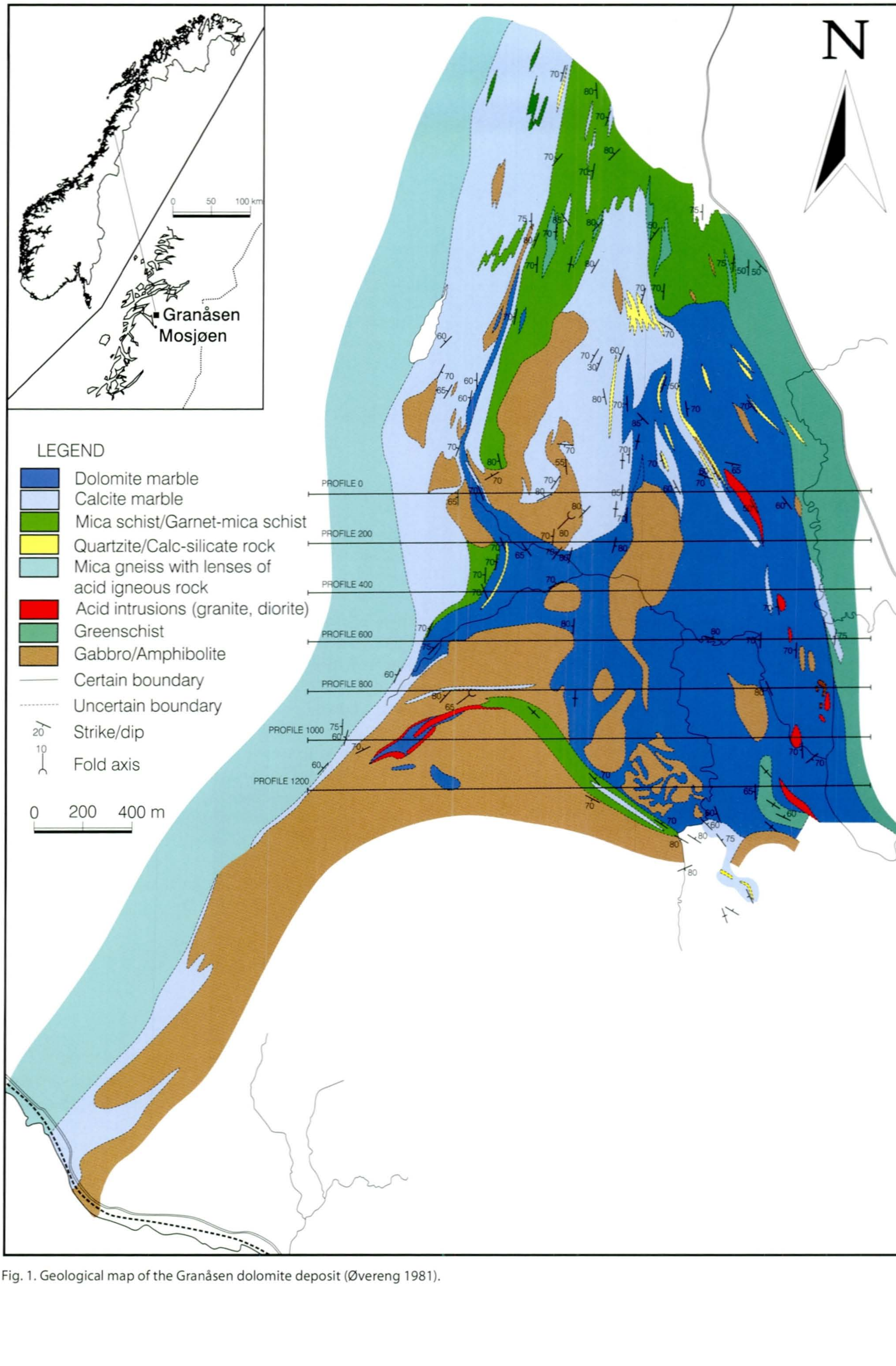

Fig. 1. Geological map of the Granåsen dolomite deposit (Øvereng 1981).

