Bergvesenet

Postboks 3021, N-7441 Trondheim

BÆRBAR MASKIN

Rapportarkivet

Bergvesenet rapport nr	Intern Journal nr	Internt arkiv nr	Rapport lokalisering	Gradering
6832				
Kommer fra ..arkiv	Ekstern rapport nr	Oversendt fra	Fortrolig pga	Fortrolig fra dato:
Grong Gruber AS		Grong Gruber a.s.		

Tittel

Geology of the vulcanogenic massive Cu-Zn sulphide deposits in Gjersvik area, Central Norway

Forfatter	Dato	År	Bedrift (Oppdragsgiver og/eller oppdragstaker)
Haitian, Sun	Des	1991	Avgitt rapport som res av 2 års post doc fellowship fra NTNF

Kommune	Fylke	Bergdistrikt	1: 50 000 kartblad	1: 250 000 kartblad
Røyrvik	Nord-Trøndelag		1924 4	Grong

Fagområde	Dokument type	Forekomster (forekomst, gruvefelt, undersøkelsesfelt)
Geologi		Gjersvik Skorovas Kirma (Tjiermajaevrieh) Annlifjell
Råstoffgruppe	Råstofftype	
	Cu, Zn	

Sammendrag, innholdsfortegnelse eller innholdsbeskrivelse

Setter forekomstene i gjersvikområdet i en paleotektonisk sammenheng, beskriver den vulkanostraigrafiske sekvens og de eruptive bergartene med sin geokjemi, samt de geologiske forhold omkting mineraliseringene og omvandling og dannelse av forekomstene.
Detaljert mikroskopistudie av Gjersvikforekomsten.
Foreslår videre undersøkelser i det vestre pyroklastrike drager Bjørkvatnet- Kirma

Dr. SUN HAITIAN
Department of Geology and
Mineral Resources Engineering
NTH, 7034 Trondheim

31. 12. 1991

To NTNF
P.O.Box 70, Tasen
0801 Oslo 8

The final report

1 Outline of the project

The present project had been carried out while I have been in possession of a two year NTNF post-doctoral fellowship (RE: ST.60.61.221309 - NTNF RESEARCH FELLOWSHIP 13222) from October 1st, 1989 to December 31st, 1991. The project was coorparatively organized under the guide of Professor F. M. Vokes by both of Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology, and Grong Gruber A/S, and was funded jointly by N.T.N.F., and Grong Gruber A/S.

The project focused on the Caledonian volcanogenic massive Cu-Zn sulphide deposits in the Gjersvik area, central Norway, aimed to study the paleotectonic setting, volcanostratigraphic sequence, meta-igneous lithologies and geochemistry, and to study geological features of the ore bodies, structure and texture of the ores, ore compositions (chemistry and mineralogy), zoning, alteration and origin of the deposits, and to study relationship between volcanic processes and formation of the deposits, as well as to establish the advantageous targets for further evaluation and explosion of the massive base metal sulphide deposits.

2 Academic activities

Main academic activities concerning the project include:

(1) Investigating and comparing the Caledonian massive sulphide deposits outside the Gjersvik area

Joma mine, located in the central Norway, two days, December, 1989

Sulitjelma mine, located in the norther Norway, one week, July, 1990

Lokken mine, located in the south of Trondheim, one day, April, 1991

(2) Joining the academic symposium

A symposium on " Ore Deposits Associated with Granitic Rocks " at Bergverksmuseet, Kongsberg April 25 - 27, 1991

A series of special lectures on topics relating to the ore deposits held in NGU (Geological

Survey of Norway) and in Department of Geology and Mineral Resources Engineering, NTH.

