

THE GEOLOGY OF THE VAKKERLIEN NICKEL PROSPECT, KVIKNE, NORWAY

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The Vakkerlien nickel prospect is a small sulfide mineralized zone centrally located within a metagabbro body. The body, and a second barren metagabbro, are elongated parallel to the regional lineation. Both are compositionally zoned across the bodies from ultramafic to metagabbro. The composition of the bodies suggests that they may represent a differentiated mafic sheet, the sheet being disrupted into its present form during regional deformation. Mineral chemistry reveals a complex, possibly two phase, metamorphic history. Three sulfide types are distinguished, all containing the same sulfide phases in varying proportions. The sulfide composition suggests that the sulfides have suffered some metamorphic re-equilibration. The mineralized zone is considered to be partially in an original magmatic position with some additional concentration during deformation.

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Introduction

The Vakkerlien nickel prospect is situated 6 km south of the village of Kvikne in central Norway (Fig. 1). The body was discovered from a reported sulfide showing by A/S Sulfidmalm in 1975. Geophysical investigations and subsequent drilling delineated a mineralized zone over 1250 metres long with an elliptical cross-section containing approximately 400,000 metric tons of 1 % Ni and 0.4 % Cu. The mineralized zone is centrally located within a similarly elongate body of metagabbro, which plunges gently southeastwards parallel to the regional lineation. The metagabbro body is cut off at its southern end by a later trondhjemitic intrusion and no major extension has been located further

to the south. A second, barren metagabbro body outcrops south of the southeastern end of the main metagabbro (Fig. 2), lying parallel to the main body, with marginally larger dimensions.

The Kvikne area has had a long history of base metal exploration and exploitation from massive Cu-Zn sulfide deposits at the old Kvikne mines (Nilson and Mukherjee, 1972) and at Røstvangen (Rui, 1973). The recently discovered occurrence of nickel sulfides in this highly deformed environment presents many problems in determining their genesis and their subsequent history. The present paper will describe the metagabbros and contained sulfide zone and postulate a model to explain their present distribution.

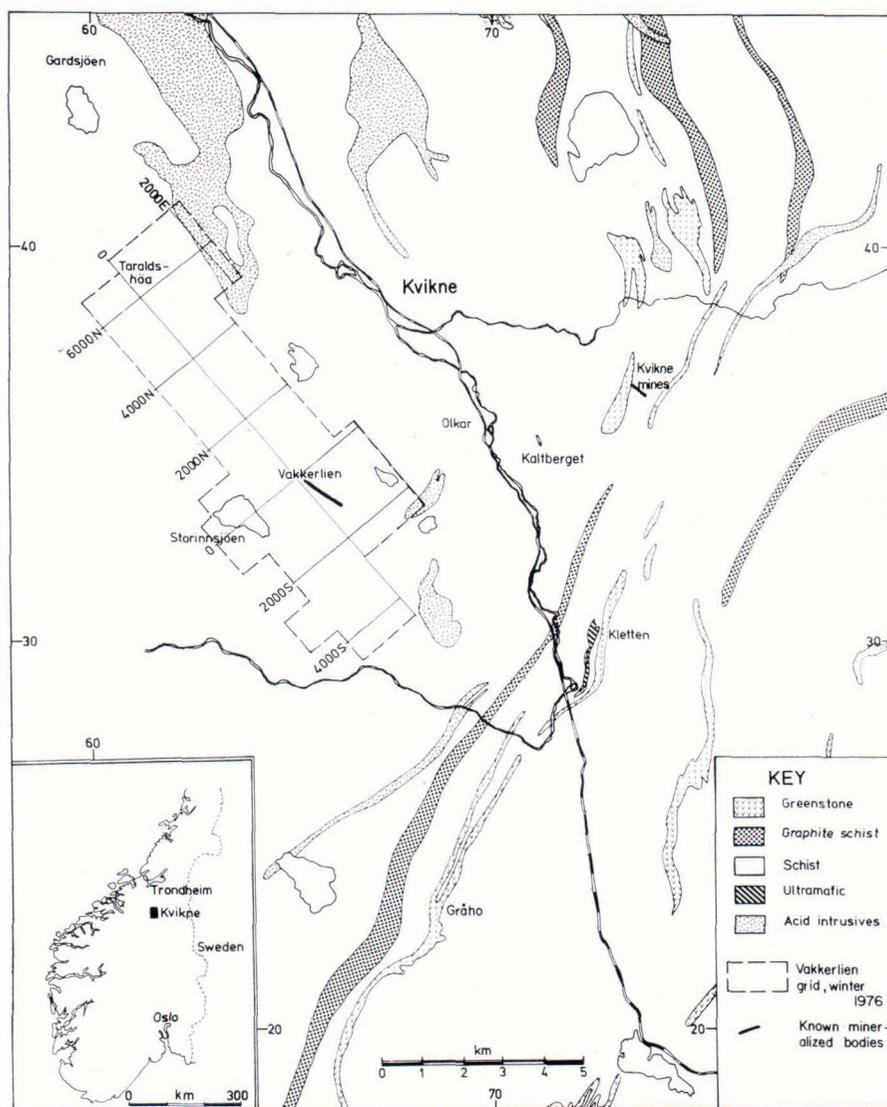


Fig. 1. Location and geology of the Kvikne area after Nilson (1974). The Vakkerlien prospect is shown.

Regional geology

Kvikne lies in the Gula group of the central Scandinavian Caledonides. The Gula group is considered to be the oldest unit of the Trondheim or 'Upper' nappe, the highest allochthonous slice in this part of the Caledonides. A variety of different structural models have been proposed for this nappe (Wegman, 1925; Wolff, 1964; Roberts, 1967;

Rui, 1971, in Rohr-Torp, 1972; Gee and Zachrisson, 1974). Recent regional tectonic models (Gee, 1975 a, b, and 1978) suggest a major tectonic break between the Trondheim or 'Upper' nappe and the units to the east, based on faunal evidence characterizing two different Palaeozoic faunal provinces (Gee and Zachrisson, 1974). Internal tectonic breaks within this nappe have also been proposed, including a break between the Gula