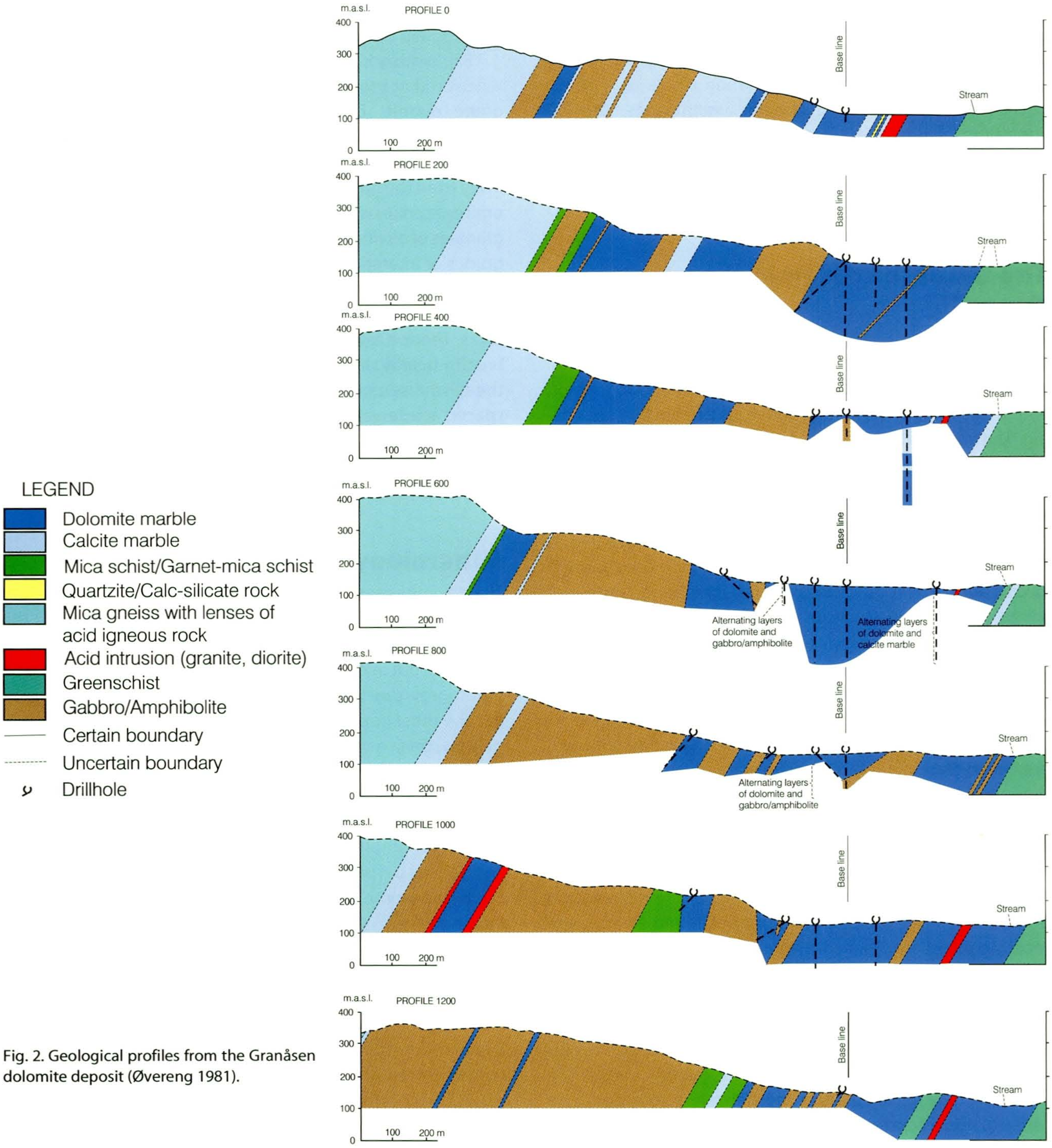

Fig. 2. Geological profiles from the Granåsen dolomite deposit (Øvereng 1981).

Traditionally, the Uppermost Allochthon had been considered as essentially comprising Cambro-Silurian rocks, deformed and metamorphosed during Caledonian mountain building (e.g., Strand 1960). No fossils have yet been found in sedimentary rocks from the Uppermost Allochthon, but radiometric ages indicate that parts of the gneissic units are of Precambrian age. Intrusive rocks, however, are of both Late Precambrian and Cambro-Silurian to Late Silurian age (Priem et al. 1975, Claesson 1979). Rock units in the area are strongly deformed and the observed mineral assemblages are the result of the major phase of deformation, metamorphism and nappe translation that took place during the Scandian phase of the Caledonian Orogeny in Late Silurian to Early Devonian time. In contrast to other nappes in the Uppermost Allochthon, the HNC hosts sizeable bodies of synorogenic intrusions which crop out over more than 30 % of the area. In accordance with the regional trend, the rock units in the Granåsen area have a complex and prolonged deformation history (Riis & Ramberg 1979). In the HNC, early folds have N-S axes and almost upright axial planes. Gabrielsen &

Ramberg (1979) suggested two phases of thrusting for the HNC, both older than the latest folding phases in the area. Metamorphism in the Mosjøen unit of the HNC is apparently linked to the second, main deformation phase (D_2), which overprints older magmatic mineral assemblages. The P-T conditions of metamorphism are assumed to be about 500 – 600° C, at 2.0 – 3.5 kb, with increasing temperatures towards the contact with the Mosjøen Igneous Complex (Theisen Juell 1985).

The Granåsen dolomite-brucite deposit

The lens-shaped deposit, which crops out between 115 and 180 m above sea level, is 1200 m in length with a maximum width of 900 m. In total, it covers an area of about 1.3 km^2, with a thickness of more than 400 m, as proven by core drilling. The area has been mapped at the scale of 1:5,000 (Fig.1). The central part of the deposit is a flat-lying swampy area. Core drilling indicates that the thickness of the overburden varies from 1 to 3 m.

The deposit is built up of a sedimentary sequence (Fig. 2) consisting of dolomite marble, underlain by a grey, impure calcite marble that gradually, with an increasing content of silicates, grades into calcite-mica schist and mica schist. Locally, the mica schist is mixed with thin bands of quartzite/quartz schist. Assuming that the succession of sedimentary rocks is not inverted, the dolomite marble is the youngest unit in the sequence. The contact between the dolomite marble and the underlying calcite marble is sharp and concordant. The metasedimentary units are strongly folded, and now dip steeply to the west at about 70°. The major fold axis strikes NNW-SSE, parallel to the regional strike, with a SW plunge.

The Mosjoen Gabbro Massif intrudes the metasedimentary strata. The contact between the gabbro massif and the metasedimentary rocks is very irregular and sharp, and mostly concordant. There are numerous apophyses of gabbroic material in the form of dykes, sills and irregular masses within the surrounding strata. Some of these occur at a considerable distance from the main contact. Isolated, irregular bodies of gabbro distributed within the sequence are considered to be stringer intrusions from the gabbro massif. The youngest geological event in the deposit is recorded by a series of minor lenses of cross-cutting pegmatites of granitic to granodioritc composition. Geophysical investigations (Eidsvik 1979, Dalsegg 1981) and exploratory core drillings indicate that the gabbro underlies a greater part of the sedimentary sequence.

