

Platinum-group minerals in the Lillefjellklumpen nickel–copper deposit, Nord-Trøndelag, Norway

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The Lillefjellklumpen Ni–Cu deposit occurs in the Gjersvik Nappe in the Upper Allochthon of the central Norwegian Caledonides. The area has been interpreted by earlier workers as part of an ensimatic island arc of Lower to Middle Ordovician age. The mineralization is associated with a small body of metagabbro occurring at the contact between gabbro and greenstone. The massive sulphide body consists of pyrrhotite, pyrite, pentlandite, chalcopyrite, magnetite and silicates. The average Ni content is 3.6% and the Cu content is 1.2%. The total platinum group element (PGE) content is 5.6 ppm, Pt (1.8 ppm) and Pd (3.1 ppm) accounting for 4.9 ppm. The Pt + Pd/Ru + Ir + Os ratio is 9.8, within the range reported for gabbro related deposits. The average chondrite normalized PGE pattern is similar to that of the Kanichee deposit although Lillefjellklumpen has lower absolute PGE values. Merenskyite is the main platinum-group mineral (PGM), but sperrylite, moncheite and temagamite (?) also occur. The PGM occur as small (<20 μm) inclusions in pyrrhotite and chalcopyrite as well as on grain boundaries. The Lillefjellklumpen deposit probably represents a magmatic sulphide segregation related to a layer 3 (ensimatic) gabbro body later remobilized during a tectonic event and redeposited in its present position.

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The Lillefjellklumpen Ni–Cu deposit is located in the Grong area, 5 km north of the Skorovas Mine and 200 km NE of Trondheim. The high PGE content of the deposit has been known since Foslie & Johnson Høst (1932), during a noble metal investigation on ores from the Grong area, found Lillefjellklumpen massive sulphides to contain 4 ppm PGE. As no PGE could be found on optical inspection, it was assumed that most of the PGE probably occurred in solid solution within the chalcopyrite lattice. The aim of this investigation was, with the help of the electron microprobe, to try to solve the problem of PGE occurrence and to identify any PGM that might be present. The electron microprobe was chosen because the PGE, if present, obviously had to occur as very small grains and, for identification purposes, as the optical properties of many of the minerals in question are very similar.

The geology of the area has been described by Halls et al. (1977) and by Reinsbakken (1980). The Lillefjellklumpen deposit is situated in the greenstone sequence of the Gjersvik Nappe (Fig. 1), which constitutes the low-grade, uppermost unit of the Seve–Køli Nappe Complex. In the west structurally above the Gjersvik Nappe lie the higher grade rocks of the Helgeland Nappe

Complex. To the east are lower tectonic units of the Køli Nappe sequence. To the north and south the Grong area is limited respectively by the Børgefjell basement window and the Grong–Olden basement culmination. The main rocks of the Gjersvik Nappe are gabbro, diorite and trondhjemitic plutons and a sequence of sub-marine volcanics. The igneous complex is overlain by polymict conglomerates and flysch sediments. According to Reinsbakken (1980) the eruptive sequence is interpreted as an ensimatic island arc, formed to the west of the Fennoscandian continent probably during Lower to Middle Ordovician times, and thrust southeastward onto the Fennoscandian continent during the Silurian.

The Lillefjellklumpen deposit occurs at the boundary between a small metagabbro body and greenstone. Three small gabbros are found to crop out in the vicinity of the deposit (Palmer 1972). The metagabbros are surrounded by a group of greenstones with dykes of quartz keratophyre. The greenstones plot in the OFB and LKT fields of Ti–Zr–Y diagrams and show flat, MORB-like, chondrite-normalized REE patterns (Grønlie & Haugen, in prep.). The REE patterns show a striking similarity to the massive Storøya lava flows of the Leka ophiolite (Prestvik 1985).