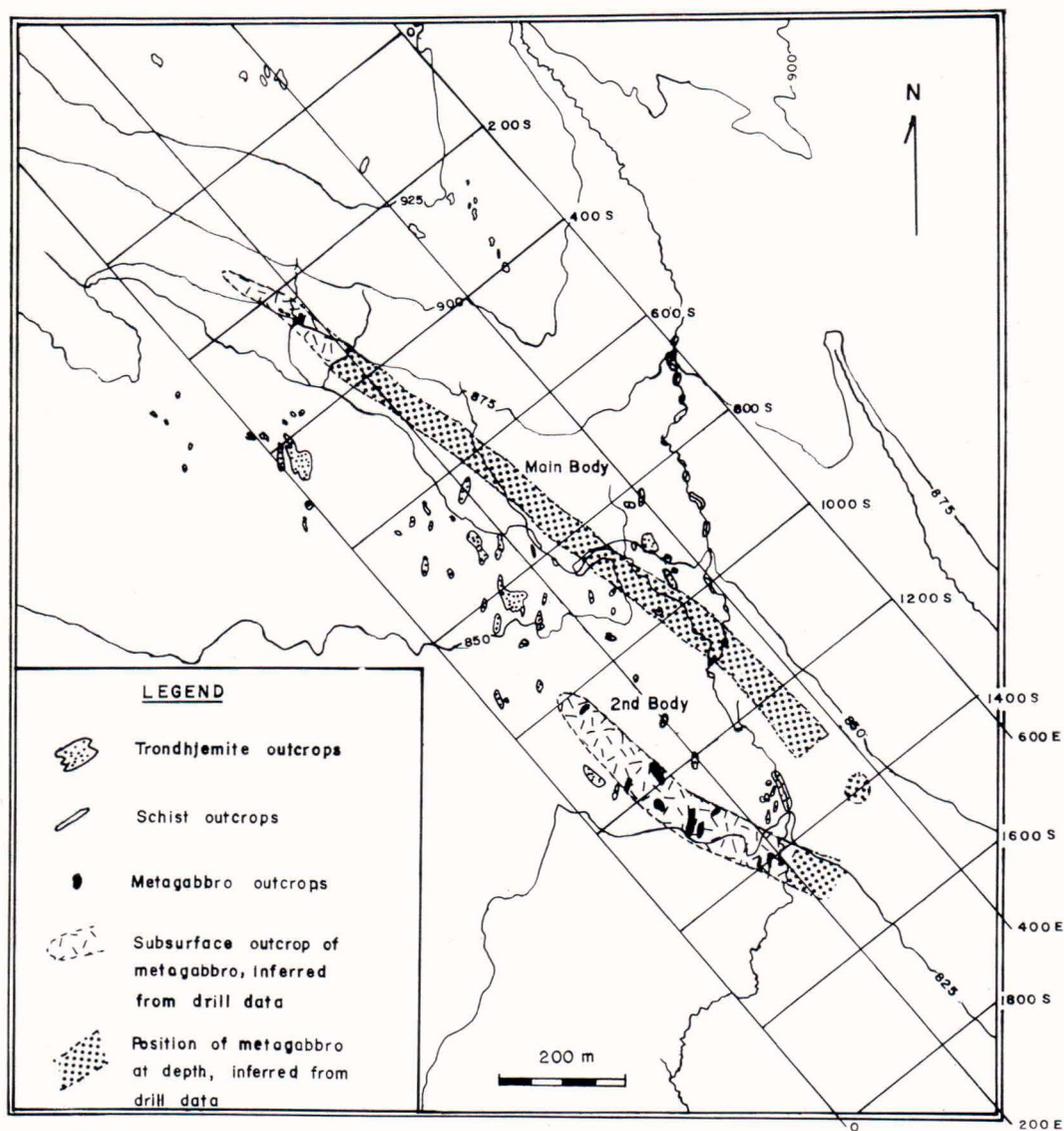


Fig. 2. Geological map in the vicinity of the Vakkerlian metagabbro bodies.

group and the overlying Støren group based on trace element geochemistry (Gale and Roberts, 1974). Such breaks present problems when correlating the Gula group in regional tectonic models. The Gula group has been postulated to be Cambrian in age, based on circumstantial evidence and the age of overlying units (Wolff, 1967). The presence of a variety of possible tectonic breaks places this age in doubt. Recent work in the Guga group,

however (D. I. Rainey, pers. comm.), may clarify some of these problems, suggesting a more continuous stratigraphic sequence and confirming a Cambro-Ordovician age for the Gula group.

The Gula group consists of largely psammitic, calcareous, graphitic and pelitic schists with subordinate amphibolites and rare bodies of ultramafic and gabbroic affinities. Various studies in the Gula of Sør

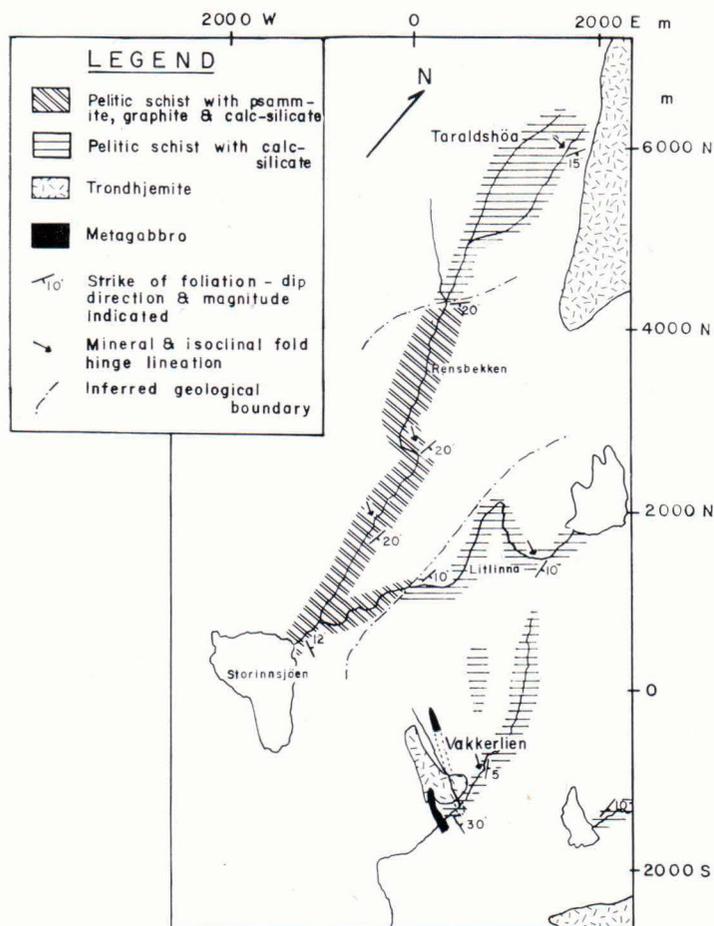


Fig. 3. Geological map of the Vakkerlien grid area, mapped largely from stream section exposure.

Trøndelag have assigned it a medium to high amphibolite grade (Nilson and Mukherjee, 1972; Guezou et al., 1972; Pinna, 1973; Rui and Bakke, 1975). Structural observations on the Gula group north of Trondheim have delineated four phases of deformation (Roberts et al., 1970), the major deformation being two isoclinal fold phases. Similar structural observations have been made south of Kvikne at Røstvangen (Rui, 1973) and at the Kvikne mines (Nilson and Mukherjee, 1972).

All the Gula group rocks are found in the Kvikne region striking parallel to the regional foliation. An attempt at establishing a stratigraphy has been made at Røstvangen

(Rui, 1973), although repetition by isoclinal folding prevents establishing any uniform stratigraphy regionally. Fig. 1 illustrates some of the major lithological units in the vicinity of Kvikne, although recent mapping of a localized portion of this area indicates that amphibolites and graphitic schists are more widespread than indicated.

Mapping of available exposure, essentially limited to stream sections, within the Vakkerlien grid area reveals two generalized units as shown in Fig. 3. In the immediate vicinity of the Vakkerlien metagabbro bodies, banded and laminated pelitic and calc-silicate schists predominate with minor psammitic bands. The contact mapped on the Litlinna

stream section northeast of Storinsjøen is an arbitrary one based on an increase in psammitic and graphitic bands. The complex interbanding of different rocks and the resultant chemical inhomogeneity have resulted in reactions occurring between layers during metamorphism and, consequently, no uniform pelitic or calc-silicate system can be found to define metamorphic grade.

Felsic intrusions, largely trondhjemites, with subordinate diorites and pegmatites, are common throughout the region (Fig. 1). Their form varies from large masses to minor bodies and concordant and discordant sheets. A range of cross-cutting relationships indicates a complex sequence of intrusion, although all the bodies in the Vakkerlien grid area (Figs. 2 and 3) postdate the major isoclinal folding events.

The Vakkerlien metagabbro bodies

Detailed observations on drill core intersecting the main Vakkerlien metagabbro indicated that considerable lithological variation is present. Petrographically and geochemically the rocks can be divided into two arbitrary types, metagabbroic and ultramafic, with alteration and deformation producing further variation. Similar rock types were noted from limited drill intersections in the second body, with some additional variation.