Along the main contact with the gabbro massif, and around minor bodies of gabbro within the deposit, the dolomite marble has been contact metamorphosed, and brucite, $Mg(OH)_2$, is one of the final products. Brucite mineralisation occurs exclusively in the dolomite marble adjacent to the gabbro and has not been found in the contact zone around granite-granodiorite pegmatite bodies. The average thickness of the mineralised zone along the main contact is estimated to be about 40 m over a length of 800 m. The brucite content is, on average, about 17 wt. %; individual samples may contain up to 23 wt. % brucite.

Exploratory core drilling in the deposit (5000 m of core) revealed that brucite occurs in distinct layers within the dolomite marble. Distribution of brucite within the layers appears to be concentrated in a very complex network of veinlets, with a gradual decrease in brucite concentration away from the gabbro contact. Layers of brucite-bearing dolomite alternate with layers of pure dolomite or dolomite with granules of olivine (forsterite), or of olivine displaying varying grades of alteration to serpentine and brucite. Since brucite is more soluble than carbonates, the brucite content can be roughly estimated from the naturally-etched weathering surfaces. There is always some olivine and/or serpentine in the brucite-bearing layers, but only a minor amount of brucite in the olivine/serpentine-rich layers. The brucite-rich layers are spaced at intervals from a few cm up to ca. 20 m. Field observations, together with examination of drillcore, suggest that the layers enriched in brucite are not always concordant with the primary bedding in the dolomite marble.

Mineralogy

The *dolomite marbles* are mostly granular, and vary from fine- to coarse-grained (0.1-1.5 mm, mean 0.6 mm), reflecting the grade of the metamorphism. Most of the dolomite marbles are white, but in certain parts of the deposit the colour is pale bluish-grey, due to minor amounts of finely dispersed graphite. The most important impurities are calcite, forsterite, serpentine, mica and tremolite (Table 1). Tremolite, as irregular masses or disseminated grains, only occurs in specific layers in the dolomite marble, but is practically absent in the brucite-rich zones. Most common accessories are quartz, feldspar, mica, graphite, diopside, zircon, rutile, apatite, titanite and various oxides and sulphides.

Based on the observations from mapping, diamond drilling and geophysics, the most promising area for quarrying pure dolomite marble would be in the central part of the deposit (Tables 2 & 3). Geochemical investigations have also been carried out in this part of the deposit.

The occurrence of brucite in marble is quite common (Table 4). The classical mechanism for brucite formation is as follows: when dolomite marble or Mg-bearing limestone is exposed to contact metamorphism, the mineral periclase (MgO) is formed and immediately hydrates to brucite in the presence of water (Turner 1954):

$$\underset{\text{dolomite}}{CaMg(CO_3)_2} \longrightarrow \underset{\text{calcite}}{CaCO_3} + \underset{\text{periclase}}{MgO} + CO_2 \quad (1)$$

$$\underset{\text{periclase}}{MgO} + H_2O \longrightarrow \underset{\text{brucite}}{Mg(OH)_2} \quad (2)$$

The final products of the carbonate rocks after contact metamorphism depend on a number of factors. The most important are the chemical composition and mineralogy of the sedimentary sequence and the temperature and pressure prevailing at the time of intrusion.

Table 1. Modal analyses of pure dolomite marble. Drillcore samples are representative of the central part of the deposit.

Mineral / sample	2-79/1	2-79/3	2-79/14	2-79/19	2-79/22	2-79/24	2-79/26
Brucite	*	*	*	*	*	*	*
Dolomite	95.0	95.4	96.9	98.8	99.0	95.5	95.6
Calcite	3.5	3.1	2.1	*	0.6	3.7	1.3
Olivine/Serpentine	1.4	1.0	0.5	0.3	nd	nd	nd
Other minerals	0.1	0.5	0.5	1.8	0.4	0.8	3.1

* not measured

nd not detected

Table 2. Major element analyses (XRF) of pure dolomite marble in wt. %. The samples are collected from 6 drillholes in the central part of the deposit. Each sample represents a core length of 30 m. Measurements by Philips PW1480 X-ray fluorescence spectrometer on glass discs made by fusing the sample and $Li_2B_4O_7$ in the ratio 1:7 (analyst: B.Nilsen).

Oxide / Sample	Bh.1/77	Bh.2/77	Bh.3/77	Bh.4/77	Bh.5/77	Bh.6/77
SiO_2	7.19	<0.1	4.31	<0.1	4.34	2.6
Al_2O_3	<0.1	<0.1	<0.1	<0.1	0.38	<0.1
Fe_2O_3	0,21	0.15	0,40	0.14	0.27	0.25
TiO_2	<0.01	<0.01	<0.01	<0.01	0.02	<0.01
MgO	22.62	21.46	21.7	21.36	21.52	21.24
CaO	31.66	31.44	31.23	31.54	32.53	31.43
Na_2O	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
K_2O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
MnO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
P_2O_5	<0.01	0.14	0.02	0.02	0.02	0.02

Table 3. Minimum and maximum values (wt. %) for acid-soluble CaO and MgO in pure dolomite marble. CaO and MgO were determined by dissolving the powdered sample in dilute HCl (1:4) during heating followed by titration with EDTA (analyst: J. Røste).

Sample	CaO		MgO	
	Min.	Max.	Min.	Max.
1/77	32.68	33.46	16.47	21.69
2/77	30.71	31.52	17.05	20.73
3/77	30.71	33.02	17.43	21.31
4/77	30.44	32.06	18.01	21.50
5/77	31.25	32.87	18.98	21.11
6/77	31.52	32.33	16.85	21.31

Table 4. Modal analyses of brucite-bearing dolomite marble.