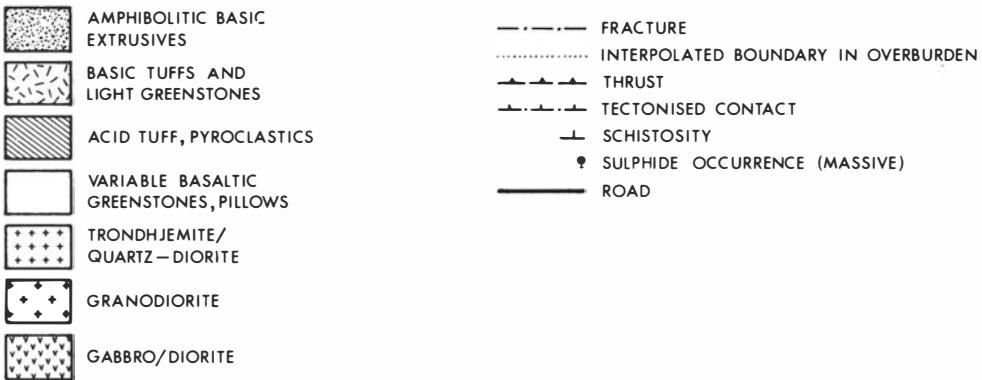
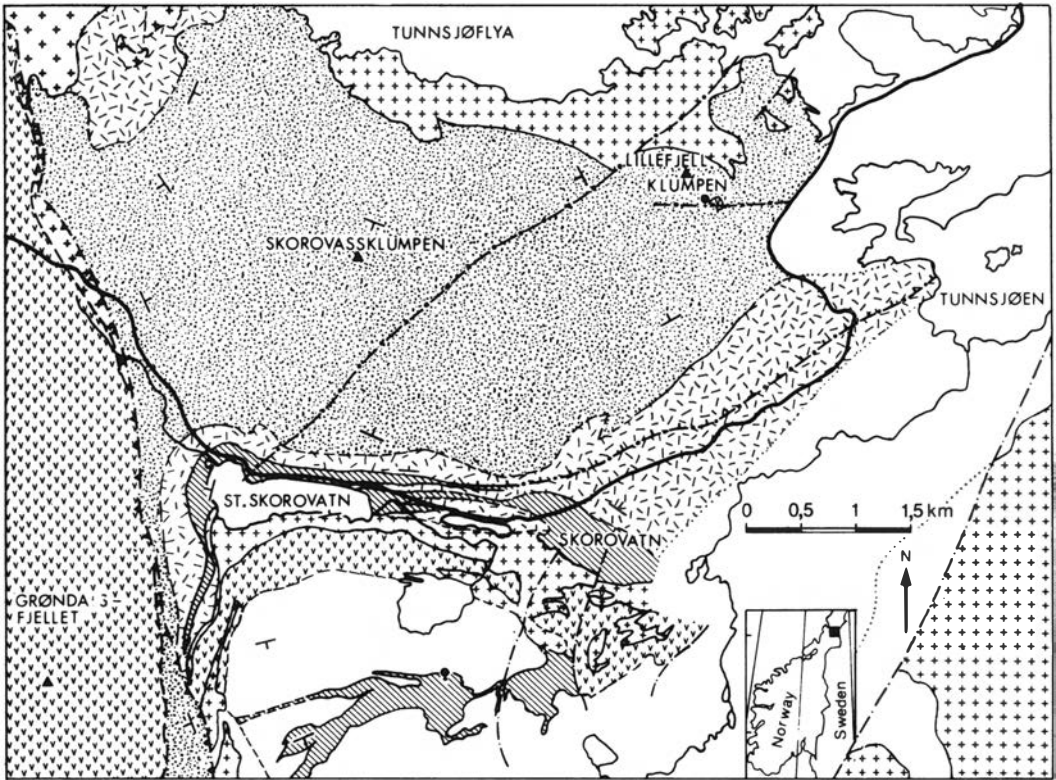


Fig. 1. Simplified geological map of the Lillefjellklumpen-Skorovatn area, based on Halls et al. (1977), Kollung (1979) and A. Reinsbakken (pers. comm. 1984).

Ore geology

The Lillefjellklumpen mineralization consists of an irregular lens of massive sulphides, trending east-west and dipping steeply to the north. The length of the massive sulphide ore is 20 m, and it is up to 2 m wide. The contact against the hanging-

wall metavolcanics and the foot-wall metagabbro is always sharp. There are some small angular fragments of greenstone in the ore. Except for the immediate contact zone the sulphide lens is nearly free from gangue minerals. The average Ni content of massive sulphide is 3.6% and the

Table 1. Content of Cu, Ni, S (%) and PGE + Au (ppb) in massive sulphide ore.

	Cu	Ni	S	Pt	Pd	Rh	Ru	Ir	Os	Au	Sum PGE + Au
X	1.2	3.6	36.2	1799	3068	214	189	170	139	219	5798
SD	0.9	0.7	2.1	1856	1156	99	100	86	76	445	
N	15	15	15	18	18	10	10	10	10	18	
C1C				1020	545	200	690	540	514	152	

C1C = C1-Chondrites, data from Naldrett (1982).