Petrography

Approximately 50 % of the main body consists of rocks arbitrarily termed metagabbro. These vary from coarse metagabbro, generally lacking any mineral foliation, to highly sheared and altered metagabbro. The coarse metagabbro consists of plagioclase and amphibole in varying but commonly equal proportions. Accessory minerals include quartz, calcite, biotite, chlorite, clinozoisite, sphene, rutile, sericite and sulfides. Individual

strained amphibole and plagioclase grains are common. Increased shearing produces a mineral foliation, some segregation and a highly recrystallized granoblastic texture. The fundamental mineralogy remains similar, although the amounts of chlorite, clinozoisite, quartz and calcite, and locally biotite, increase. Similar coarse and sheared metagabbro occur in the second metagabbro body, although amphibole porphyroblasts, up to 1 cm. across, are common in unshaped variants of this unit.

Ultramafic rock types also vary from largely undeformed to highly sheared and altered. Coarse ultramafic is composed of amphibole and chlorite in highly variable proportions. Commonly amphibole occurs as porphyroblasts, up to 0.8 mm. across, in a groundmass of matted acicular chlorite. Accessory minerals include talc, carbonate and biotite in the more chlorite-rich samples, and quartz (commonly intergrown with jagged amphibole grains) biotite, plagioclase, sphene and rutile in more amphibole-rich samples. Shearing results in a clear amphibole and chlorite foliation and a dramatic increase in the biotite content, varying from 20 % homogeneously distributed in weakly foliated ultramafic to 80 % in prominent confined shear zones. Similar rock types were noted in the second body with the more common presence of large amphibole porphyroblasts. Talc, carbonate and apatite bearing ultramafic rocks also appeared to be more common in the second body.

The mineralogy of the rock types above reflects the whole rock composition with the additional alteration being most apparent in sheared areas. Although the division into metagabbro and ultramafic is quite arbitrary, intermediate rock types are rare.

Rock type distribution

The distribution of rock types in any one drill hole is exceedingly complex. Various

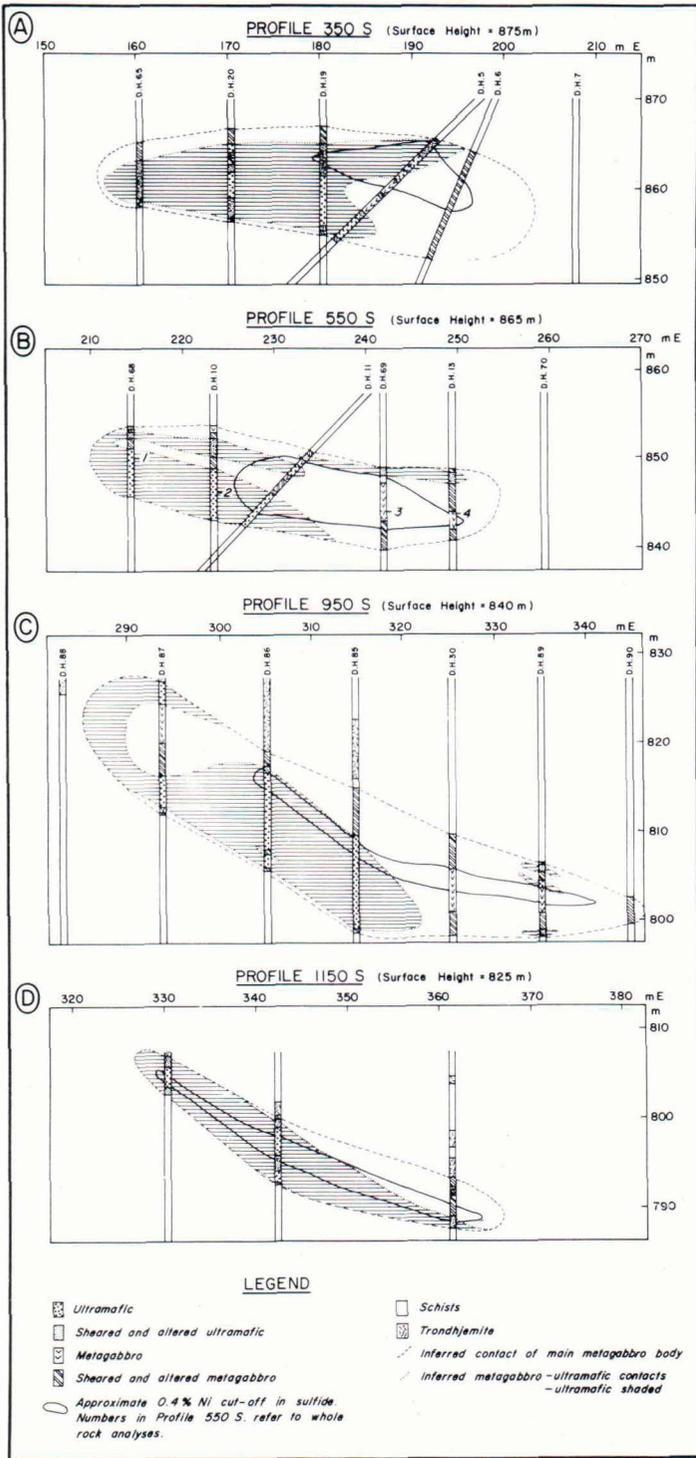


Fig. 4. Four profile cross-sections through the main metagabbro body.

rocks appear to enclose other rocks with zones of deformation and alteration most apparent at the contacts. If, however, the rock types are grouped into essentially ultramafic and metagabbroic types, a simple zonation emerges across the main metagabbro. This zonation is shown in four profile sections (Fig. 4), with ultramafics clearly dominating the southwest side of the body and metagabbro on the northeast side. Only one profile was drilled across the second metagabbro (Fig. 5), which may not be representative. Within the limited observations, however, a similar zonation to that of the main body is exhibited.

Petrochemistry

The major elements of the representative rock types have been analyzed at the University of Toronto by XRF (Siemens) method using a sample fused with lithium tetraborate in the technique described by Norrish and Hutton (1969). FeO was determined by potassium dichromate titration and loss on ignition was determined by heating in a furnace with correction for the oxidation of FeO. Each analysis was determined in duplicate.

Table 1. Whole rock analyses and CIPW norms of ten characteristic main body samples.

	Um — Am + Chl + Tc	Um — Am + Chl	AUm — Am + Chl + Bi + S	AUrn — Am + Chl + Bi + S	Mg — Am + Pl + (Bi)	Mg — Am + Pl (Mg layer in Um)	Mg — Am + Pl	SMg — Am + Pl + Cz + Cc + Chl	Mg — Am + Pl + S	Mg — Am + Pl
	1	2	3	4	5	6	7	8	9	10
SiO ₂	46.46	44.76	50.92	49.66	50.63	52.32	51.61	53.15	50.52	52.33
TiO ₂	0.87	0.69	0.5	0.62	0.64	0.89	0.93	0.82	1.08	1.43
Al ₂ O ₃	8.67	9.35	7.51	10.46	11.63	11.8	14.19	13.84	15.63	16.43
Fe ₂ O ₃	1.69	2.64	1.02	0.91	1.23	1.08	1.25	0.64	2.06	1.06
FeO	8.48	7.78	7.44	7.13	6.77	5.54	5.37	5.82	6.88	5.87
MnO	0.16	0.16	0.18	0.17	0.17	0.11	0.13	0.14	0.11	0.13
MgO	21.62	20.46	17.77	16.39	14.18	11.92	10.56	8.77	8.06	7.92
CaO	5.65	7.82	8.92	9.16	9.03	10.42	10.78	11.91	9.22	8.91
Na ₂ O	0.37	0.51	0.25	1.1	2.08	3.02	3.04	2.86	3.81	3.7
K ₂ O	0.28	0.08	2.37	2.22	1.06	0.46	0.35	0.22	0.65	0.7
P ₂ O ₅	0.11	0.06	0.04	0.01	0.05	0.04	0.02	0.09	0.09	0.09
L.O.I.	5.13	5.87	2.32	1.67	2.26	2.26	1.72	1.81	2.22	1.65
Total	99.49	100.18	99.24	99.5	99.73	99.86	99.95	100.07	100.33	100.22
FeO*	10.0	10.16	8.37	7.95	7.88	6.51	6.49	6.4	8.73	6.82
FeO*/FeO* + MgO	0.33	0.33	0.32	0.33	0.36	0.35	0.38	0.42	0.52	0.46
Q	0	0	0	0	0	0	0	0.61	0	0
Or	1.75	0.5	14.45	13.41	6.43	2.79	2.11	1.32	3.91	4.20
Ab	3.32	4.58	2.18	9.51	18.06	26.18	26.19	24.63	32.86	31.76
An	22.43	24.37	12.76	17.42	19.77	17.71	24.47	24.70	24.08	26.53
Di	5.18	12.99	26.04	24.13	20.68	27.91	23.83	28.06	17.73	14.25
Hy	48.37	32.41	31.86	12.12	18.11	13.55	11.22	17.94	2.05	12.73
Ol	14.33	19.55	10.10	21.83	13.77	8.43	8.49	0.00	14.02	6.0
Mt	2.60	4.06	1.53	1.35	1.83	1.60	1.84	0.94	3.04	1.56
Ilm	1.75	1.39	0.98	1.2	1.25	1.73	1.8	1.58	2.09	2.76
Ap	0.2	0.15	0.1	0.02	0.12	0	0.05	0.22	0.22	0.22