Mineral / Sample	2A-79	2B-79	2C-79	2D-79	2E-79	2F-97	2G-79	2H-79	2I-79
Brucite	21.1	20.5	19.3	20.4	20.6	22.4	21.4	18.9	18.5
Dolomite	49.1	45.1	45.3	41	43.4	43.3	43.0	43.7	38.1
Calcite	28.8	33.8	35.0	37.8	35.9	33.9	34.6	36.7	38.4
Olivine/Serpentine	1.0	0.6	0.4	0.8	0.1	0.4	1.0	1.0	5.0

In the Granåsen area, brucite mineralisation occurs exclusively in the dolomite marble adjacent to gabbro. This suggests that the brucite is genetically related to the intruding gabbro, and that the intrusion supplied the heat necessary to form hydrothermal solutions which decomposed dolomite to form brucite and accompanying minerals. The major brucite mineralisation in Granåsen area occurs along the main contact with the gabbro massif, which indicates a direct correlation between the size of intrusion and the degree of dolomite breakdown into brucite and calcite. Brucite content typically decreases away from the contact.

In individual samples of brucite-bearing dolomite marble, the dolomite/calcite ratio is widely variable, depending on the intensity of the alteration of dolomite to brucite, calcite and other minerals. The calculated dolomite/calcite ratio in the area of brucite-bearing dolomite varies within a wide interval (0.8-1.3), but the molecular ratio MgO/CaO for dolomite marble with or without brucite only varies within a narrow range (0.62 – 0.68) and is close to that of pure dolomite (0.72). These results indicate that the original strata at the border were pure dolomite marbles prior to the intrusion of gabbro.

Most of the brucite in the Granåsen area occurs as irregular and rounded grains ranging in size from < 0.01 mm up to 1 mm; on average, around 0.35 mm. The granules appear milky-white in colour in a fresh hand specimen and colourless or faintly brown under the microscope. This granular brucite texture occurs in dolomite, calcite and olivine/serpentine assemblages. Differences in the shape of brucite granules are noted to depend on the dominant mineralogy of the matrix, calcite or dolomite. Generally, rounded brucite grains occur within calcite, whereas brucite within dolomite shows angular grain boundaries, which in many cases conform to the carbonate cleavage. Projecting tongues or veinlets of brucite in some cases extend from both angular and rounded brucite granules into the surrounding carbonates, along cleavages or grain boundaries. Some of the brucite grains have the well-known, concentric, onion-skin texture (Hunt & Faust 1937), with flakes or fibres in differing orientations in each successive layer. In plane-polarised light the grains appear colourless; the complex foliated texture is optimally revealed under crossed nicols (Fig. 3). Veins of brucite are rare, though they are occasionally seen in drill cores and are composed of pale green, translucent, flaky brucite with a pearly lustre. Other minerals are calcite and minor amounts of quartz, feldspar, spinel, epidote, titanite, apatite, actinolite, forsterite and diopside. In addition, opaque minerals such as pyrite and hematite are sporadically present.

In the Granåsen area, some of the brucite grains occur as alteration products of forsterite. The distribution and general appearance of the forsterite, which is distributed throughout the dolomite and calcite as round small grains 0.01–0.5 mm in size, is similar in many respects to those of the granular brucite. There are many examples of progressive replacement of forsterite by brucite. In many thin-sections, polycrystalline aggregates of brucite have replaced whole grains of forsterite, retaining the original crystal shape. Forsterite has also in varying degrees altered to chrysotile. Brucite may, in

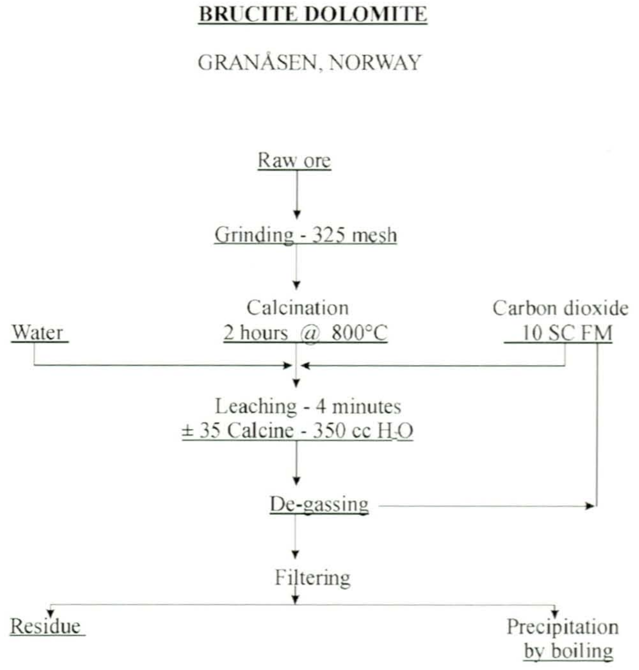

Fig. 3. Flow sheet for selective calcination and leaching (Jepsen 1981).

such cases, occur as extremely fine-grained intergrowths with chrysotile. In spite of careful examination of thin-sections from a large number of representative specimens, no periclase has been found. At Granåsen, spinel occurring as cores in brucite has been proven by electron microprobe examination. Table 5 shows the chemical composition of brucitic dolomite marble from different places along the main contact of the gabbro massif. Table 6 shows element compositions of brucite, dolomite, calcite and forsterite from different places along the contact zone. One of the holes drilled in the contact zone has a particularly high brucite content, varying from 20 to 30 wt. %, over a thickness of about 120 m.