Cu/Cu + Ni = 0.25 Pt + Pd/Ru + Ir + Os = 9.77.

Cu content is 1.2% (Table 1), in good agreement with figures published by Foslie & Johnson Høst (1932); consequently no new modal analyses have been done. Foslie & Johnson Høst estimated the modal composition to be: pyrrhotite (64%), pyrite (15%), pentlandite (12%), chalcopyrite (3%), magnetite (3%) and silicates (2%). There are two distinct ore types, although pyrrhotite is always the most abundant mineral.

1. Pyrrhotite ore, the dominant ore type, consists of pyrrhotite, pentlandite and magnetite. Pyrite and chalcopyrite are not abundant, although pyrite sometimes occurs as rounded grains up to 5 mm across in a groundmass of the other sulphides.
2. Pyrrhotite–chalcopyrite ore occurs less frequently than the pyrrhotite ore. Anhydral chalcopyrite makes up a significant portion of the ground-mass or occurs as a network of veins. This ore type seems to predominate at the margins of the deposit.

The sulphide mineralogy has been described by Foslie & Johnson Høst (1932) and recently by Palmer (1972).

Platinum-group minerals

Foslie & Johnson Høst (1932) found no discrete PGM with conventional optical methods, but Palmer (1972) recognized one grain of a PGM enclosed in pyrrhotite. The observed PGM, in decreasing order of abundance, are:

Merenskyite (ideal formula PdTe₂)

Sperrylite (PtAs₂)

Moncheite (ideal formula PtTe₂)

Mercurian palladium telluride (temagamite (?) Pd₃HgTe₃)

Merenskyite, ideal PdTe₂, general (Pd, Pt, Ni)(Te, Bi)₂ is by far the most abundant PGM. The analysed grains are all platinian–bismuthian merenskyite (Fig. 2). The mineral usually occurs as small (<20 μm) hexagonal or rounded grains. The most frequent mode of occurrence is as inclusions in pyrrhotite (Fig. 3) on grain boundaries in pyrrhotite aggregates, or on boundaries between pyrrhotite and chalcopyrite grains. Merenskyite also occurs embedded in late chalcopyrite replacing pyrrhotite (Fig. 4) or exsolved from chalcopyrite (Fig. 3). All observed grains, except one containing a small inclusion of temagamite (?) are apparently homogeneous. Merenskyite forms a complete solid solution series with moncheite (Hoffman & MacLean 1976). Data from Lillefjellklumpen illustrate this (Fig. 2).

Sperrylite, PtAs₂, occurs less frequently than merenskyite. The mineral has previously been identified in this ore by Hysingjord (Neumann 1985). Sperrylite, generally euhedral, is commonly found enclosed in chalcopyrite, but also occurs as inclusions in pyrrhotite.

Moncheite, ideal PtTe₂, general (Pt, Pd, Ni)(Te, Bi)₂. Only two grains have been identified, only one being large enough for microanalysis. This 10 μm grain occurred embedded in silicates replacing chalcopyrite in type 2 ore. The other, being only 5 μm, occurred at the contact between two pentlandite grains.

Mercurian palladium telluride, occurring as a <5 μm inclusion in merenskyite, again enclosed in pyrrhotite, gave an electron microprobe analysis close to (Pd, Hg)Te. This mineral is probably temagamite (Pd₃HgTe₃). Previously, Buchan (1981) reported an occurrence of kotulskite intergrown with a Pd–Hg–Te mineral, possibly temagamite, from the Fæøy deposit, southwest Norway.