Abbreviations: Um — Ultramafic
 AUm — Altered & sheared ultramafic
 Mg — Metagabbro
 SMg — Sheared & altered metagabbro
 Am — amphibole
 Chl — chlorite

Bi — biotite
 Pl — plagioclase
 Cz — clinzoisite
 Cc — calcite
 Tc — talc
 S — sulfides

Ten analyses of representative rock types from the main body are given in Table 1 in order of decreasing MgO. The rock types, as defined by the mineralogy and the state of deformation, are also given. Table 2 gives four analyses across profile 550 S and five analyses across the second body, profile 1400 S, with sample locations indicated by the numbers on Figs. 4 and 5 respectively.

With decreasing MgO content of the rocks, the following observations may be made:

1. Al₂O₃ and Na₂O increase fairly uniformly
2. SiO₂ and CaO show an erratic and variable increase
3. TiO₂ rises gently
4. Fe₂O₃ and total iron are extremely erratic
5. K₂O is generally low with sporadic higher values, particularly at low MgO contents.

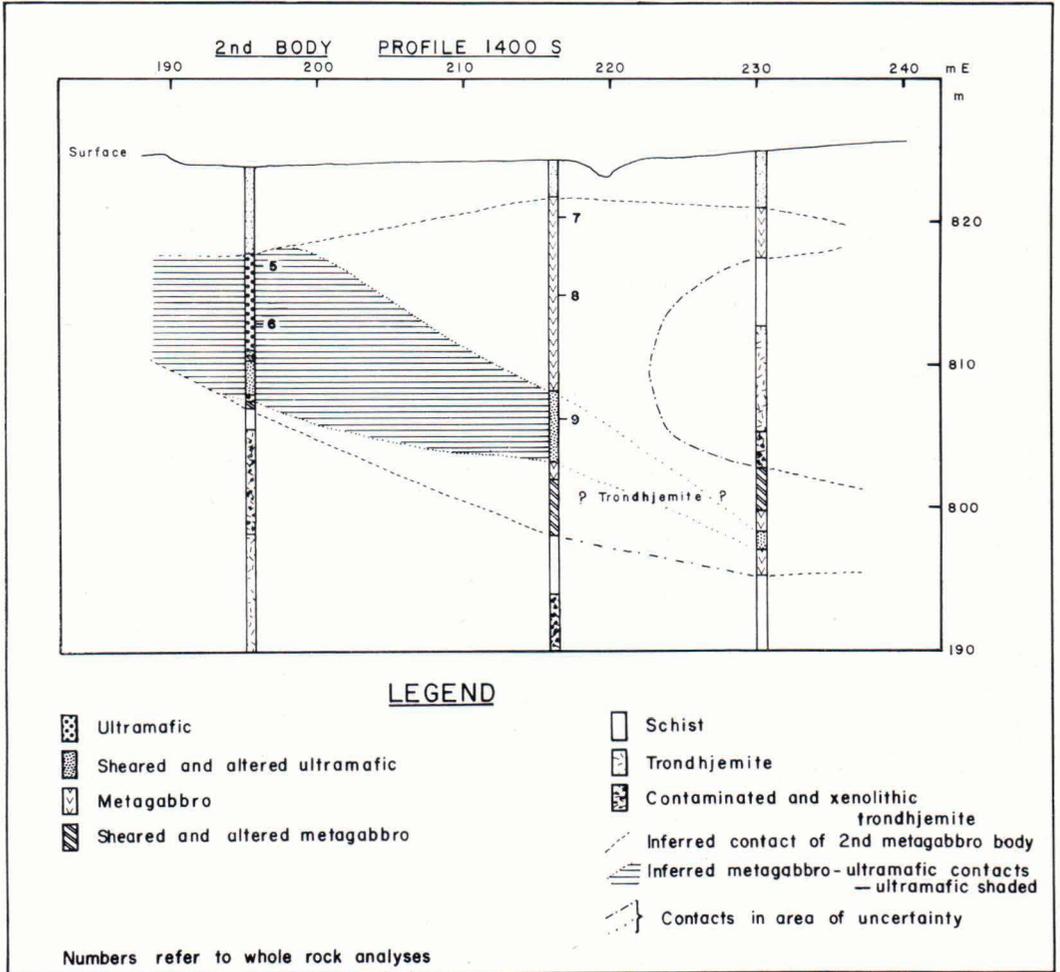


Fig. 5. Cross-section through the second body.

Some of this behaviour clearly relates to alteration and metamorphism. The presence of numerous small quartz veins, occasional calcite veins, sulfide stringers and biotite-rich shear zones can account for the erratic behaviour of SiO_2 , CaO , FeO^* and K_2O . A plot of the analyses on an AFM diagram (Fig. 6) shows a fairly regular variation even allowing for some of the alteration effects. The trend is compared to trends from other igneous complexes, indicating the weak iron enrichment of the Vakkerlien rocks with closer similarities to a 'calc-alkaline' trend. The field of Gula metavolcanics is shown

after Nilson (1974), suggesting a somewhat different chemical trend. Consideration of the regional metamorphism and local alteration effects, however, means that the use of this diagram to discriminate the petrogenetic affiliations of these rocks is subject to some uncertainty.

Nilson (1974) suggests that this and other mafic and ultramafic bodies of the Gula group represent intracrustal cumulates related to the Gula metavolcanics. The presence of numerous schist inclusions within the metagabbro bodies indicate that the Vakkerlien bodies were intruded as a liquid and

Table 2. Whole rock analyses and CIPW norms of samples from Profiles 550S, Main body and 1400S, Second body. Location of these samples are shown in Figs. 4 and 5 respectively.