3 Main work

(1) Surface geological mapping work

In order to establish the geological and stratigraphic relationship between meta-intrusive and meta-extrusive rocks as well as metafelsic and metamafic volcanic rocks and to investigate a potentiality finding of new massive sulphide bodies, the detailing surface geological mapping on the scale of 1:5,000 was carried out by the author in the Gjersvikklumpen-Royrvatnet area about 18 kilometers squares, located in the west of the Limingen Lake and the northeast of the Royrvatnet Lake in the Gjersvik area. Two sheets of the geological map in the area were finished, which spent a total of nine weeks from 19th June to 24th August, 1990. Further regional surface geological mapping work on the scale of 1:20,000, combined with some detailing mapping of 1:5,000, was taken in the Gjersvik area in the summer from June to August of 1991 by Sun Haitian, Reinsbakken and Vokes.

In addition, the drill hole #4 about 370 m in depth within the mapping area was logged.

(2) Identifying work for the rocks and the ores under microscope

A series of samples representative of different types of the rocks and the ores were collected from the massive sulphide orebodies, alteration zones, metavolcanic and meta-intrusive rocks in the mapping area and in the regional district. Among them, a total of 117 thin sections, 27 polished thin sections, and 26 polished sections have been determined under microscope, which they include mostly essential types of the rocks and the ores occurring within the Gjersvik volcanic arc.

(3) Geochemical work for the rocks and the ores

A total of 82 specimen, 74 rock samples representative of different types of the meta-intrusive and meta-extrusive rocks collected mostly from the surface and a few from drill hole, and 8 altered rock samples of different types from the Gjersvik felsic complex, were selected to make a full silicate chemical analyses and trace element analysis, which were carried out at laboratory in Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology. 14 specimen of the massive sulphide ores and 11 of the alteration zones were selected to make analysis in major ore metal elements such as Cu, Zn, Pb and Fe as well as precious element Ag in laboratory of Grong Gruber A\S, among which most of the ores and all of the altered samples were collected from the Gjersvik orebody, some of the ores being from exposure of the massive sulphide mineralization in the regional area.

4 Main results

During work of the research project, a series of the results related to the project was delivered to the Grong Gruber A\S or kept in the Department of Geology and Mineral Resources Engineering, NTH. They include:

I Informal geological maps

(1) 5 sheets on the scale of 1:5,000 (Gjersvikruet DP 159-5-3, Vester-Gjersvikseteren DP 159-5-1, Gjersvik DP 160-5-3, Bjorkvatnet DO 160-5-4 and part of Kirma Dp 160-5-1,)

(2) 1 sheet on scale of 1:20,000 in the Gjersvik area.

II Reports

(1) Brief Summary of Mapping Work in The Gjersvikklumpen-Royrvatnet Area of the Gjersvik, 1990

(2) Brief Summary for The Core Logging Bh 4, at RORVATN, in Gjersvik Area

(3) Final Research Report

Title ` GEOLOGY OF THE VOLCANOGENIC MASSIVE Cu-Zn SULPHIDE DEPOSITS IN GJERSVIK AREA, CENTRAL NORWAY ' which consists of 5 sections with 83 figures and 10 Tables ( seeing enclosure of `contents'). The final report has been held in Department of Geology and Mineral Resources Engineering, NTH., and Grong Gruber A\S.

III Publications related to the project

The paper ` GENERAL REVIEW OF VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS IN CHINA ' has been accepted by an international magazine ` ORE GEOLOGY REVIEW '

The paper ` DEERNI VOLCEX-TYPE MASSIVE Cu-Zn SULPHIDE DEPOSIT HOSTED BY ULTRAMAFIC ROCKS IN QINGHAI PROVINCE, CHINA ' was published in EUG VI Supplementary Programme, pp. 11

Reported from
Sun Haitian
SUN HAITIAN

c.c. Professor F. M. Vokes

Geology of The Gjersvik Volcanogenic Massive Cu-Zn Sulphide Deposits, Central Norway

SUN HAITIAN

(Department of Geology and Mineral Resources
Engineering, University of Trondheim-Norwegian
Institute of Technology, N-7034 Trondheim, Norway)

GRONG GRUBER A.S

GJERSVIK 1991.

