The geology, exploration and characterisation of graphite deposits in the Jennestad area, Vesterålen, northern Norway

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This paper reviews graphite exploration in the Jennestad area, Nordland. As a result of helicopter aeromagnetic surveying and subsequent ground geophysics, mapping and trenching, some 30, variously sized bodies of graphite schist were identified. The graphite-bearing schist occurs associated with dolomite marbles, amphibolites and pyroxene gneisses, all of which are intruded by charnockites and granites. The graphite is coarse, fully ordered, crystalline and flaky. Grades up to 40% carbon were found. Gangue minerals in the ore are quartz, plagioclase, K-feldspar, biotite and orthopyroxene. Some of the largest ore bodies contain about 250,000 tonnes each with an average grade of 20% carbon. Bench-scale beneficiation tests shown that the ore can be upgraded to a maximum grade of 97% C, with a recovery of 89%. It is believed that the graphite schists were originally sediments rich in organic matter which wase converted to graphite during granulite-facies metamorphism.

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Introduction

Norway has been a major European producer of flake graphite for almost a century and is today one of two European producers. Three major graphite mines have been operating in Norway during the last century: the Rendalsvik mine in Holandsfjord south of Glomfjord, Nordland county; the Skaland graphite mine on the island of Senja, Troms county; and the Jennestad mine in Vesterålen, Nordland county. Norway is therefore a country with good potential for graphite deposits. However, only the Skaland mine is currently active; about 7000 tonnes of graphite concentrate are produced annually.

In the economic evaluation of graphite deposits, the following factors are important: a) size, grade and tonnage of the ore bodies, and b) the grain size and distribution of the graphite flakes in the ores. Commercial graphite is a relatively expensive industrial mineral and to obtain good quality graphite concentrates, beneficiation is essential in order to obtain optimal prices for the finished product.

In this paper, we aim to (1) give a review of the general geology and history of graphite exploration in Jennestad area, (2) describe the geological setting and the petrography of the graphite ores, and (3) describe the results of recent beneficiation tests and mineral characterisation of the graphite ore.

Regional geological setting

The rocks of the Jennestad area belong to the Archaean to Proterozoic rocks of the Lofoten- Vesterålen province. The regional tectonomagmatic and metamorphic evolution has been described elsewhere (Griffin et al. 1978, Tveten 1978). The oldest rocks in the Lofoten-Vesterålen area are migmatitic gneisses of an intermediate, andesitic composition. They are intruded by granodiorite/granite plutons dated to about 2600 Ma (Pb/Pb whole rock Griffin et al. 1978) and metamorphosed to granulite facies at about 2000 Ma. Unconformably on the gneisses and granitoids lies a Proterozoic supracrustal series comprising felsic to intermediate metavolcanic gneisses, dolomite and calcite marbles, quartzites, graphite schists and iron formations. The entire package underwent a granulite-facies metamorphic event, dated at 1830 Ma (Rb/Sr whole rock Griffin et al 1978), with a metamorphic peak of 900°C and 10 kbar. Carbon and oxygen isotopes in the marbles were studied by Baker & Fallick (1988, 1989), who found them to have unusually heavy $\delta^{13}C$ isotopic signatures, with evidence of large-scale CO_2 infiltration during granulite-facies metamorphism. The metamorphic maximum coincided with the emplacement of large volumes of mangeritic to charnockitic intrusions, which dominate the geology of the area. Finally, a series of younger granites were intruded at about 1300 Ma.

History of graphite investigations

The investigated area is situated in the central part of the island of Langøya in the Vesterålen archipelago (Fig. 1). The graphite deposits in the Jennestad area were first visited and registered by B.M Keilhau in about 1820. The first period of commercial mining started in 1899 and ended in 1914. During this period some tens of different deposits were exploited in the Lofoten-Vesterålen district, the main activity being in the Jennestad area. In 1938, the graphite occurrences were reinvestigated by ground geophysics and diamond drilling. From 1948 to 1960 there was a second period