	PROFILE 550 S				2nd BODY — PROFILE 1400 S				
	1	2	3	4	5	6	7	8	9
SiO ₂	46.67	44.05	50.0	50.81	39.45	48.38	50.94	53.13	50.11
TiO ₂	0.47	0.56	0.5	0.64	0.29	0.79	0.92	1.03	1.06
Al ₂ O ₃	8.11	7.75	13.12	14.96	6.85	7.11	15.18	14.73	11.74
Fe ₂ O ₃	2.4	1.6	2.3	0.94	1.11	1.29	1.21	1.03	1.29
FeO	7.8	8.12	6.7	5.44	8.04	7.93	5.86	6.5	7.37
MnO	0.15	0.16	0.12	0.13	0.11	0.16	0.13	0.13	0.15
MgO	22.99	23.91	11.21	11.83	24.23	21.39	10.45	7.99	14.71
CaO	4.47	4.13	10.19	9.94	5.37	6.36	10.45	9.93	8.16
Na ₂ O	0.39	0.26	2.32	2.72	0.02	0.25	2.77	3.0	1.95
K ₂ O	0.2	0.01	0.67	0.53	0.8	1.99	0.96	0.29	1.18
P ₂ O ₅	0.17	0.17	0.07	0.06	0.1	0.11	0.04	0.17	0.13
Total	100.55	99.17	99.22	99.99	99.53	99.85	100.06	100.15	100.67
FeO*	9.96	9.56	8.77	6.29	9.04	9.09	6.95	8.02	8.53
FeO*/FeO*+MgO	0.3	0.29	0.44	0.35	0.27	0.3	0.4	0.5	0.37
Q	0	0	0	0	0	0	0	2.43	0
Or	1.26	0.07	4.07	3.2	5.47	12.28	5.74	1.75	7.13
Ab	3.52	2.42	20.20	23.48	0.20	2.21	23.70	25.92	16.86
An	21.09	21.36	24.08	27.6	18.80	12.95	26.44	26.41	20.2
Di	1.08	0	22.03	17.83	8.97	15.31	20.59	18.40	16.21
Hy	55.13	51.40	16.86	12.47	20.04	33.62	6.82	21.24	20.99
Ol	12.84	20.35	8.19	12.65	43.75	19.84	13.08	0	14.30
Mt	3.71	2.56	3.43	1.39	1.86	1.95	1.77	1.52	1.91
Ilm	0.95	1.17	0.98	1.24	0.64	1.57	1.77	2.0	2.06
C	0	0.23	0	0	0	0	0	0	0
Ap	0.43	0.44	0.17	0.1	0.27	0.27	0.10	0.4	0.31

probably differentiated in place. Whole rock chemistry, however, fails to support the genetic connection suggested by Nilson, and

the lack of metavolcanics within 7 km. of Vakkerlien casts further doubt on his suggestion. It is our opinion that the actual relationship of Vakkerlien to the Gula metavolcanics, both with respect to timing and genesis, remains uncertain.

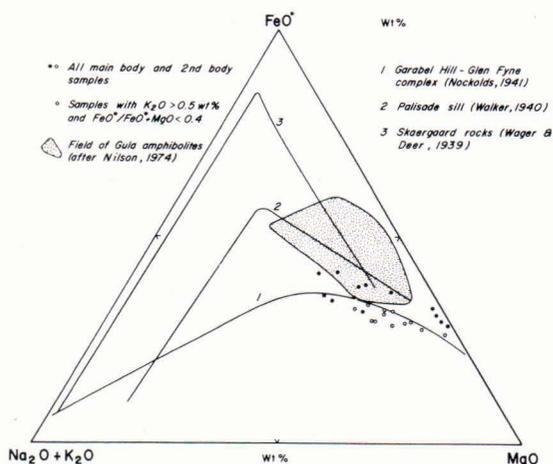


Fig. 6. AFM — diagram of Vakkerlien rocks with the field of Gula metavolcanics and some fractionation trends shown for comparison.

Mineral chemistry

Microprobe analyses of minerals were performed on the University of Toronto ARL microprobe using energy dispersive procedures with a 15 kV incident beam and a beam current normalized to 3000 c.p.s. Counting times were varied for each mineral from 50 to 150 seconds live time. A series of natural standards was used, and computer reduction and correction was carried out using an adapted version of the Smith and Gold (University of Alberta) program.

Table 3. Microprobe analyses of zoned amphiboles from a variety of Vakkerlien rock types.

Sample	76Va5		77Vpl		76Vs98		76Val		77V2S6	
	C	M	C	M	C	M	C	M	C	M
SiO ₂	42.45	48.81	46.65	50.99	49.29	51.7	49.82	55.24	48.4	54.61
Al ₂ O ₃	16.12	9.53	11.55	7.61	8.56	5.97	8.3	2.17	7.68	2.9
TiO ₂	1.63	0.44	1.07	0.4	1.09	0.33	0.42	—	0.55	0.2
Cr ₂ O ₃	0.12	—	—	0.1	—	0.13	—	—	0.13	0.14
FeO	12.15	10.43	10.35	9.72	9.6	8.45	8.7	7.04	9.1	5.98
MgO	11.09	15.17	14.21	16.44	15.79	17.26	16.83	20.04	17.72	20.94
MnO	—	0.21	—	0.21	0.22	0.2	0.13	—	0.1	—
CoO	0.12	0.13	0.1	0.14	0.17	0.18	0.15	—	0.12	0.13
CaO	11.81	11.99	12.04	12.1	12.19	12.63	11.83	12.57	10.26	12.18
Na ₂ O	1.74	0.89	0.95	0.47	—	—	1.04	—	1.11	—
K ₂ O	0.57	—	0.36	—	0.26	—	0.19	—	1.23	—
Sum	97.78	97.59	97.27	98.2	97.18	97.85	97.41	97.37	96.4	97.08
At%										
Si	6.198	6.992	6.73	7.21	7.062	7.292	7.101	7.773	7.024	7.642
Al	2.775	1.609	1.964	1.269	1.445	1.159	1.395	0.358	1.314	0.479
Ti	0.179	0.048	0.116	0.042	0.118	0.035	0.045	—	0.06	0.021
Cr	0.013	—	—	0.012	—	0.014	—	—	0.015	0.015
Fe	1.484	1.25	1.249	1.15	1.15	0.997	1.037	0.824	1.104	0.7
Mg	2.413	3.239	3.056	3.466	3.373	3.628	3.576	4.182	3.833	4.369
Mn	—	0.025	—	0.025	0.027	0.024	0.016	—	0.013	—
Co	0.014	0.015	0.012	0.016	0.019	0.02	0.017	—	0.013	0.014
Ca	1.848	1.84	1.86	1.833	1.871	1.909	1.807	1.886	1.596	1.827
Na	0.492	0.246	0.265	0.129	—	—	0.288	—	0.314	—
K	0.106	—	0.066	—	0.048	—	0.035	—	0.227	—
O	23	23	23	23	23	23	23	23	23	23
CATSUM	15.51	15.25	15.32	15.15	15.07	15.1	15.30	15.02	15.54	15.06
Mg*	0.62	0.72	0.71	0.75	0.74	0.78	0.77	0.83	0.77	0.86
MgO*	0.48	0.59	0.58	0.62	0.62	0.67	0.66	0.74	0.66	0.78
Al ^{IV}	1.802	1.008	1.27	0.79	0.938	0.708	0.899	0.227	0.976	0.358
Al ^{VI}	0.973	0.601	0.694	0.479	0.507	0.451	0.496	0.131	0.338	0.121
Na+K	0.598	0.246	0.331	0.129	0.048	—	0.323	—	0.541	—

Mg* = Mg/Mg+Fe+Mn
MgO* = MgO/MgO+FeO+MnO
C = core
M = margin

Amphibole is ubiquitous to all rock types in both the main body and the second body. In unshered varieties the amphibole is commonly zoned from a brown to pale green pleochroic core to a pale green to colourless pleochroic margin. Analyses from five zoned amphiboles in a variety of rock types are given in Table 3. Amphibole compositions range from tschermakite cores to magnesio-hornblende margins in metagabbroic rock types and from magnesio-hornblende cores to actinolite or rarely tremolite margins in ultramafic rock types. The amphibole compo-

sitions strongly reflect the composition of the host rock coupled with an overprinting due to metamorphism. Cores of zoned amphiboles commonly lie parallel to the regional lineation, indicating their metamorphic origin and thus demanding a metamorphic origin for the zonation. A detailed discussion of the varying amphibole chemistry, the chemical zonation, the relationship to whole rock chemistry and the possible effects of metamorphic grade is given by Thompson (1978).

In metagabbroic rock types, plagioclase is commonly zoned, both when occurring as

Table 4. Microprobe analyses of Vakkerlien zoned plagioclases.