Prøver fra HAI TIAN SUN
Rap.nr 333B
346
380B
382

Prøve:	% Cu	% Zn	ppm Pb	% Fe	ppm Ag	ppm Cd	ppm Ni
GS1-22 Massive py.	0,4000	0,0205	86	42,0	6	1	34
GS1-23 Massive po.chal.py.	0,7600	0,6300	64	45,5	6	17	15
GS1-24 Massive po.chalco.py	1,1000	0,2900	147	44,5	7	9	15
GS1-25 Massive py. + chalco	1,0600	0,2000	58	45,0	7	4	40
GS1-29 Strong alteration, weak min.	0,0037	0,0240	44	2,1	1	1	32
GS1-31 Feeder zone.	0,0550	0,0370	38	6,5	2	2	12
GS1-32 Massive banded py. Sphal.	0,3700	4,6400	180	27,6	7	83	10
GS1-33 Massive py. + sphale	0,8500	6,2900	62	32,3	8	110	14
GS2-9-1 Feeder zone.	0,0040	0,9900	1750	3,7	5	2	36
GS2-9-3 Massive pyrite.	0,5000	0,0300	48	20,3	5	3	12
GS3-2 Weak altered rock.	0,0032	0,0130	11	5,7	1	1	16
GS3-3 Weak alteration.	0,0062	0,0062	7	4,1	1	1	18
GS3-4 Weak alteration.	0,0140	0,0160	6	3,2	1	3	12
GS3-6 Weak alteration.	0,0230	0,0052	7	3,3	0	1	14
GS3-7 Strong alteration, weak mineralization.	0,0013	0,0088	10	1,9	1	1	26
GS3-8 Altered rock.Strong. Weak min.	0,0018	0,0180	63	3,9	1	1	24
GS3-9 Strong alteration, strong mineralization	0,0260	0,1400	75	8,7	2	3	11
GS3-11 Strong alteration, min.	0,1300	0,0450	20	15,3	2	3	10
RS2-3 Massive py. ~~spha.~~	0,0210	0,0150	25	30,2	3	3	73
RS2-4 Massive py.	0,0068	0,0350	27	35,1	3	5	4
J314 Massive py.	0,1900	0,0990	83	40,6	5	6	16
J302 Massive py. sph(?).	0,2200	4,7600	127	27,2	6	96	13
GJK. 90.7 (90.1?) Massive po.chpy.py.	4,4100	0,1600	43	41,4	12	8	13
GJK. 90.11 Banded py.Mt.	0,0056	0,0094	15	21,4	1	8	62

Laboratoriet Grong Gruber A/S
Hans Øines
Hans Øines
(Lab.leder)

Table 3.1

Major (%) and Trace (ppm) Element Chemistry of the Dark Greenstones

	1 RS4-1	2 RS4-2	3 RS4-8	4 RS4-3	5 DR4#	6 M16-32	7 M15-17	8 M15-23
SiO_2	53.43	49.83	49.81	51.07	53.19	53.53	52.15	51.03
TiO_2	1.65	1.20	2.04	1.35	1.33	1.67	1.40	1.43
Al_2O_3	14.31	15.11	13.61	14.92	14.33	13.97	14.95	14.47
*FeO	14.02	13.99	13.19	14.47	13.43	13.96	14.04	13.81
MgO	2.75	7.83	4.91	5.20	3.89	3.39	4.68	4.20
CaO	3.70	4.38	6.23	3.69	4.65	3.62	4.97	5.36
Na_2O	5.70	4.96	4.41	6.06	5.67	5.05	5.32	5.16
K_2O	0.06	0.09	0.02	0.19	0.13	0.05	0.61	0.45
MnO	0.27	0.27	0.16	0.19	0.22	0.29	0.22	0.22
P_2O_5	0.53	0.11	0.17	0.11	0.18	0.56	0.13	0.13
Loss	4.14	3.23	5.70	2.92	3.17	4.47	1.78	1.96
SUM	100.56	100.40	100.25	100.71	100.19	100.38	100.25	98.22
Sr	122	112	148	81	126	97	111	173
Rb	<1	<1	<1	1	<1	<1	5	4
Nb	18	18	17	19	8	20	20	15
Y	41	30	48	35	33	38	31	27
Zr	54	48	68	49	57	52	52	51
Ba	<10	<10	<10	<10	<10	<10	<10	<10
V	61	403	465	490	305	65	377	287
Ni	3	33	23	11	6	1	19	3
Co	28	55	42	56	41	24	55	48
Cr	13	27	30	17	16	9	33	14
Pb	<1	<1	<1	<1	2	<1	<1	<1
Cu	14	14	11	43	40	21	47	28
Zn	151	167	140	151	137	151	146	124