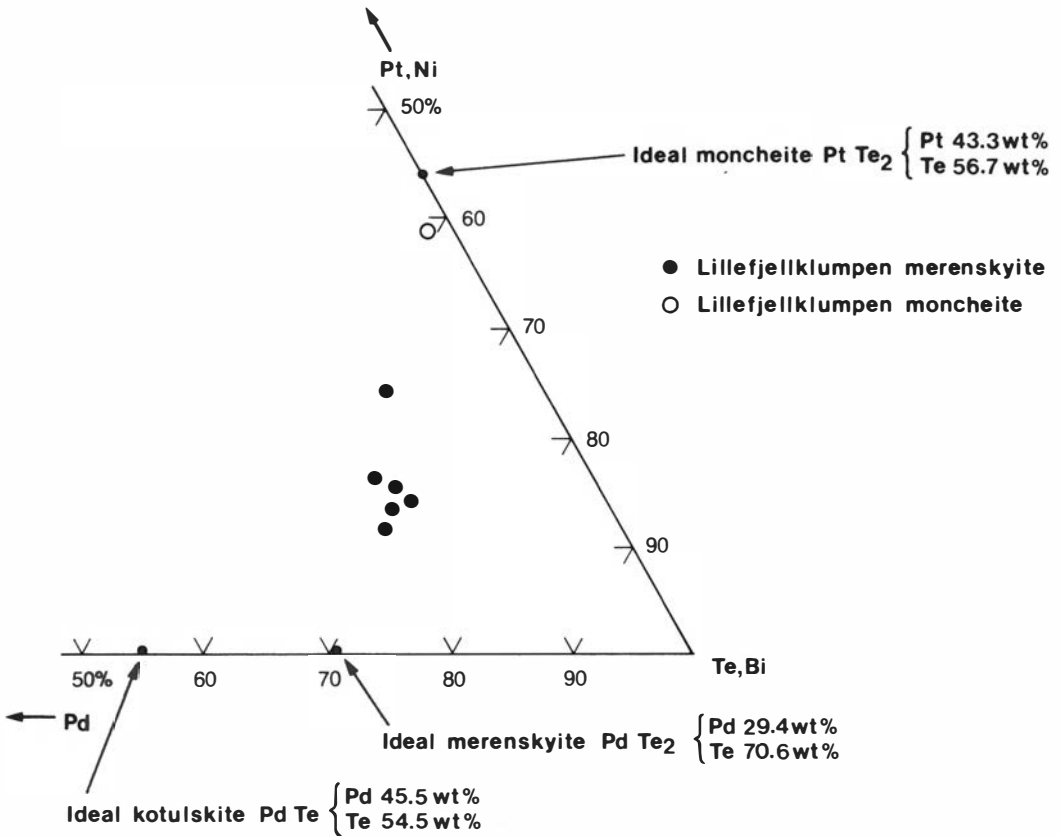


Fig. 2. Compositional variation in Lillefjellklumpen merenskyite and moncheite compared with the ideal mineral compositions.

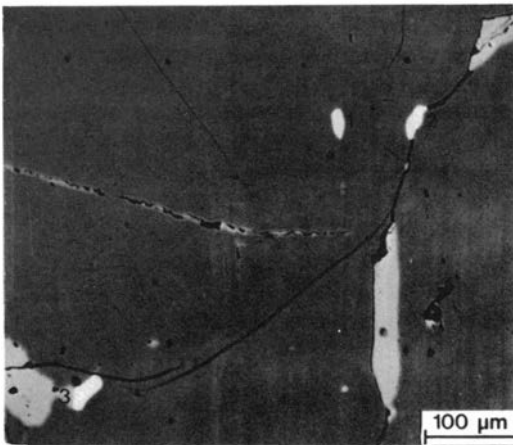


Fig. 3. Three merenskyite grains (white) occurring as: (1) Inclusion in pyrrhotite (dark grey); (2) on grain boundary pyrrhotite/pyrrhotite, and (3) exsolved from chalcopyrite (grey). Backscatter electron image.

Platinum-group element chemistry

Eighteen samples of massive sulphide ore have been analysed for PGE and Au by neutron activation analyses (X-Ray Assay and Chemex Labs., Canada). Cu, Ni and S have been analysed at the Geological Survey of Norway by atomic absorption and fire-assay. The analyses show an average total content of 5.8 ppm PGE + Au, Pd and Pt accounting for 4.9 ppm (Table 1). It is evident (Table 2) that the analyses show a bimodal distribution of Pt and Pd, there being one dominant group where Pd ≥ Pt and one group where Pt > Pd. This roughly reflects the amount of chalcopyrite in the original ore samples, the Pd ≥ Pt group corresponding with the pyrrhotite (type 1) ore and the Pt > Pd group corresponding with the pyrrhotite–chalcopyrite (type 2) ore as defined in a previous section.