Sum	Coarse Grains						Recrystallized Grains			
	76Vs98		76Vc44-2		77V2S36		76Vs98		76Vs91	
	C	R	C	R	C	R	C	R	C	R
SiO ₂	54.57	61.35	53.17	60.5	56.54	58.34	58.95	60.13	55.99	58.02
Al ₂ O ₃	28.59	24.06	28.57	23.94	27.72	26.38	25.17	23.77	26.17	24.82
CaO	11.9	5.97	12.27	6.17	10.19	8.8	7.55	6.28	9.41	7.73
Na ₂ O	4.93	8.26	5.74	9.59	6.08	7.05	8.79	10.16	7.73	9.1
Sum	99.99	99.64	99.75	100.2	100.53	100.57	100.46	100.34	99.3	99.67
At%										
Si	2.457	2.73	2.423	2.7	2.522	2.589	2.634	2.689	2.547	2.622
Al	1.52	1.262	1.534	1.259	1.458	1.38	1.326	1.253	1.403	1.322
Ca	0.575	0.285	0.599	0.295	0.487	0.418	0.361	0.301	0.459	0.374
Na	0.431	0.712	0.507	0.83	0.526	0.607	0.762	0.881	0.682	0.797
O	8	8	8	8	8	8	8	8	8	8
CATSUM	4.983	4.989	5.063	5.085	4.993	4.995	5.083	5.124	5.091	5.115
%An	57	29	54	26	48	41	32	25	40	32

C = core

R = rim

large 0.5 mm. grains and as small recrystallized grains (<0.1 mm). Analyses from five representative samples are given in Table 3, showing a maximum variation from cores of An 57 to margins of An 29. The degree of zonation is highly variable and is most marked in samples with a high CaO content, which are also characterized by calcite, clinozoisite, rutile mantled by sphene and a high CaO content of amphiboles.

With the exception of the mantling of rutile by sphene, no other mineral zonation or mineral reaction rims were discovered. Mafic minerals, biotite, chlorite and talc were found to be strongly compositionally controlled by the whole rock composition (Thompson, 1978).

Detailed petrographic work and the determination of mineral chemistry have failed to locate any diagnostic mineral assemblages or invariant reactions to characterize the metamorphic grade. Mineral zonation appears to reflect changing P-T conditions, although it is not clear whether this is a retrogressive event or a separate second lowergrade event. Both grades are tentatively placed in the

upper greenschist to upper amphibolite grade (Thompson, 1978) consistent with the grade assigned to other areas in the vicinity of Kvikne (Rui, 1973; Nilson and Mukherjee, 1974).

The Vakkerlien sulfide body

The Vakkerlien sulfide body occupies an approximately central position along the axis of the main metagabbro body. Generally it compares in shape to the main body (Fig. 4) and pinches and swells along its length. A variety of sulfide types are exhibited, hosted both by metagabbroic and ultramafic rock types. The first sulfide type, designated massive vein sulfide, constitutes up to 50 % of the mineralization, occurring as discrete veins varying from 2 cm. to 30 cm. in width. The veins commonly cut through the host rock carrying angular randomly oriented clasts and are marginally discordant to the host rock foliation. The second sulfide type, stringer sulfide, is essentially a variant of the above type. Stringer sulfide constitutes less

than 20 % of the mineralization and is restricted to highly sheared rock types. Sulfides occur as stringers and shears less than 1 cm. in width, both concordant and discordant to foliations, cutting these with angles as high as 75°. Massive vein sulfide can grade into stringer sulfide with increasing host rock deformation. The final sulfide type, disseminated sulfide, constitutes approximately 30 % of the mineralization. This type is characterized by disseminated sulfides interstitial to metagabbro or ultramafic silicates and varying in proportions from 5—40 % sulfide. The host rock type for disseminated sulfides is consistently non-foliated and apparently undeformed.

Sulfide petrography and chemistry

All the major sulfide phases are ubiquitous to the three sulfide types, although the modal proportions are highly variable both between and within these types. Disseminated sulfide is the most compositionally uniform sulfide type. The most common phases are pyrrhotite and pentlandite in modal proportions varying from 10:1 respectively to 3:1. Chalcopyrite is the other common sulfide showing a completely non-uniform distribution. Generally chalcopyrite constitutes approximately 10 % of the sulfide, although it may reach 90 % in some stringers. Pyrite is present in most samples, and it is estimated to constitute a maximum of 5 % of the sulfides. Accessory gersdorffite and violarite are present, the latter occurring as an alteration product of pentlandite.

Pyrrhotite generally forms large uniform grains with rare pentlandite exsolution flames emanating from fractures, grain boundaries and twins. Typical pyrrhotite analyses, obtained by the microprobe techniques previously described, are given in Table 5. The type of pyrrhotite (monoclinic or hexagonal) was investigated using magnetic

colloids. This indicated the predominance of monoclinic varieties with the exception of a few samples containing hexagonal pyrrhotite. The type of pyrrhotite is indicated in Table 5. Monoclinic pyrrhotites are seen to contain more than 1 wt.%, Ni, ranging up to 3.05 wt.% Ni, anomalously high when compared to the nickel contents of pyrrhotites reported from other nickel sulfide localities (Blatt, 1972; Harris and Nickel, 1972). Hexagonal pyrrhotites, however, contain a more typical value, less than 0.31 wt.% Ni. A considerable increase in the abundance of pentlandite exsolution flames was noted in the hexagonal pyrrhotites, relative to the monoclinic pyrrhotites, in a proportion approximately equivalent to that expected if monoclinic pyrrhotite containing 3 wt.% Ni exsolved pentlandite until it contained 0.3 wt.% Ni. No known mechanism can adequately explain the above observations, although it may be postulated that local removal of sulfur resulted in the formation of hexagonal pyrrhotite with a consequent increased ease of nucleation of pentlandite. Whatever the mechanism postulated, it must have occurred below 200°C as experimental studies (Misra and Fleet, 1973; Craig, 1973) indicate on iron-rich Mss containing 10 wt.% Ni at 200°C.

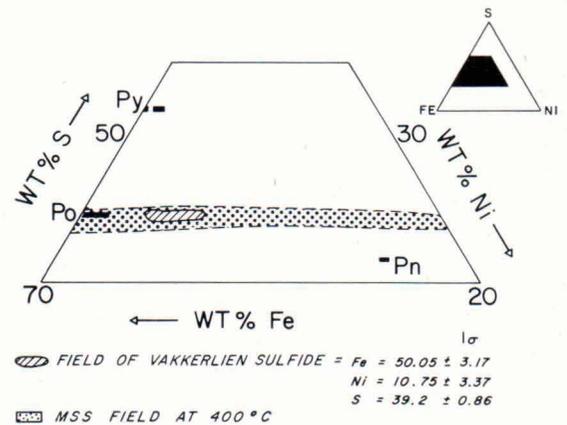


Fig. 7. The composition of Vakkerlien sulfide and individual sulfide phases projected from chalcopyrite onto a Fe-Ni-S diagram.

Table 5. Microprobe analyses of sulfide phases from the Vakkerlien mineralized zone.

PYRRHOTITE										
Sample Profile	77Vp34 A		76Vc17		76Vc35		76Vc45		76Vc52	
	350	350	550	550	750	750	1050	1050	1150	1150
Fe	57.16	58.26	58.2	58.21	58.77	58.56	57.28	57.25	61.71 ^H	60.6 ^H
Ni	3.05	2.41	1.92	1.85	1.46	1.4	2.47	2.64	0.28	0.31
S	39.46	39.3	39.04	39.5	40.53	39.23	39.44	39.44	38.78	39.48
Sum	99.67	99.97	99.16	99.56	100.76	99.19	99.19	99.33	100.79	100.39

H = Hexagonal pyrrhotite, all other samples are monoclinic.