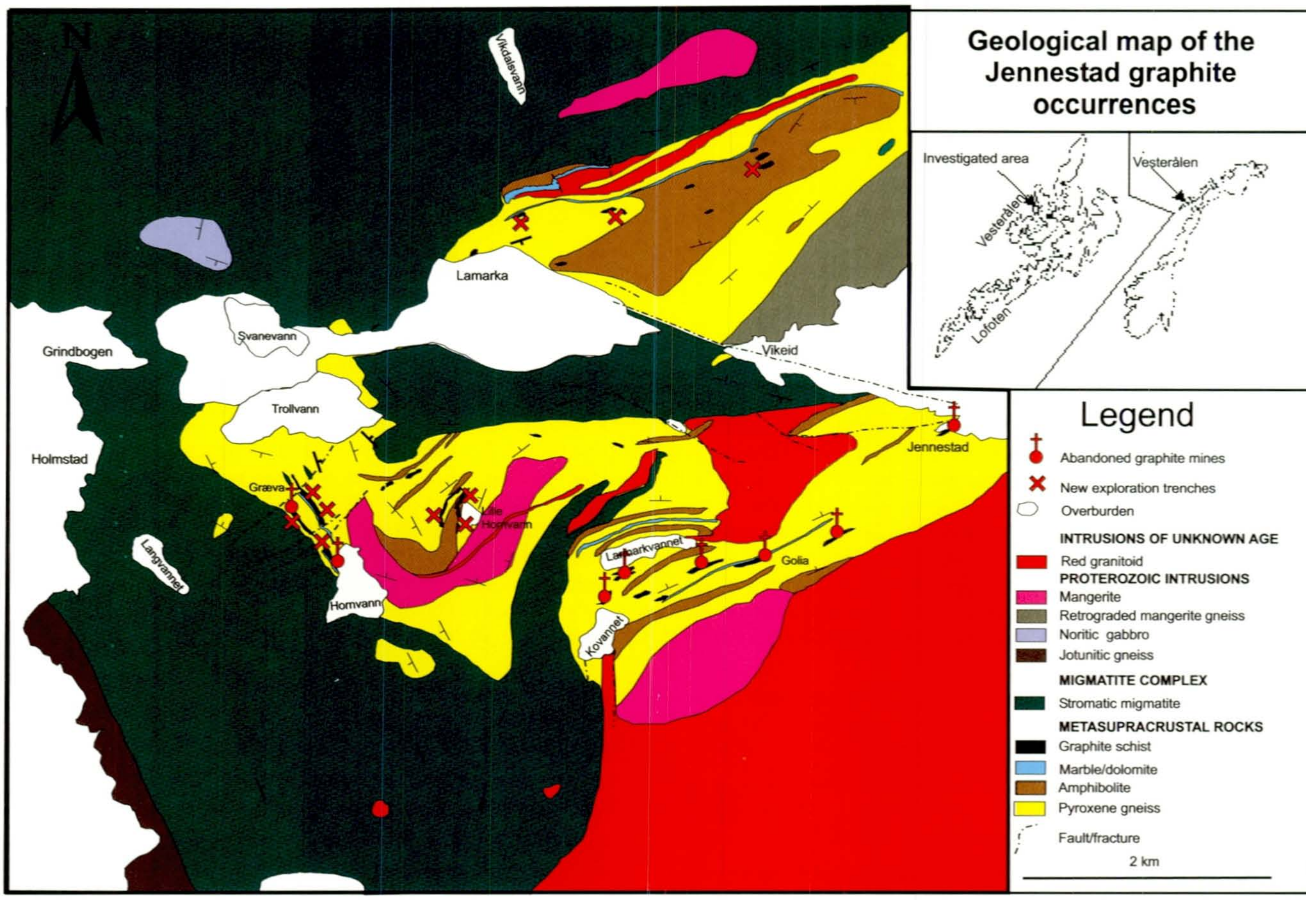

Fig. 1 Geological map of the Jennestad graphite occurrences.

Fig. 2 Photo from Golia mine entrance. The graphite ore is seen just to the right of the mine entrance. Somewhat farther to the right, dolomite marble can be seen. Amphibolite occurs to the left of the entrance.

of active mining during which a total of 770 m of underground adits and drifts were dug, together with several large surface trenches. During this period Heier (1960) carried out a regional geological study, and a number of unpublished reports (Skjeseth 1952, Vokes 1954) described the graphite deposits. In 1987, NGU performed a helicopter geophysical survey of the area, which included 3800 flight km of magnetic, electromagnetic and radiometric measurements (Mogaard 1988). This geophysical survey indicated a 50% increase in the area of potential graphite-bearing rocks. The aero-geophysical measurements were followed up by general mapping, trenching, drilling, ground geophysical measurements and bench scale beneficiation tests (Rønning 1991, 1993, Øzmerih 1991 Gautneb & Tveten 1992, Gautneb 1992; 1993, 1995, Dalsegg 1994).