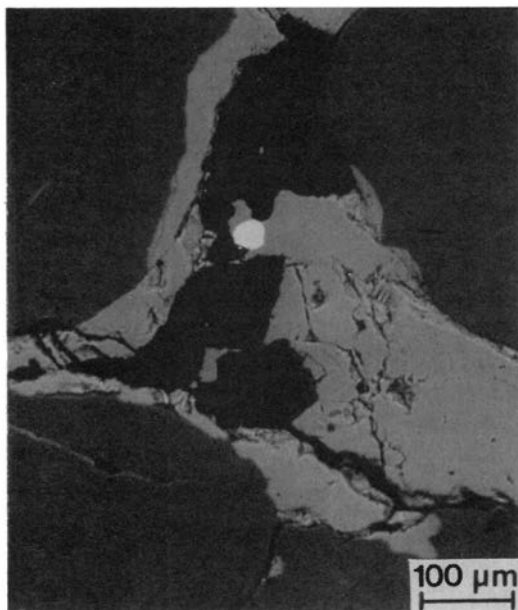


Fig. 4. Chalcopyrite (grey) containing euhedral merenskyite (white) replacing pyrrhotite (dark grey). Backscatter electron image.

This is contrary to what one finds at Levack West, Sudbury, where the Cu-rich (28%) stringer ores are more enriched in Pd than Pt, and total PGE-contents are high (Hoffman et al. 1979).

As at Strathcona, the Cu-rich (32%) ore zone is more enriched in Pt than Pd, but the total PGE contents are very low. Cu-rich stringers analogous to those at Levack West, however, were not investigated (Naldrett et al. 1982).

The Levack West stringers do, however, contain more than 20 times as much Cu as Lillefjellklumpen type 2 ore and the ores are therefore not readily comparable. The mechanism of thermal diffusion explaining metal zoning at Levack, favoured by Hoffman et al. (1979), cannot have been operative to the same degree at Lillefjellklumpen, perhaps because of this orebody's small size and tectonic emplacement (see Discussion).

The chondrite normalized PGE pattern (Fig. 5) does show a close similarity to the main trend of the Sudbury ores, suggesting a general genetic similarity.

Discussion

Four main possible origins are considered for the mineralization:

1. The sulphides and PGE represent a magmatic segregation, having settled out of the magma in their present position.
2. The sulphides and PGE represent a magmatic segregation, but settled out of the magma elsewhere and were remobilized during tectonic disturbances, possibly while the sulphides were still fluid.
3. The sulphides and PGE have been mobilized from a lower level in the oceanic crust, the simatic foundation of the Gjersvik island arc, by hydrothermal activity, and deposited in a zone of dilation.
4. The deposit is volcanic exhalative, the sulphides and PGE being leached out of the host rocks by circulatory brines discharged through sea-floor fumaroles and precipitated on the sea floor.

Considering *alternative 1*, this represents the traditional interpretation of the origin of massive Ni-Cu sulphide ores. Cabri & Laflamme (1976) in a study of PGE behaviour in Sudbury ores, maintain that the Pd and Pt bismuth-tellurides concentrated in a Cu-rich liquid fractionated relative to monosulphide solid solution (*mss*), following crystallization of *mss* and magnetite. The subsequent crystallization of intermediate solid solution (*iss*) with a coexisting liquid rich in Pd-Pt-Te-Bi-Sb on further cooling produced the PGM now observed in the ores. Melting temperatures for PdTe₂ (740°C) and PtTe₂ (825–900°C) indicate that they would be liquid when *iss* crystallized out of a Cu-rich sulphide melt. At Lillefjellklumpen much of the Pd-Pt bismuth-tellurides, arsenides and Au have fractionated into a Cu-rich liquid, as sperrylite, electrum and much merenskyite are either inclusions in, or found bordering on, chalcopyrite grains. The other Pd-Pt bismuth-tellurides occur either enclosed in pyrrhotite or on grain boundaries in pyrrhotite; this could be interpreted as a trapping of most of the Pd-Pt-Te-Bi elements in the *mss* structure due to rapid cooling of the sulphides. This could also explain why merenskyite and moncheite are the only Pd-Pt bismuth-tellurides present. Because of later metamorphism the sulphides, however, show no textural evidence of the rapid cooling of the orebody.

Counter to a straightforward magmatic origin is the fact that the gabbro body with which the mineralization is now associated is very small (Fig. 1), and it is unlikely that it could have hosted

Table 2a and 2b. Content of Cu, Ni, S (%) and PGE + Au (ppb) in type 1 and type 2 ore.

Table 2a. Type 1 Ore, Pd \gg Pt.