PENTLANDITE				
Sample	76Vc17	76Vc35	76Vc45	76Vc52
Fe	28.11	29.27	28.75	29.78
Co	0.75	0.21	0.43	0.67
Ni	37.86	37.0	38.26	36.75
S	33.16	32.92	33.23	33.4
Sum	99.88	99.4	100.66	100.59

All results are averages of two analyses

PYRITE				
Sample	76Vc35	76Vc45	76Vc52	
Fe	44.73	44.2	46.4	
Ni	1.96	2.74	0.0	
S	53.77	53.1	53.41	
Sum	100.46	100.04	99.81	

Thus, pyrrhotite with 1–3 wt.% Ni is likely to be in equilibrium with pentlandite at some temperature below 200°C.

Pentlandite occurs predominantly as coarse, blocky grains and rare exsolution flames in pyrrhotite. Pentlandite analyses are shown in Table 5, again indicating a high nickel content for this assemblage when compared to the data of Harris and Nickel (1972). Cobalt, in contrast, is generally low.

Pyrite appears to be largely secondary, replacing pyrrhotite and inheriting the high nickel content (Table 5). Chalcopyrite was found to be essentially stoichiometric.

The Ni, Cu and S content of 156 samples, analysed by A/S Sulfidmalm, have been normalized to massive sulfide, assuming sul-

fide compositions typical of the Vakkerlien sulfides. The resultant composition has been projected from chalcopyrite onto the Fe-Ni-S system (Fig. 7) in addition to the composition of the sulfide phases. The full range of normalized ore compositions fall within the range of the continuous Mss at 400°C (Naldrett et al., 1967). In spite of uncertainties regarding metamorphic conditions, it is probable that the temperature exceeded 400°C throughout metamorphism. All pentlandite and pyrite would, therefore, have been in solid solution in Mss during metamorphism, and textures observed for these minerals have evolved during the cooling following metamorphism. The approximate average copper content is 4 wt.% in massive sulfide.

Table 6. The chemical composition of six Vakkerlien ore samples converted to the values expected in 100 % massive sulfide. Ni, Cu, Co and S analyzed by X-ray Assay Labs, Toronto. Se analyzed by neutron activation; Zn, Pb, Cd, As and Sb by atomic absorption — analyst Ms. S. Gentleman. PGMs and Gold analyzed by fire assay and neutron activation — analyst, J. F. H. Thompson.

Sample	wt ⁰ / ₀						ppm										
	Ni	Cu	Co	S	Se	Zn	Pb	Cd	As	Sb	Os	Ir	Ru	Rh	Pt	Pd	Au
1	12.22	4.1	0.18	37.19	60.2	113.6	7.04	1.91	72.6	< 1.61	0.025	0.025	0.016	0.044	0.081	0.38	0.039
2	11.31	1.51	0.18	37.7	72.8	101.4	14.3	1.69	146.4	< 2.08	0.028	0.016	—	0.025	1.022	0.26	0.037
3	10.92	0.84	0.17	37.2	67.1	74.4	21.6	1.32	47.3	< 1.44	0.012	—	—	0.011	2.168	0.281	0.038
4	10.77	1.25	0.4	37.62	105.7	48.5	34.2	2.85	122.6	< 4.56	0.039	0.076	0.108	0.027	0.561	0.547	0.071
5	8.94	3.06	0.2	38.42	92.5	105.4	20.4	2.38	47.9	< 2.38	0.05	0.106	0.127	0.078	0.522	0.313	0.043
6	11.34	2.12	0.23	37.12	62.2	72.5	21.8	2.61	50.2	< 1.45	0.052	0.084	0.125	0.067	0.373	0.316	0.067

Experimental evidence (Yund and Kullerud, 1966; Moh and Kullerud, 1963; and McQueen, 1979) suggests that this amount of copper could not exist in solid solution in Mss and that a separate Iss phase must have existed during metamorphism. It is possible that selective mobilization of this phase during metamorphism and deformation is responsible for the highly variable copper distribution.

Sulfide Ore Chemistry

Six sulfide-bearing samples have been analyzed for 17 elements by a variety of techniques. Ni, Cu, Co, Zn, Pb, Cd, As, and Sb were determined by atomic absorption; S by titration; Se by neutron activation, and the platinum group elements and gold by chemical pre-concentration and neutron activation according to the technique described by Hoffman et al. (1978). Results from these analyses have been recalculated to express the concentration expected in 100 % sulfide ore and are shown in Table 6. The first three samples are massive vein sulfide and the second three samples are disseminated sulfide.

The high sulfide nickel content and the variable copper content are apparent. Naldrett and Cabri (1976) correlated the wt.⁰/₀ MgO of the parent silicate liquid with the Cu/Cu + Ni ratio of the sulfides. For a gabbroic magma, a Cu/Cu + Ni ratio of 0.5 or more is anticipated. The average Vakkerlien sulfides show a Cu/Cu + Ni ratio of 0.3, while the individual samples shown in Table 6 all have ratios of less than 0.3. Although no silicate liquid composition can be identified for Vakkerlien, the range and proportions of rock types would suggest an initial gabbroic magma. The sulfide composition, however, indicates that either the parental magma was more mafic than indicated or the sulfide composition has been modified during metamorphism. Thompson (1978) suggests a mechanism for the release of silicate nickel

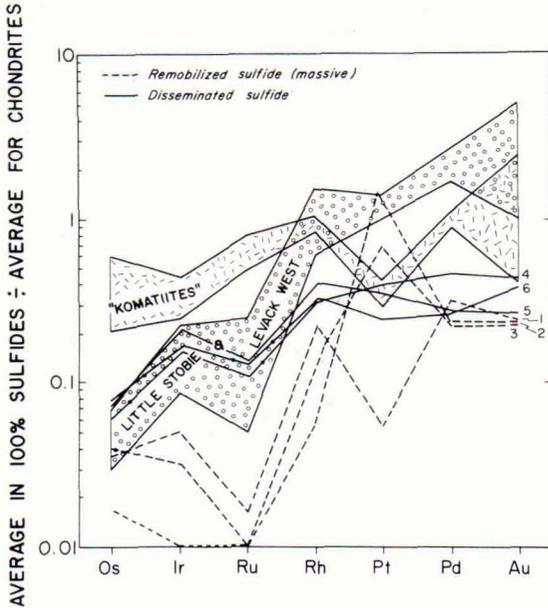


Fig. 8. A plot of the PGE and Au contents of six Vakkerlien sulfide-bearing samples relative to an arbitrary average chondrite content. The fields of three Sudbury ore bodies, Little Stobie #1 and 2 and Levack West, and three komatiite-hosted ore bodies, Kambalda, Mt. Edwards and Langmuir, are shown for comparison.

contained in igneous olivines during metamorphism, with uptake of this nickel by the sulfides consequently modifying their composition.

No particular difference is apparent for most of the elements between massive vein sulfide and disseminated sulfide. The platinum group elements, however, show a marked difference between the two sulfide types. This difference is demonstrated in Fig. 8, a plot of the metal content of the sulfide divided by an arbitrary chondrite metal content used by Naldrett et al. (1979) for all the platinum group elements. All three disseminated sulfide samples have similar trends, while trends for the samples of massive vein sulfide, while erratic, are strongly depleted in Os, Ir and Ru. A variety of evidence exists to suggest that Os, Ir and Ru are highly immobile, but Rh, Pt, Pd and Au are clearly mobile (Fucks and Rose, 1974; Cousins and

Vermaak, 1976; Stumpfl and Tarkian, 1976; Travis et al., 1976). Thus, the difference in trends exhibited by the ore types suggests that massive vein sulfide have been remobilized, possibly by hydrothermal solutions during metamorphism, from original disseminated sulfides. One anomalous point in the Vakkerlien data is the similar levels of Pd and Au in all samples. In the studies referred to above, these metals show mobility to an even greater extent than Pt and Rh. It is possible that their high mobility allowed continued transportation and homogenization of these elements once the massive sulfide had been emplaced and the particular conditions responsible for large scale sulfide remobilization had relaxed.