Mineral resource assessment

Based on existing drillcore intersections and geological mapping, the available tonnage of pure dolomite marble down to sea level is estimated to be between 80 and 100 M tonnes. The tonnage estimation of the brucite ore, however, is less certain. A tentative estimate in two restricted areas (Finnhaugen, Stuvremma) in the main contact zone to the gabbro, 1 km in length and 40 metres in thickness and with an indicated average of 17 wt. % brucite, gave the following results: (Ryssdal 1984)

Total volume:	3.2 M m^3
Total rock tonnage (S.G = 2.7):	8.64 M tonnes
Total tonnage of brucite (17 wt. %):	1.50 M tonnes
Recoverable brucite (assuming 80 % recovery):	1.2 M tonnes

Diamond drilling shows that brucite mineralisation of potential economic value occurs not only in the border zone along the main contact, but also in the contact zone around

Table 5. Major element analyses (XRF) of dolomite marble with different contents of brucite in wt. %. Measurements by Philips PW1480 X-ray fluorescence spectrometer (analyst: B.Nilsen). Brucite content is determined by the Phenfield method (Graff 1983).

Sample	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	Brucite
Pr.1	0.28	<0.10	0.08	<0.01	23.3	35.4	<0.1	0.02	0.05	<0.01	23.3
Pr.2	0.35	<0.10	0.12	<0.01	23.0	33.8	<0.1	0.02	0.06	<0.01	16.2
Pr.3	<0.10	<0.10	0.12	<0.01	22.0	32.0	<0.1	0.02	0.06	<0.01	2.5

Table 6. Element compositions of brucite, dolomite, calcite and forsterite (wt. % oxides). Minerals were analysed with a Jeol 733X Superprobe instrument (accelerating voltage = 15 kV, probe current = 15 nA, count time = 10 s, raster mode analysis. Raw data were corrected using the Jeol ZAF-correction.

	SiO_2	Al_2O_3	TiO_2	FeO	MgO	CaO	Na_2O	K_2O	MnO	NiO
Brucite:										
Dh1.1/1	0.26	0.03	0.00	0.29	74.31	0.20	0.07	0.09	0.01	0.03
Dh1.1/2	0.09	0.08	0.07	2.71	67.43	0.28	0.03	0.00	0.00	0.00
Dolomite										
Dh.5/1a	0.04	0.05	0.02	0.00	23.18	32.22	0.011	0.13	0.00	0.05
Dh.5/1b	0.03	0.03	0.00	0.09	24.07	34.95	0.000	0.04	0.00	0.02
Dh.5/1c	0.02	0.00	0.00	0.15	21.89	32.54	0.000	0.02	0.02	0.02
Calcite										
Dh.5/1a	0.00	0.06	0.03	0.04	1.82	55.07	0.075	0.44	0.03	0.07
Dh.5/1b	0.00	0.05	0.00	0.07	3.22	67.41	0.000	0.17	0.00	0.01
Forsterite										
Dh.6/1a	38.87	0.07	0.02	0.31	55.07	0.09	0.034	0.00	0.03	0.01
Dh.6/1b	36.35	1.51	0.00	0.32	41.88	0.05	0.000	0.05	0.05	0.00
Dh.6/1c	41.81	0.04	0.05	0.36	55.11	0.08	0.026	0.00	0.03	0.01
Dh.6/1d	39.48	0.47	0.04	0.18	40.22	0.07	0.031	0.07	0.00	0.03

the largest bodies of gabbro within the dolomite marble. Because of the complexity of the mineralisation it is necessary to undertake extensive additional diamond drilling to obtain sufficient data to provide a reliable tonnage estimate for the brucite ore.

Brucite concentration

The brucite ores are relatively fine-grained and require milling to 30-40 % minus 40-150 µm, to obtain 80-90 % total liberation of brucite. Crushing and milling tests show that the brucite ore did not fit into existing liberation models because of the different milling properties of brucite versus the carbonate minerals. The dominant liberation mechanism is liberation of single grains along the contact. A characteristic of the milling products is the high content of brucite in the coarse fraction and in the 40-150 µm fraction. Brucite has a layered crystal structure, which manifests itself as a micaceous foliation and a perfect basal cleavage. Thus, crushing, impact or vigorous attrition of individual brucite grains should be avoided in the process. Otherwise, the brucite may cleave into thin plates which would be difficult to separate in a sizing apparatus. The tests carried out at NTNU, Trondheim, indicate that crushing /milling methods with a low abrasive effect give the lowest selective milling of brucite and, as a result, reduced contents of brucite in the finer fractions (Malvik 1980, 1982). A range of processes for developing a brucite concentrate have been tested. This article reviews only the most fruitful methods and the results.

Flotation

The Ore-treatment Laboratory at the University of Trondheim (NTNU) carried out a preliminary test flotation, without obtaining an acceptable brucite concentrate (Dybdahl 1980). The best result from the test programme was a concentrate with 40-50 wt. % brucite with a recovery of 30-40 wt.%.

Tests carried out at Basic Inc. Gabbs, Nevada, USA (Jepsen 1981)

Material sent to Basic Inc. Gabbs, was tested using (i) heavy liquids, (ii) direct leaching and (iii) selective calcination and leaching. The last method gave the best results. Samples varying from a low silica content of 0.33 % to a high of 16.57 % SiO_2 were tested. The low-silica samples, after selective calcination, produced precipitates assaying more than 94 % MgO at recoveries over 64 % of the available magnesia, leaving