Sample no.	Cu	Ni	S	Pt	Pd	Rh	Ru	Ir	Os	Au
8501	0.30	2.53	39.2	290	2900	240	190	190	220	18
8502	1.29	3.07	37.0	710	3100	330	330	290	250	54
8504	1.25	3.52	33.2	580	4100	50	30	30	23	120
8505	0.15	4.33	36.5	460	4600	270	220	210	170	8
8507	0.53	4.04	34.8	1500	3300	180	180	160	110	460
8508	2.26	3.09	39.8	1500	2500	230	210	180	120	300
8510	0.48	4.02	35.6	2100	3400	200	190	180	110	140
SF10	0.22	4.00	37.9	200	4200					<10
1179	—	—	—	<100	4700					<10
1187	—	—	—	1180	3230					1910
1209	—	—	—	455	3600					<10
\bar{X}	0.8	3.6	36.8	820	3603	214	193	177	143	275
SD	0.7	0.6	2.2	654	710	87	88	77	77	562

Table 2b. Type 2 Ore, Pt > Pd.

Sample no.	Cu	Ni	S	Pt	Pd	Rh	Ru	Ir	Os	Au
8503	0.53	4.74	36.2	4100	2200	310	280	240	170	15
8506	0.54	2.98	36.5	5900	2900	280	250	210	190	9
8509	1.26	3.46	32.8	5500	4000	45	<21	14	26	350
SF01	2.10	3.10	37.1	1500	1500					250
SF03	2.85	3.01	33.0	700	410					60
SF05	1.11	4.38	37.1	1330	1250					<10
SF07	2.82	3.07	36.0	4330	3330					225
\bar{X}	1.6	3.5	35.5	3337	2227	212	180	155	129	131
SD	1.0	0.7	1.8	2128	1265	145	148	123	89	142

the amount of sulphides in question. It is also unlikely that the sulphides originated at this high level position in the body and were deposited together with the volcanic extrusives, the gabbroic (layer 3; Tarling 1981) and ultramafic layers at deeper levels being a more probable setting for a deposit with this Ni and Cu content.

Alternative 2, that the ore is of magmatic origin, but later remobilized by a tectonic disturbance and brought to its present position, possibly while still fluid, seems to be in agreement with mineralogical and textural evidence, and is also able to explain the orebody's present location. As mentioned previously, the trapping of many of the Pd–Pt–Bi–Te elements in the *mss* structure indicates a rapid cooling of the sulphides, possibly after the emplacement of the sulphides in their present position by a tectonic event.

Considering *alternative 3*, the chondrite-normalized PGE and Au pattern (Fig. 5) show that Lillefjellklumpen exhibits a positive slope rather similar to the Sudbury deposits and almost identical with the pattern for the Kanichee deposit which occurs at the base of a tholeiitic layered intrusion (Naldrett 1982). The Pt + Pd/Ru + Ir + Os ratio, which is dependent on this ratio in the silicate magma at time of saturation is 9.8, within the range reported for gabbro-related deposits (Naldrett 1982).

Several ophiolites have recently been investigated with respect to PGE content in rocks and sulphide deposits. Economou & Naldrett (1984) studied the sulphide bodies occurring in ultramafic ophiolitic rocks at Eretria. They suggested that the sulphides and PGE were precipitated by hydrothermal fluids, possibly those responsible

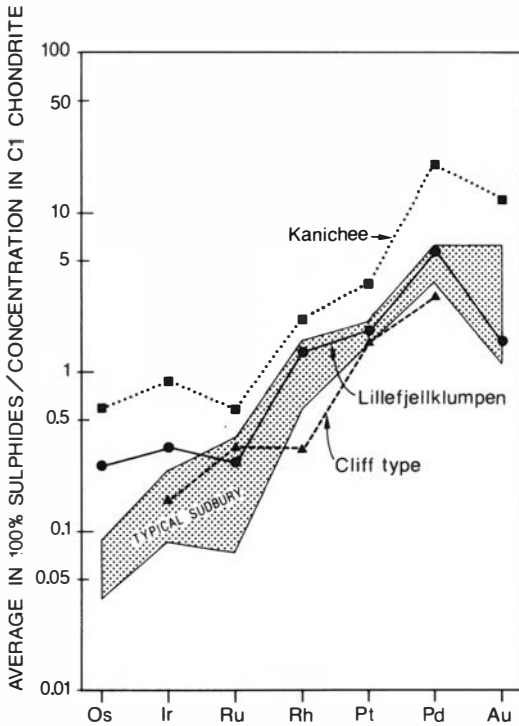


Fig. 5. Chondrite-normalized PGE and Au concentrations for Lillefjellklumpen compared with other gabbro related deposits (Naldrett 1982) and the Cliff deposit (Gunn et al. 1985).