Table 3.1, continue 1

	9	10	11	12	13	14	15	16
	M20-23	911213-2	913108	913111	913112	913113	913103	913104
SiO_2	53.22	47.45	50.58	53.30	51.06	53.50	52.25	58.32
TiO_2	1.34	1.55	1.65	1.39	1.82	2.06	1.36	1.48
Al_2O_3	15.09	16.76	15.87	15.41	16.28	13.72	15.15	15.17
*FeO	13.72	16.40	13.98	12.91	14.65	15.15	14.64	14.02
MgO	4.15	5.69	5.47	5.70	4.92	5.35	4.63	2.67
CaO	7.54	7.17	6.65	6.34	6.75	5.22	8.98	3.22
Na_2O	2.09	4.25	4.34	4.73	4.41	3.49	3.85	5.28
K_2O	0.06	0.02	0.51	0.14	0.04	0.59	0.20	0.15
MnO	0.21	0.23	0.18	0.17	0.23	0.24	0.23	0.28
P_2O_5	0.13	0.14	0.14	0.11	0.17	0.16	0.13	0.46
Loss	2.83	7.39	2.15	2.07	2.13	2.28	2.00	2.63
SUM	100.38	99.66	99.37	100.20	100.15	99.48	101.42	101.05
Sr	246	82	130	95	148	99	181	132
Rb	2	5	12	7	6	16	7	9
Nb	18	12	12	11	13	13	11	13
Y	32	31	32	29	34	39	22	40
Zr	56	39	47	40	48	57	34	44
Ba	39	<10	<10	<10	<10	<10	<10	<10
V	382	452	354	316	416	403	368	33
Ni	13	22	20	18	19	14	14	9
Co	54	69	60	45	64	33	56	22
Cr	23	21	19	17	23	19	18	14
Pb	<1	<1	<1	<1	<1	<1	<1	<1
Cu	46	54	54	19	18	32	17	19
Zn	85	151	43	132	137	188	103	188

Table 3.1, continue 2

	17	18	19	20	21	22	23	24
	913105	913106	913107	913506-2	913606	913701	913702	913703
SiO_2	53.20	54.30	54.09	52.68	54.34	61.48	54.30	54.95
TiO_2	1.43	1.30	1.20	1.68	1.21	1.07	1.90	1.27
Al_2O	15.14	15.39	14.67	14.75	15.54	14.15	13.87	15.86
*FeO	15.07	12.16	14.34	15.25	14.36	9.94	14.62	13.29
MgO	7.11	5.20	4.09	4.78	4.36	3.48	4.24	4.51
CaO	3.63	6.67	6.38	5.84	5.56	6.10	7.19	6.49
Na_2O	4.49	4.96	4.89	3.87	4.57	4.49	3.70	4.09
K_2O	<0.03	0.06	0.23	<0.03	0.03	0.50	<0.03	0.30
MnO	0.24	0.27	0.23	0.29	0.21	0.15	0.24	0.18
P_2O_5	0.11	0.12	0.10	0.25	0.12	0.27	0.16	0.12
Loss	3.12	4.97	1.81	5.51	5.41	5.39	4.34	6.21
SUM	100.42	100.43	100.22	99.39	100.30	101.63	100.23	101.06
Sr	72	120	167	47	90	103	115	107
Rb	6	7	11	7	<2	9	<1	3
Nb	13	11	12	13	15	18	18	17
Y	26	26	20	22	31	39	39	35
Zr	31	38	32	29	50	60	63	58
Ba	<10	<10	<10	<10	<10	<10	<10	<10
V	455	343	350	257	379	197	345	331
Ni	11	19	9	9	8	28	24	18
Co	51	29	48	54	56	28	45	49
Cr	16	24	17	15	21	52	34	28
Pb	<1	<1	<1	<1	<1	<1	<1	<1
Cu	3	37	21	20	23	29	54	50
Zn	154	76	131	161	140	87	134	135