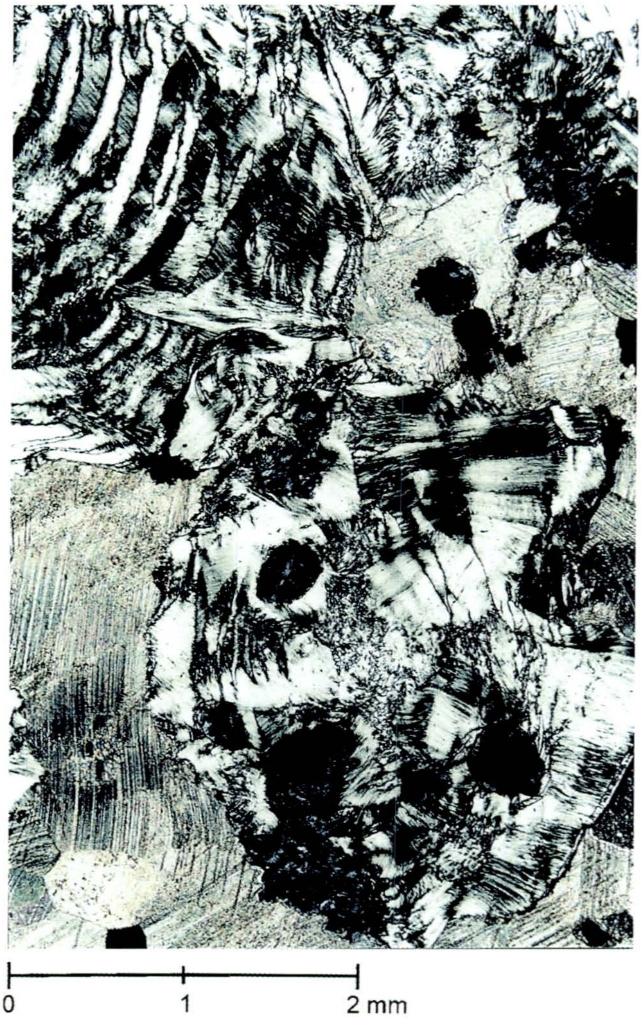

Fig. 4. Brucite as a series of concentric swirls of foliated aggregates. The bluish/black enclosed grains are fragments of unaltered forsterite. Photomicrograph under crossed nicols.

residues containing more than 75 % CaO. The results from the testing with selective calcination and leaching are given in Table 7 and a flow sheet for the process is shown in Fig. 4.

Direct leaching

The Institute for silicate and high-temperature chemistry at NTNU/SINTEF carried out a leaching test on a sample of representative brucite ore. The test procedure was a modified version of the so-called Sulmag-process and resulted in 150 kg brucite per tonne of ore. The raw material had a content of brucite of about 15 wt. % (Monsen & Seltveit 1984).

Gravity separation

Basic Inc. Gabbs, Nevada, USA used a patented sink-float method with heavy liquid media (methylene bromide, 2.48 kg/dm^3). The result was a concentrate with 93.3 wt. % of brucite (Jepsen 1981). Tests carried out at Purdue University, USA, with Wolframat dissolved in water as medium, gave a concentrate of 85 wt % brucite with a recovery of about 80 % (Øvereng 1987a).

Selective flocculation

Brucite is a very brittle mineral and, as a result, it will usually be enriched in the finer fractions in the crushing and milling process. Preliminary tests indicated that about 40 % of the brucite of the feed ore goes into the fines (less than 30-50 µm) during the crushing and milling process and cannot be treated by the traditional separation methods. Brucite ore from the Granåsen deposit has been tested by traditional separation methods without obtaining a satisfactory brucite concentrate.

At Purdue University, USA, the late Prof. Kullerud and his group developed a separation method which is very efficient for finer grain fractions. The group had earlier used this technique to separate alunite from quartz in alunite ore. Results show that the technique is very efficient for particle size <40 µm. The method of selective flocculation is also dependent on an efficient technique to separate the brucite flocs from the other minerals in the slurry. Research work has been carried out at Purdue University, Indiana, USA, and a flow sheet using the new technique was developed. Testing at bench scale gave a concentrate with ≈ 87 wt. % brucite at a recovery of ≈ 76 % (Øvereng 1987b) These results also indicated that if

Table 7. Results from the test with selective calcination and leaching. Brucite content is determined by the Phenfield method.

Sample no.	Total	Total	Residue	Precipitated	MgO	Raw materials
	% MgO	% SiO_2	% CaO	% MgO	% Recovery	% Brucite
G-3	22.0	0.33	89.98	98.18	85.49	2.5
G-10	22.2	0.53	88.38	97.80	86.90	1.1
G-4	23.3	0.72	94.26	97.16	94.60	23.95
G-2	23.0	1.68	75.08	94.58	64.12	16.23
G-9	23.5	3.43	74.18	91.78	70.84	11.79
G-1	20.9	4.22	64.99	92.47	31.84	23.3
G-7	24.3	7.90	67.63	89.18	59.72	15.13
G-5	22.6	8.37	70.83	85.53	60.21	13.32
G-6	23.1	13.30	59.81	84.91	45.35	6.61
G-8	21.9	16.57	56.99	74.45	22.67	7.91

Table 8. Physical data of dead-burned samples tested at Dolomittwerke GmbH, Wülfrath, Germany and SINTEF, Trondheim.

	Dolomitwerke	SINTEF
Density, g/cm^3	2.86	-
Volume weight, g/cm^3	2.78	2.79 - 2.84
Open porosity, %	2.80	1.24 - 1.90
Total porosity, %	2.80	-

Table 9. Physical data from a calcination / dead-burned test of samples of pure dolomite marble.

	Burned at	1650° C	Burned, 2h. 1800 °C	oxidising atm.
	Split 5-10 mm	Briquettes ø = 50mm	Split 5 - 10 mm	Briquet-tes ø = 10 mm
Density, g/cm^3	3.43	-	-	-
Volume weight, g/cm^3	2.08	2.83	3.05	3.18
Open porosity, %	39.0	15.8	9.2	2.2
Total porosity, %	39.4	17.5	11.1	7.3

not developed

Table 10. Volume weight and porosity of dolomite marble, sintered in Ar-atm. at 2000 °C for different lengths of time, in minutes (SINTEF).