Geology of the graphite mineralisation

Graphitic schists are part of a suite of high-grade metasupracrustal rocks which also contain marbles, iron formations, amphibolites and pyroxene gneisses. The two last mentioned have been interpreted as representing originally vol-

Table 1. Modal analysis of graphite ore.

Sample	Gra1	Gra2	Gra3	Gra4	Gra5	LH1	LH2
Locality	1	1	1	1	1	2	2
Quartz	2.42	1.60	0.56	0.15	0.97	52.79	30.78
Plagioclase	13.29	1.03	3.21	2.47	3.51	5.79	27.29
K-feldspar	42.75	48.86	49.51	58.02	56.14	6.01	17.93
Graphite	37.46	38.33	39.33	35.49	37.04	30.04	40.16
Biotite	1.21	0	7.25	0	0	0	0
Orthopyroxene	2.87	9.95	0.14	3.70	1.95	2.14	3.89
Others	0	0.23	-	0.15	0.39	3.20	4.48

Locality refers to place name in Fig. 1: 1 = Græva, 2 = Lille Hornvann.

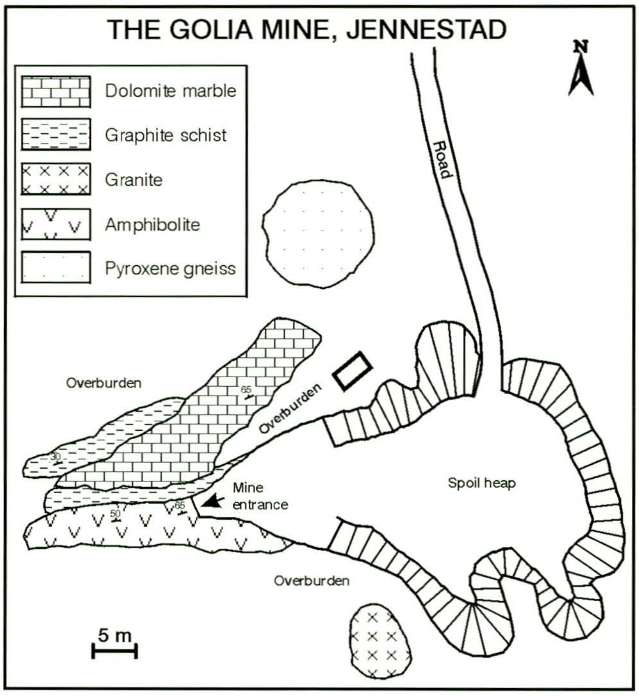

Fig. 3 Sketch map of the Golia mine showing the typical rock association for the graphite occurrences.

canic rocks (Griffin et al. 1978). A good locality illustrating the geological setting of the graphite mineralisation can be seen at the entrance of the abandoned Golia mine (Figs. 2 and 3). The mine adit has been driven parallel to a 3 m-wide graphite schist horizon, with dolomite marble in the hanging wall and amphibolite in the footwall. Pyroxene gneisses and intrusions of younger granites occur associated with these rocks. In the area, marbles, amphibolites and gneisses are always observed in the vicinity of graphite mineralisation, although the exact contacts and mutual relationships between these rocks can rarely be studied, due to overburden. The outlines of the outcropping parts of the orebodies were established by use of electromagnetic and self-potential geophysical measurements. About 30 different graphite bodies of variable size were discovered and some 20 trenches were dug for sampling. The underground extensions of the selected orebodies were studied by means of CP (*mise à la masse*) geophysical measurements (Rønning, 1991, 1993; Dalsegg 1994), and the most promising anomalies were drilled (total 800 m of drillcore). The graphite-bearing bodies occur as elongated lenses commonly situated *en echelon* and following the dominating folds, which trend NE-SW in the area. The greatest thickness of graphite is observed in fold-hinge areas; the graphite-bearing units have been observed with a thickness up to 7-8 metres, but 2-4 metres is more common. Grade and tonnage modelling of some of the largest graphite lenses indicate that they each contain in the order of about 250,000 tons of graphite ore with an average grade of about 20% carbon (Gautneb 1993, 1995).