7 - 9 massive stilpnomelane- and biotite-bearing greenstone

All elements analysized by I. Romme and I. Vokes, with PHILIPS PW1480 X-Ray Spectrometer in Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology, 1991

Table 3.2

Major (%) and Trace (ppm) Element Chemistry of the Pale Greenstones

	1	2	3	4	5	6	7	8
	RS441	RS442	RS451	RS452	RS491	RS492	RS4-7	911509
SiO_2	50.07	51.10	48.40	47.55	47.30	47.04	50.80	51.54
TiO_2	0.62	0.63	0.76	0.81	0.52	0.52	0.87	0.54
Al_2O_3	15.50	15.70	15.63	15.35	13.75	13.65	13.93	14.66
*FeO	9.09	9.30	9.79	10.30	9.24	9.22	10.83	10.57
MgO	7.35	7.55	8.03	7.97	11.46	11.62	6.00	8.42
CaO	7.22	6.72	7.46	7.17	8.45	8.39	6.27	8.85
Na_2O	4.76	4.90	4.63	4.51	3.11	3.05	5.73	4.14
K_2O	0.53	0.52	0.44	0.42	0.52	0.52	0.07	0.63
MnO	0.15	0.14	0.18	0.19	0.17	0.17	0.18	0.18
P_2O_5	0.11	0.11	0.11	0.13	0.06	0.06	0.10	0.08
Loss	4.53	4.11	5.78	5.72	6.78	6.76	3.99	5.99
SUM	100.11	100.78	101.21	100.12	101.36	101.00	98.77	99.61
Sr	103	101	137	153	61	60	86	75
Rb	6	2	<1	3	8	8	<1	13
Nb	17	15	16	17	17	17	17	11
Y	19	17	21	22	15	17	23	11
Zr	46	44	51	53	38	39	47	21
Ba	<10	<10	<10	<10	25	35	<10	14
V	253	254	226	230	195	197	277	266
Ni	82	82	96	95	222	226	76	106
Co	43	42	52	53	63	63	47	45
Cr	153	159	164	162	246	249	129	187
Pb	1	<1	9	11	<1	<1	<1	<1
Cu	69	64	69	74	18	11	7	63
Zn	76	74	91	91	94	97	105	81

Table 3.2, continue 1

	9	10	11	12	13	14	15
	911611	911906	910612	911213-1	910609-1	910609-2	910204
SiO_2	51.86	49.61	52.93	50.46	50.68	50.32	53.71
TiO_2	0.60	0.89	1.09	0.80	1.24	1.02	0.94
Al_2O_3	14.99	16.12	15.39	15.23	15.92	16.41	15.68
*FeO	11.30	12.69	11.39	10.23	11.22	10.77	9.08
MgO	8.97	8.60	6.43	10.55	7.53	7.39	7.93
CaO	8.89	6.89	8.14	9.01	9.08	9.78	7.59
Na_2O	2.79	3.70	4.79	3.72	2.96	2.90	4.73
K_2O	0.29	0.55	0.23	0.03	<0.03	1.41	0.24
MnO	0.17	0.20	0.19	0.21	0.19	0.25	0.14
P_2O_5	0.08	0.07	0.12	0.08	0.13	0.12	0.13
Loss	5.18	6.05	4.85	8.21	4.21	9.73	3.91
SUM	99.94	99.32	100.70	100.32	98.95	100.37	100.17
Sr	144	88	118	129	337	72	109
Rb	11	14	8	5	6	28	9
Nb	11	11	11	11	12	11	11
Y	12	18	20	16	24	20	16
Zr	25	31	33	32	54	40	39
Ba	<10	61	<10	<10	<10	135	<10
V	258	320	279	217	262	264	202
Ni	112	106	78	194	72	73	145
Co	54	60	46	59	47	46	49
Cr	226	183	127	288	132	157	209
Pb	<1	<1	<1	<1	<1	4	<1
Cu	65	52	37	38	64	32	68
Zn	89	125	99	76	99	96	74