Sintered at 2000°C	Volume weight in g/cm^3	Open porosity
30 min.	2.89 2.78	13.6 16.4
60 min.	3.01 3.05	10.3 10.7
120 min.	3.01 3.05	10.9 9.5
180 min.	3.11 3.00	8.2 11.4

Table 11. Representative reflectance values for the pure dolomite marble.

Filter	Collectsample*
R 457 Tappi (Brightness)	92.3
FMX/C Red (Amber)	93.7
FMY/C Green	93.3
FMZ/C Blue	92.3
R 46	1.50

* fractions < 200μm.

each step in the flow sheet could be optimised, the process could still be improved.

Product development

In 1975, a co-operative effort between NGU and SINTEF was initiated to evaluate technical aspects for the use of Norwegian dolomite marble in the production of basic refractories. Dolomite marble from a number of localities was tested for this purpose. The dolomite marble from Granåsen, tested at SINTEF, gave excellent results (Seltveit et al. 1977). Material from Granåsen was also sent to one of the leading producers of refractory brick, Dolomitwerke GmbH, Wülfrath, Germany. Results were comparable to those obtained at SINTEF (Table 8). This encouraged an additional core-drilling programme in 1978. Material from the core drilling was tested by SINTEF. These tests confirmed the previous results (Øvereng 1977, 1978). Results from different tests indicate that the dolomite marble is suitable as a raw material for the production of basic refractories (Seltveit et al. 1977).

Melted dolomite

The interest to use melted dolomite marble is growing and different institutions and companies have tested Norwegian dolomite marble for production of melted dolomite. Results from different tests indicate that dolomite marble from Granåsen may be of interest for the production of melted dolomite (Tables 9, 10).

Filler/ coating

Dolomite marble for fillers and coating is a growing market and high-quality dolomite marble from the Granåsen deposit should be of interest for this market. Chemical analysis and other test data indicate that a significant portion of the dolomite marble fulfils criteria for the mineral filler industry. Brightness is an important parameter of filler/coating materials and average values of a representative sample from the central part of the deposit are given in Table 11.

Conclusions

The Granåsen deposit contains around 100 M tonnes of high-quality dolomite marble and 10-15 M tonnes of brucite-bearing dolomite containing around 17 wt. % brucite. The brucite mineralisation occurs in the contact aureole to a gabbro massif and formed by contact metamorphism associated with the intrusion. The results from different tests indicate that the existing mineral resources at the Granåsen deposit can potentially be used in a large range of products. Pure dolomite marble from the Granåsen deposit seems to be a suitable raw material for the production of magnesium metal, basic refractories, glass, filler, insulation, various building materials, mineral wool, special cements, and also in various applications in agricultural and environmental uses.

A variety of different separation techniques have been tested for the production of brucite concentrate. The most promising methods gave the following results:

- Selective flocculation: brucite concentrate (brucite 87 wt. %), recovery 76 %.
- Gravity separation: brucite concentrate (brucite 85 wt. %), recovery 80 %.
- Leaching (Sulmag): brucite concentrate: 150 kg/tonne (raw ore 15 wt. % brucite).
- Brucite concentrates from Granåsen would be especially suitable for the production of high-quality basic refractories, MgO, Mg-metal and different fillers. The deposit of Granåsen is therefore a mineral resource with great potential. Future investigations of the deposit need to be focused on a total evaluation of its possibilities.

Acknowledgements

The investigation programme has been carried out as a joint project between Norges geologiske undersøkelse and Vefsn Utbyggingsselskap A/S, Mosjøen. Selective flocculating tests have been carried out at Purdue University, Indiana, USA. The author expresses his thanks to the late Prof. G. Kullerud and his staff who introduced him to that technique. Thanks are also due to my colleagues, T.A. Karlsen and the late B.A. Sturt for their valuable criticism and advice in a early stage of preparing this manuscript and to Nigel J. Cook for correcting the manuscript and improving the English language. David Harrison (BGS) and Yryo Pekkola (GSF) are thanked for their helpful reviews.

References

Ambrose, J.W. 1943: Brucitic limestone and hastingsite syenite near Wakefield, Quebec. *Transactions of the Royal Society of Canada*: Sec. IV, Third Series, 9 -22.

Burnham, C.W. 1959: Contact metamorphism of magnesium limestones at Crestmore, California. *Geological Society of America Bulletin 70*, 879-920.

Claesson, S. 1979: Pre-Silurian orogenic deformation in the north-central Scandinavian Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar*. 101, 353-356.

Dalsegg, E. 1981: IP-og magnetiske målinger i Granåsen dolomittfelt, Vefsn, Nordland. *Norges geologiske undersøkelse Report 1822*, 9 pp. + appendices.

Dybdahl, B.A. 1980: Orienterende oppredningsforsøk med brucitt fra Granåsen *Oppredningslaboratoriet NTH, Report 02/80*, 6 pp. + appendices.

Eidsvik, P. 1979: IP-og magnetiske målinger i Granåsen dolomittfelt, Vefsn, Nordland. *Norges geologiske undersøkelse Report 1822*, 9 pp. + appendices.

Hunt, W.F. & Faust, G.T. 1937 : Pencatite from the Organ mountains, New Mexico. *American Mineralogist 22*, 1151-1160.

Faye, G.Chr. & Øvereng, O. 1979: Granåsen dolomittfelt, Vefsn, Nordland fylke. Funn av brucitt. *Norges geologiske undersøkelse Report 1712*, 9 pp. + appendices.

Gabrielsen, R H. & Ramberg, I. B. 1979: Skyvesonen mellom Rødingsfjelldekket og Helgelandsdekket i området Tustervatn, Helgeland. *Geologinytt 13*, 22-23.