for the serpentinization of the host rocks, and that the source of the metals could have been the ultramafic rocks themselves. In the Unst ophiolite, the Cliff deposit (Gunn et al. 1985) is dominated by Pd and Pt and has a PGE pattern with a positive slope (Fig. 5), being similar to those of the Sudbury deposits, or Lillefjellklumpen. They interpret the Cliff PGM which occur in close association with Ni sulphides and arsenides as being hydrothermal in origin, most likely connected with serpentinization. Fleet et al. (1977) and Fleet & MacRae (1983) have argued that most Ni-Cu deposits have been precipitated by hot aqueous fluids. Using Ir and Pd values as discriminants between different types of Ni-Cu deposits (Keays et al., 1982), the Lillefjellklumpen values for Ir and Pd place this deposit on the trend line for magmatic Ni-Cu deposits (Fig. 6), distinctly removed from hydrothermal or volcanic exhalative deposits, which are very low in Ir. Mineralogically, hydrothermal deposits tend to be highly copper-enriched, like the Eretria deposit (Economou & Naldrett 1984), which has

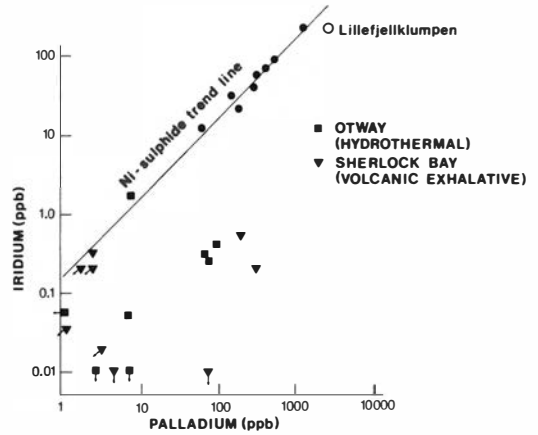


Fig. 6. Pd and Ir contents of major Ni-sulphide deposits of western Australia (Keays et al. 1982) define a Ni-sulphide trend line, close to which analyses from the Lillefjellklumpen deposit plot.

a Cu/Cu + Ni ratio of 0.78 or the New Rambler Mine (McCallum et al. 1976), where Pd and Pt are associated with copper sulphides occurring in shear zones. The Eretria deposit has a chondrite-normalized PGE pattern distinctly different from the Lillefjellklumpen deposit, the Eretria pattern being flat with a pronounced negative Pd anomaly.

Alternative 4, that the metals were leached out of the gabbro and greenstone in the vicinity of the deposit by a hydrothermal cell driven by the igneous activity in the island-arc system, is difficult to evaluate unless one knows the content of PGE in the greenstones and gabbros likely to be affected by the hydrothermal system. Generally MORB have extremely low contents of PGE (Hertogen et al. 1980), and the volcanic exhalative model does not seem to be a likely alternative. Keays et al. (1982) showed that the volcanic exhalative Sherlock Bay Ni-Cu deposit plotted well off the Ir-Ni and Ir-Pd trend line for the other magmatic Ni-Cu deposits on which Lillefjellklumpen plots.

Conclusions

The Lillefjellklumpen deposit probably represents a magmatic sulphide segregation related to an ensimatic gabbro body later remobilized during a tectonic event and redeposited in its present position. The chondrite-normalized PGE

and Au pattern (Fig. 5) shows similarity to the Sudbury deposits and to gabbro-related deposits in general.

Textural and mineralogical evidence indicates that the sulphides could have been fluid when subject to the tectonic event. The orebody was later subject to a small-scale mobilization of silicates and chalcopyrite, particularly affecting the deposit margins, possibly related to the metamorphism of the host rocks.

The main platinum-group mineral is merenskyite, followed by sperrylite and moncheite. Lillefjellklumpen is the only Ni–Cu–PGE deposit described in which merenskyite is the dominant PGM, a fact that could be due to rapid cooling of the liquid sulphides after emplacement. The PGE content, dominated by Pd, is also consistent with a magmatic origin.

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