Table 3.2, continue 2

	16	17	18	19	20	21	22
	910323-1	910323-2	913114	913506-1	913601	913602	913603
SiO_2	48.34	51.88	55.03	49.69	54.28	51.28	52.31
TiO_2	1.06	1.11	0.74	0.82	0.73	0.72	0.56
Al_2O_3	17.69	16.70	14.79	17.75	15.39	14.59	14.97
*FeO	8.40	8.75	9.89	12.37	10.47	9.13	9.83
MgO	5.24	6.06	7.64	7.85	7.31	5.32	7.21
CaO	14.50	12.05	7.60	8.11	8.07	14.02	10.73
Na_2O	3.87	3.94	4.38	2.78	3.66	4.57	3.24
K_2O	0.17	<0.03	0.08	<0.03	0.46	0.47	0.66
MnO	0.12	0.15	0.21	0.31	0.17	0.17	0.17
P_2O_5	0.22	0.21	0.06	0.08	0.10	0.14	0.08
Loss	7.81	4.75	2.08	4.61	2.96	7.14	3.48
SUM	99.61	100.86	100.42	99.76	100.64	100.41	99.76
Sr	102	353	190	198	181	131	152
Rb	9	6	6	5	13	6	6
Nb	9	11	11	12	11	15	16
Y	21	20	16	19	17	18	14
Zr	39	57	31	32	44	44	47
Ba	<10	<10	<10	<10	<10	<10	<10
V	246	226	235	234	243	218	244
Ni	119	89	74	66	96	115	107
Co	57	30	44	67	45	45	47
Cr	200	189	146	119	205	140	190
Pb	<1	<1	3	<1	<1	<1	<1
Cu	45	25	<1	44	49	21	62
Zn	90	68	125	102	84	62	74

All elements analysized by I. Romme and I. Vokes, with PHILIPS PW1480 X-Ray Spectrometer in Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology, 1991

Table 3.3

Major (%) and trace (ppm) element chemistry
of the keratophyric pyroclastic complexes

	1	2	3	4	5	6	7	8
	M22-7-1	M22-7-2	M15-13-1	M15-13-2	M17-26	GS3-12	913102	913109
SiO_2	75.20	75.05	72.78	72.40	66.73	71.28	75.23	77.67
TiO_2	0.21	0.22	0.37	0.37	0.54	0.35	0.25	0.19
Al_2O_3	11.90	12.00	12.95	12.77	14.24	12.94	13.01	11.46
*FeO	4.33	4.46	5.04	5.28	8.53	5.05	4.10	3.41
MgO	0.64	0.73	0.62	0.68	1.21	0.96	0.22	0.67
CaO	0.73	0.75	0.80	0.83	0.51	0.23	1.92	0.55
Na_2O	6.07	6.02	5.51	5.57	7.28	6.47	5.27	5.03
K_2O	0.27	0.27	0.96	0.79	0.04	0.14	0.19	0.20
MnO	0.06	0.06	0.11	0.11	0.10	0.05	0.10	0.04
P_2O_5	0.03	0.03	0.06	0.07	0.07	0.06	0.04	0.02
Loss	0.56	0.60	1.22	1.28	0.85	0.90	0.43	0.66
SUM	100.00	100.19	100.42	100.15	100.10	98.43	100.33	99.24
Sr	131	135	64	70	31	56	165	66
Rb	<1	<1	3	4	<1	<1	7	6
Nb	14	20	15	19	13	18	8	5
Y	60	63	67	69	58	68	39	44
Zr	133	138	137	135	94	118	114	100
Ba	<10	<10	248	164	<10	<10	45	<10
V	29	27	34	34	69	36	19	18
Ni	9	7	5	5	10	5	8	9
Co	5	3	4	3	11	6	3	2
Cr	75	58	69	70	40	39	61	90
Pb	10	<1	<1	<1	4	4	14	3
Cu	36	39	15	8	10	13	3	10
Zn	45	52	133	127	113	31	46	69