Gavelin, S. & Kulling, O., 1955: Beskrivning till berggrundskarta över Västerbottens Län. *Sveriges geologiska undersökelse, Ser., Ca 37*, 5-99.

Gee, D. G. & Zachrisson, E. 1979: The Caledonides in Sweden. *Sveriges geologiska undersøkelse, C769*, 1-48.

Goudge, M. F. 1957: Brucite. The geology of Canadian Industrial Mineral Deposits. 6th *Commonwealth Mining and Metallurgy Congress, Canadian Institute of Mining and Metallurgy, Industrial Minerals Division, Winnipeg 1957*, 61-69.

Graff, P. R. 1983: Bestemmelse av brucitt i karbonatbergarter. *Norges geologiske undersøkelse 388*, 13-15.

Gustavson, M. 1981. Geologisk kart over Norge, bergrunnskart Mosjøen 1: 250.000. *Norges geologiske undersøkelse*.

Jepsen, T.L.B. 1981: Brucitic Dolomite- Granaasen Orebody. *Consultancy report for Vefsn Utbyggingsselskap A/S*. (also as an appendix in NGU report 1780; Øvereng 1981).

Malvik, T. 1980: Undersøkelse av frimalingsegenskapene til brucitt fra Granåsen. *Unpubl. consultancy report, Geologisk institutt NTH*, 8pp. + appendices, (also as an appendix in NGU report 1780; Øvereng 1981).

Malvik, T. 1982: Granåsen, brucitt-mineralisert dolomitt-bergart. Maleforsøk. *Unpubl. Consultancy report*. Geologisk institutt NTH.

Monsen, B. & Seltveit, A. 1984: Innledende forsøk med utluting av brucitt fra "Granåsen dolomitt". *Unpubl. SINTEF report, prosjekt nr. 341356.*

Priem, H.N.A., Boelrijk, N.A.I.M., Hebeda, E.H., Verdurmen, E.A.T. & Verschure, R.M. 1975: Isotopic dating of Caledonian Bindal and Svenningdal Granite Massifs, Central Norway. *Norges geologiske undersøkelse 319*, 29-36.

Ramberg; I. B. 1965: Regional-geologiske undersøkelser i Røssvatnområdet, sydlige Nordland (Abstract). *Geologi* (Helsinki) *17*, 141.

Ramberg; I. B. 1967: Kongsfjell-områdets geologi, en petrografisk og strukturell undersøkelse i Helgeland, Nord-Norge. *Norges geologiske undersøkelse 240*. 125pp.

Ryssdal, K. 1984: Diamantboring i Granåsen. Resultater. *Unpubl. Report, Vefsn Utbyggingsselskap A/S.*

Riis, R.A. & Ramberg, I. B. 1979: Nyere data fra Nordlands høymetamorfe dekkekompleks. *Geologinytt 13*, 60-61.

Seltveit, A., Steinmo, M. & Viken, K. 1977: Ildfaste dolomittmaterialer (testing av nordnorske dolomitter). *SINTEF-rapport nr. STF34.A77049.* (Rapport for NTNF, kjemisk komite).

Seltveit, A. & Viken, K. 1977: Ildfaste dolomittmaterialer (testing av nordnorske dolomitter). SINTEF-rapport nr. STF34.A79049. (Sluttrapport for NTNF, kjemisk komite).

Strand, T. 1960: The pre-Devonian rocks and structures in the region of Caledonian Deformation. *In:* Holtedahl O. et. al. Geology of Norway. *Norges geologiske undersøkelse 208*, 170-284.

Theisen Juell, F. 1985: *En petrologisk og strukturgeologisk undersøkelse av Reinfjell-området*. Unpublished Thesis, University of Oslo, 279 pp.

Turner, F.J. 1954: *Petrology, An Introduction to the Study of Rocks in Thin Section*, W.H. Freeman and Company, San Francisco, 1046 pp.

Øvereng, O. 1972: Råstoffundersøkelser i Nord-Norge. Kalkstein og dolomitt undersøkelser Nordland fylke, delrapport 1118/9F. Kalkstein og dolomitt i Vefsn kommune. *Norges geologiske undersøkelse Report 1118/9*, 53-60 + appendices.

Øvereng, O. 1974: Granåsen dolomittfelt, Vefsn, Nordland. Geologi,geologisk beskrivelse av borkjerner,uttak og analysering av borkjerneprøver. *Norges geologiske undersøkelse Report 1242 C*, 7 pp. + appendices.

Øvereng, O. 1977: Råstoffundersøkelser i Nord-Norge. Granåsen dolomittfelt, Vefsn kommune, Nordland. *Norges geologiske undersøkelse Report 1556/4A*, 32 pp. + appendices.

Øvereng, O. 1978: Råstoffundersøkelser i Nord-Norge. Granåsen dolomittfelt, Vefsn kommune, Nordland fylke. *Norges geologiske undersøkelse Report 1625/5A*, 34 pp. + appendices.

Øvereng, O. 1981: Granåsen dolomittfelt, Vefsn, Nordland. *Norges geologiske undersøkelse Report 1780*, 38 pp. + appendices.

Øvereng, O. 1987a: Granåsen-prosjektet. Fremstilling av brucitt-konsentrater ved bruk av tunge vesker. *Unpublished report for Vefsn Utbyggingsselskap A/S*, 45 pp. + appendices.

Øvereng, O. 1987b: Granåsen-prosjektet. Utvikling av metode (selektiv flokulering) for fremstilling av brucitt-konsentrater. *Unpublished report for Vefsn Utbyggingsselskap A/S*, 45pp.

Øvereng, O. 1995: Granåsen dolomittfelt, Vefsn kommune, Nordland. Sluttrapport. *Norges geologiske undersøkelse Report 95.025*, 34 pp.