Petrographic characterisation of the graphite ore

Graphite ores generally occur in strongly foliated rocks in which the foliation is defined by the parallel orientation of graphite flakes. The main gangue minerals are quartz, plagioclase and K-feldspar with subordinate orthopyroxene and biotite (Table. 1, Fig, 4). The graphite grains are situated interstitially between grain boundaries of gangue silicates, and more rarely as inclusions in the silicate minerals. XRD analysis of pure graphite flakes shows that the d_{002} interlayer spacing is 3.40 Å which is characteristic of fully ordered (crystalline) graphite, with a temperature of formation of above 700° C (Landis 1971, Katz 1987).

Carbon content and flake size are the main parameters controlling the quality and price of flake graphite. Many of the important physical properties, e.g. thermal stability, are favoured by coarser grain size. Characterisation of size and morphology of the graphite flakes is therefore important in ore evaluation. A representative selection of thin-sections was therefore selected for microscopic image analysis, This involves the acquisition of digital images of the thin sections

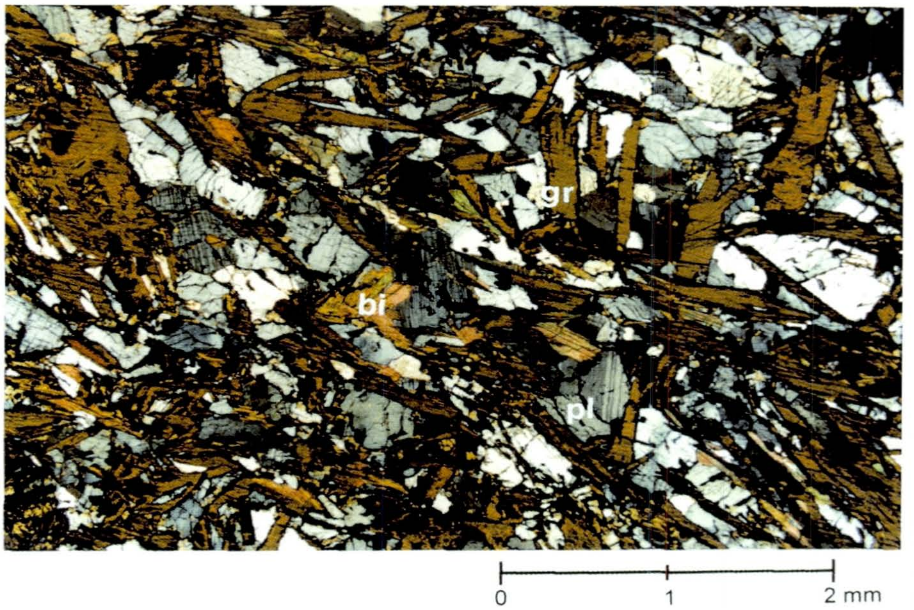

Fig. 4: Photomicrograph of graphite ore. The graphite grains occur along the grain boundary of the silicate minerals. gr = graphite, bi = biotite and pl = plagioclase.

and, after several steps of processing, morphological parameters such as area, perimeter, longest and shortest axes, etc., of mineral grains are recorded. These were automatically recorded for each graphite grain in the thin-sections examined. Aggregate measurements from several thin-sections are usually necessary to give a statistically significant description of the ore. An example of the results of such measurements is shown in Fig. 5 which shows aggregate grain morphological measurements of the ore at Lille Hornvann (Fig. 1), including the samples LH 1 and LH 2 in Table 1. The dominating size of the graphite flakes is 0.01 mm^2 and the mean length of the longest grain axis is 0.3 mm. Most graphite flakes are oblong shaped, but not particularly fibrous, and the ratios between their long and short axes are in the range of 2 to 4 for the majority of the flakes. These results are typical for Jennestad graphite and are also characteristic of a coarse, high-quality, flake graphite ore. The results of the graphite morphological data aquisition are important for establishing appropriate procedures for crushing and liberation procedures as a part of the beneficiation tests.