The shaded areas on Fig. 8 represent the trends obtained from three Sudbury nickel sulfide deposits and those obtained from three Archaean komatiite-hosted nickel sulfide deposits (Naldrett et al., 1979). The trend of the Vakkerlien disseminated sulfides falls within the Sudbury trend for Os, Ir and Ru, although it is relatively depleted in Rh, Pt, Pd and Au. The relative increase from Os to Au across the diagram for the Vakkerlien disseminated sulfides is, however, typical of the gabbroic-hosted sulfide deposits rather than the ultramafic komatiite-hosted deposits. Thus, this data supports the inferred gabbroic host magma with the effect of metamorphism being reflected in the difference between the two sulfide types.

Structure

All schist types in the Vakkerlien area show a characteristic lamination or banding, producing a clear foliation. This foliation generally dips gently between 5° and 10° to the southeast. At least two temporally distinct, but spatially coincident, deformation phases involving isoclinal folding and extreme flattening have produced the observed

foliation. Each phase may have transposed the previous foliation into the subsequent foliation orientation or have involved a similarly oriented stress field. The phases of isoclinal folding are delineated by phases of quartz veining showing varying degrees of deformation in single outcrops. Trondhjemite intrusion transgressed the closing stages of isoclinal folding. Some trondhjemite bodies are clearly foliated, while the majority of the bodies are quite massive.

The foliation commonly undulates forming symmetrical folds with a wave length greater than 5 metres. The axes of these folds dip gently to the southeast, coinciding with the isoclinal fold hinges and indicating a final weak phase of deformation parallel to the major isoclinal phases.

Isoclinal fold hinges form a prominent regional lineation parallel to the local development of a mineral lineation. The average lineation direction from 57 readings in the Vakkerlien area was $113^{\circ} \pm 12.7^{\circ}$, plunging at approximately 5° . This lineation is essentially parallel to the Vakkerlien metagabbro bodies.

A final phase of deformation has been delineated in the northern part of the Vakkerlien grid. This phase is quite different from those previously described and involves tight upright kink bands trending north-south and overturned to the west.

A deformation model for the Vakkerlien metagabbros

Early phases of quartz veining suffered at least two phases of isoclinal folding. During this deformation, the competency difference between the schists and the quartz veins commonly resulted in attenuation of quartz veins in isoclinal fold limbs and isolation of the fold hinges. Quartz is commonly found occurring in isolated fold hinges throughout the Vakkerlien area. The deformation style

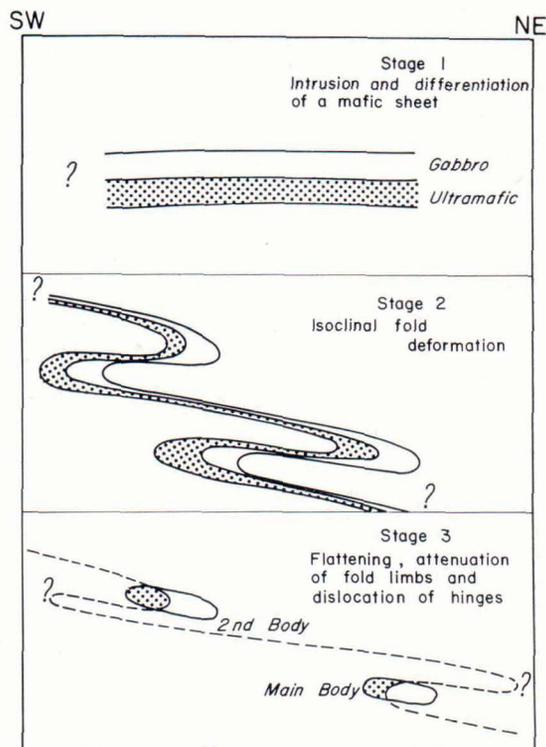


Fig. 9. A deformation model for the formation of the separate Vakkerlien metagabbro bodies.

in the Vakkerlien metagabbros has involved intense deformation on localized shear zones with the preservation of comparatively undeformed regions between these zones. Cross-cutting shear zones are common, but it is not possible to correlate the resultant complex foliation with the regional isoclinal fold phases. It seems likely, however, that the Vakkerlien metagabbros have suffered extensive isoclinal folding if not all the events demonstrated regionally. As such, it is suggested that isoclinal folding of a differentiated gabbro sheet would result in attenuation of the limbs and isolation of the fold hinges in a manner analogous to that of the quartz veins. This model is shown in Fig. 9 and has the attraction of explaining the distribution of rock types within the two bodies.

Magmatic sulfide ore bodies commonly occupy a basal position in mafic igneous com-

plexes. It is, thus, important to consider to what extent the present centrally located mineralized zone is the result of deformation and metamorphism. Deformation studies on sulfides (Clark and Kelly, 1973) and sulfides with silicates (Zolotukhin et al., 1972) have indicated the relative ease with which sulfides can behave plastically. Both studies were carried out at relatively low P and T conditions, but it is likely that sulfides would continue to be more plastic than silicates at elevated P and T conditions. The Vakkerlien area has clearly been plastically deformed and, thus, it can be assumed that the Vakkerlien sulfides were potentially more mobile under these conditions. No deformation model, however, can adequately explain the present distribution of sulfides if an original basal position is envisaged. Massive vein sulfide and stringer sulfide show clear evidence of remobilization, the sulfide chemical data suggesting that metamorphic fluids may have been active in this process. Local plastic remobilization may also have occurred, particularly in highly discordant sulfide stringers. Disseminated sulfides have clearly been recrystallized in that they now occupy an interstitial position to metamorphic silicates, presumably originating as sulfide interstitial to igneous silicates. Their position, however, in essentially undeformed metagabbro and ultramafic, suggests that large scale remobilization has not affected these sulfides and that the deformation style within the metagabbro, the majority of the strain being absorbed on discrete shear zones, has preserved the disseminated sulfide in a relatively primary position. Thus, it is suggested that the highly unusual position of the sulfides reflects an original igneous concentration with additional remobilization of some sulfide in deformed metagabbro and ultramafic into the fold hinge containing the main metagabbro body. The fact that the second metagabbro body, argued to be lying in a fold hinge, is

barren of sulfides also suggests that local igneous concentration of sulfide existed prior to deformation and metamorphism and that deformation alone is not responsible for the central location of sulfides within the main body.

Conclusions

A mafic sheet was intruded into the Gula group and differentiated in place. Although metamorphosed volcanics are present in the area, geochemical evidence does not clearly support a petrogenetic connection. A connection is, however, not ruled out as it is not possible to quantify the effects of metamorphism on the composition of the volcanics and the Vakkerlien bodies.

The Vakkerlien bodies clearly suffered severe deformation. Conclusive correlation with regional deformation events is, however, hindered by the inhomogeneous deformation style of the metagabbro bodies. Comparison with deformed quartz veins suggests a deformation model for the mafic sheet involving isolation of individual bodies in isoclinal fold hinges, which consequently lie parallel to the regional lineation. This model explains the position and orientation of the bodies and the distribution of rock types within them. No igneous mineralogy is preserved. Zonation of amphiboles and plagioclases indicate a complex, possibly two-phase metamorphic history, although it is not possible to define precise P and T conditions.

Pyrrhotite, pentlandite and chalcopyrite are the major sulfide mineral phases in the mineralized zone. Pyrrhotite phases and compositions reflect a complex low temperature history. Three sulfide types are defined, two of which were clearly remobilized during deformation. The third sulfide type may have remained in place, and it is suggested that the mineralized zone occupies a partially

primary position with additional concentration during deformation.

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