Table 2. Chemical composition of selected samples of the Jennestad graphite ores. A complete analytical database is available from the senior author on request. All samples were of 1-2 kg size 1 = Lille Hornvann. 2 = Hornvann. 3 = Golia.

Sample	**LH-1**	**LH-2**	**LH-3**	**LH-4**	**90-7B**	**90-7C**	**90-5D**	**90-9A**	**90-9B**	**90-9C**	**90-9D**
Locality		1	1	1	2	2	2	2	3	3	3
SiO_2	55.29	49.37	53.49	38.63	36.37	37.87	36.26	39.49	37.47	31.8	30.86
Al_2O_3	7.94	4.66	6.26	5.39	10.1	11.02	10.48	8.13	10.56	9.47	8.93
$Fe_2O_3^{tot}$	4.42	7.13	6.13	12.97	5.16	2.43	3.20	3.97	1.24	6.10	4.65
TiO_2	0.68	0.22	0.31	0.16	0.55	0.57	0.45	0.36	0.37	0.48	0.58
MgO	2.07	7.23	4.75	8.65	0.93	0.45	0.81	6.07	0.80	1.28	1.53
CaO	3.50	6.01	5.18	11.72	1.38	1.41	3.71	11.36	1.99	2.47	2.78
Na_2O	2.23	0.87	1.21	1.37	1.60	1.51	2.75	2.01	1.63	1.93	2.29
K_2O	0.94	1.58	1.68	0.35	4.15	5.19	0.42	0.18	5.34	2.98	1.81
MnO	0.03	0.24	0.13	0.17	0.04	0.02	0.05	0.19	0.03	0.04	0.05
P_2O_5	0.41	0.08	0.36	0.45	0.05	0.08	0.05	0.07	0.03	0.06	0.05
C	18.02	18.18	14.79	14.52	35.86	36.88	39.65	26.22	37.23	39.23	44.31
S	2.70	1.77	2.07	6.65	0	0	1.95	0	0	1.11	1.00
SUM	98.23	97.34	96.36	101.03	96.19	97.43	99.78	98.05	96.69	96.95	98.84

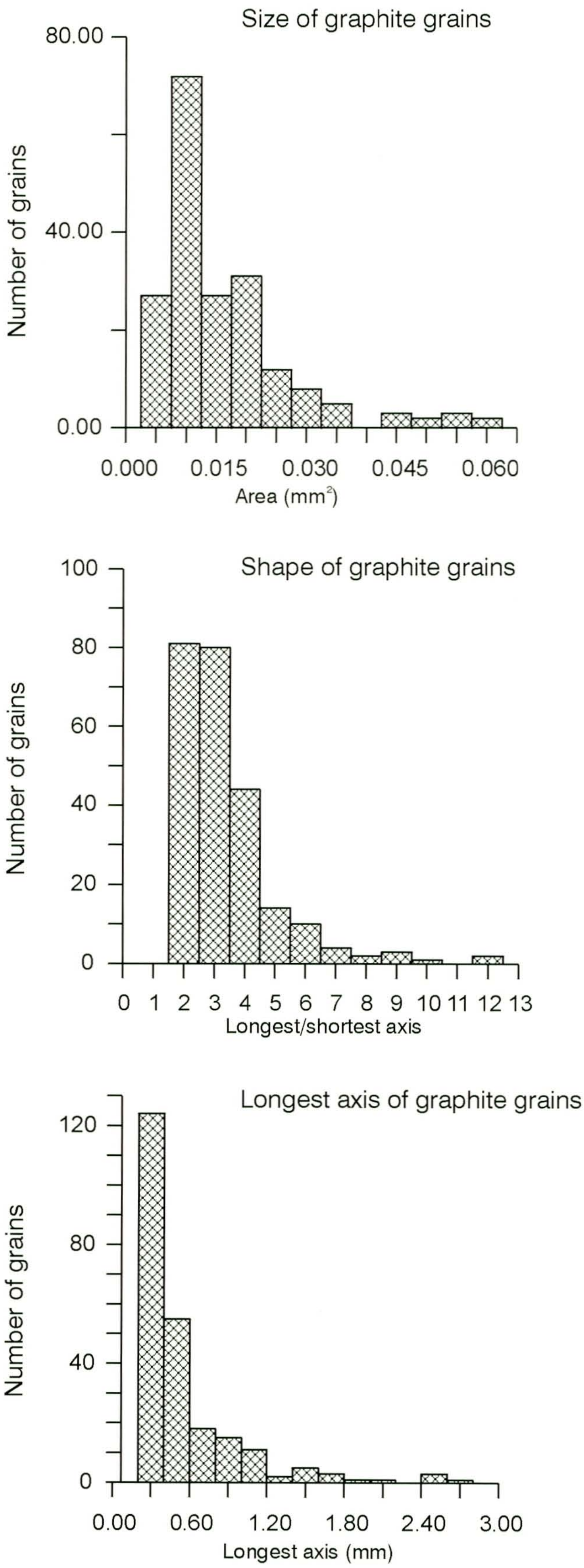

Fig 5: Histograms showing the morphological variation of the graphite grains in thin-section. Data were collected by digital image analysis using the KS 300 system. The data represent aggregate measurements of several thin-sections, and are believed to be representative of the Jennestad graphite ore

Chemical composition of the graphite ore

The graphite ore was crushed, milled and analysed for major elements using XRF; while the carbon content was analysed with a LECO gas flow carbon analyser. Representative analyses of graphite ore are shown in Table 2. The carbon content varies from 18 to 44 %. If the analyses are recalculated on a 100% volatile-free basis, the ore would have a compositional variation comparable to that of arenites and mudrocks (Blatt et al. 1980). The variation in the content of clay minerals in the initial sediments was probably large, as seen from the variation in K_2O content.

Beneficiation of the graphite ore

A series of crushing, milling and bench-scale flotation tests was performed on a 300 kg sample of graphite ore (Øzmerih 1991). The head sample had a grade of 17.4% C. Following crushing and milling, an initial step of flotation was performed where about 75% of the head sample was removed as a rougher tailing. The rougher concentrate went through a series of gentle regrinding and cleaning steps to increase the grade and to obtain as large a proportion of coarser flakes as possible. MIBC (metylisobutylcarbinol) was used as a frother and kerosene and Flotol B as collectors.

The combined results from a series of flotation tests including several cleaning steps can be summarised as follows. To produce a concentrate of about 90% C, the recovery was found to be around 75 %. For a slightly lower concentrate grade (88-89%) the recovery is higher (82%). A maximum grade of about 97% C was found in the final concentrate of the +208 µm size fraction. These results show that the Jennestad ore can be readily beneficiated and that concentrates of a quality comparable with commercial grades can be produced. Most likely the recovery can be improved if the beneficiation procedure is optimised on an industrial scale. The various beneficiation tests are summarised in Tables 3 and 4.

Graphite formation

Somewhat simplified, there are basically three different processes leading to the formation of economic graphite deposits (Harben & Kuzvart 1996):

1) Contact metamorphism of coal deposits: such deposits are usually of low quality and produce low-priced products.
2) Epigenetic graphite deposits. The formation of these deposits is assumed to involve, among others, the following reactions:

$$C + H_2O = CO + H_2 \quad (1)$$

$$2CO = C + CO_2 \quad (2)$$

It is believed, for example, that this process was active during the formation of the Sri Lankan type of vein graphite deposits (Weis et al. 1981, Rumble & Hoering 1986, Katz 1987, Santosh & Wada 1989, Ulmer & Luth 1991).

Table 3. Summary of bench-scale flotation tests of Jennestad graphite. The benficiation test consisted of an initial step of rougher flotation and several steps of cleaner flotation combined with gentle regrinding. MIBC was used as a frother, and kerosene and Flotol B were used as collectors. The grade and recovery results are shown in Table 4. (Data from Øzmerih 1991).

	Flotation test no.										
Procedure	1	2	3	4	5	6	7	8	9	10-13	14-17
Mill time (min.)	30	30	25	35	30	35	40	25	40	35	35
Rough flot.	x	x	x	x	x	x	x	x	x	x	x
MICH cc/t	200	200	200	200	150	150	200			200	
Kerosene	200	200	200	200	100	100	150	200	150	150	150
Flotol B								200	200		200
Regrind 1 (min.)					15	15	15		15	15	15
Cleaner flot. 1		x	x	x	x	x	x	x	x	x	x
MIBC cc/t										25	
Kerosne										25	25
Flotol B											25
Regrind 2										15	15
Cleaner flot. 2		x	x	x	x	x	x	x	x	x	x
MICB cc/t		100		50	25	15				10	
Kerosene		10		50	15	15				10	
Cleaner flot. 3						x	x		x	x	x
MICB cc/t						25	15			10	
Kerosene						15	15			10	10
Flotol B											10
Cleaner flot. 4							x			x	x
MICB cc/t										15	
Kerosene										15	15
Flotol B											15

Table 4. Grade and recovery of graphite concentrates from flotation of Jennestad ore. (Data from Øzmerih 1991).

			Grain size (micron) %					
Product	Grade % Carbon	Recovery	+208	208-147	147-104	104-74	-74	Flot.test no.
Head sample	17.40							
Rough conc.	59.06	86.56						1
Cleaner conc. 1	79.48	58.88						2
Cleaner conc. 2	60.85	72.20						3
Cleaner conc. 2	88.20	36.86						4
Cleaner conc. 1+2	84.05	62.18						5
Cleaner conc. 2+3	88.29	79.12	10.04	32.53			57.43	6
Cleaner conc. 2+3+4	88.29	79.12	9.24	29.32			61.44	7
Cleaner conc. 2	69.24	63.83						8
Cleaner conc. 3	88.38	80.06						9
Cleaner conc. 2+3+4	89.17	80.58	9.32	13.98	14.98	19.68	42.04	10-13
Cleaner conc. 2+3+4	88.61	81.91	5.76	11.52	14.60	20.72	47.40	14-17

From an industrial perspective, the graphite in these epigenetic deposits is classified as 'vein' or 'lump' type.

3) Syngenetic flake graphite deposits. The formation of these deposits involves the alteration of organic matter to graphite during metamorphism. From studies of coal and anthracites, the operating processes have been shown to be highly complex (Bonijoly et al. 1982). The kinetics of flake graphite formation have shown to be controlled or influenced by the following factors:
   a) The nature of the hydrocarbon precursors. Aromatic compounds with existing C-H rings are more easily graphitised than aliphatic (C-H strings) compounds (Buseck & Huang 1985).
   d) The partial pressures of CO_2, CO, CH_4, H_2O and H_2.
   e) The regional P-T conditions. Diessel et al. (1978) showed that coal and graphite coexist in the P-T range of 3kbar/255°C - 5.5kbar/335°C. All organic matter is converted to graphite before the epidote isograd at 6.3kbar/390°C.

All the Norwegian, as well as most of the world's, operating graphite deposits belong to this third type. In the Jennestad area, we believe that graphite is syngenetic and we have seen no evidence of epigenetic graphite. However, migration of CO_2-rich fluids similar to those described by Baker & Fallick (1988) has been shown to be associated with epigenitic graphite formation elsewhere (Galbreath et al. 1988, Duke et al. 1990, Santosh & Wada 1993). The influence of CO_2 infiltration on graphite formation in the Jennestad area was beyond the scope of our exploration work, but it could be a challenging study for the future. The coexistence of carbonate rocks and graphite schists probably shows that the schist initially represented an organic-rich sediment, and the orgasnic material was converted to graphite during the granulite-facies metamorphism.

Summary and conclusions

The graphite occurrences of the Jennestad area are associated with marbles, amphibolites and pyroxene gneisses, intruded by different charnockitic rocks and granites. The graphite schists contain up to 40% C and occur as lenses situated *en echelon*, following the main fold structures in the area. During the investigations, some 30 different graphite-bearing bodies have been discovered. The largest have been modelled to contain about 250,000 tonnes each, with an average grade of 20% C. In thin-section, the ore comprises the following gangue minerals: quartz, plagioclase, K-feldspar, biotite and orthopyroxene. Image analysis of thin-sections shows that the ore has a dominant flake size of 0.01 mm^2 and a ratio between the longest and shortest grain axis in the order of 2 to 3. Bench-scale flotation tests show that it is possible to obtain a maximum grade of 97% C, with a recovery of 89%. We believe that the graphite ore formed as a result of granulite facies metamorphism of organic-rich sediments.

Acknowledgements

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