All elements were analysized by I. Romme and I. Vokes with PHILIPS PW1480 X-Ray Spectrometer, Department of Geology and Mineral Resources Engineering, University of Trondheim- Norwegian Institute of Technology, 1991

Table 3.6

Major (wt.%) and Trace (ppm) Element
Chemistry of the Intrusive Rocks

	1	2	3	4	5	6	7	8	9
	M15-14-1	M15-14-2	M18-16	913403	913206	M6-5	911711	911712	911713
SiO_2	74.10	74.14	74.28	75.20	73.62	73.25	75.00	78.15	76.77
TiO_2	0.23	0.22	0.36	0.48	0.36	0.41	0.31	0.19	0.25
Al_2O_3	13.18	13.05	13.65	13.77	14.67	13.72	13.28	12.92	13.65
*FeO	3.52	3.61	2.66	3.31	3.10	3.05	3.04	1.73	2.16
MgO	0.31	0.27	0.32	0.58	0.29	0.46	0.56	0.15	0.43
CaO	0.88	1.00	0.67	1.47	1.30	1.02	2.95	2.28	2.52
Na_2O	5.36	5.43	5.14	5.41	5.56	6.88	3.90	3.63	4.06
K_2O	1.24	1.06	1.55	0.97	1.48	0.32	1.24	0.88	1.00
MnO	0.04	0.05	0.17	0.11	0.09	0.10	0.05	0.04	0.04
P_2O_5	0.04	0.05	0.07	0.09	0.05	0.08	0.06	0.02	0.04
Loss	1.05	1.09	1.40	0.76	1.20	1.00	0.93	0.64	0.68
SUM	99.95	99.97	100.27	101.39	100.62	100.29	100.49	99.99	100.92
Sr	94	112	101	129	86	136	196	250	144
Rb	28	21	33	22	32	<1	29	24	27
Nb	9	10	15	12	15	10	9	9	10
Y	42	43	58	41	46	47	17	20	18
Zr	120	115	157	127	167	115	123	123	131
Ba	96	91	257	188	231	<10	484	269	585
V	23	21	10	16	26	29	36	20	31
Ni	6	7	43	5	6	3	10	6	7
Co	3	3	3	3	4	3	4	2	3
Cr	92	118	63	74	61	50	137	113	94
Pb	3	7	9	4	10	15	6	14	6
Cu	15	13	28	7	43	15	14	17	1
Zn	23	28	51	74	37	66	21	11	10

Table 3.6, continue

	10	11	12	13	14	15	16	17	18	19
	912323	912502	M6-9	M7-20	M7-4	M6-41	M6-42	M6-49	913110	913101
SiO_2	72.11	74.31	74.99	70.32	74.92	47.54	44.65	50.13	52.27	53.29
TiO_2	0.31	0.28	0.22	0.17	0.19	0.80	1.55	0.63	1.04	1.12
Al_2O_3	14.45	14.03	12.80	14.80	14.19	15.36	17.44	11.97	15.83	14.50
*FeO	3.32	2.70	2.23	2.10	1.60	13.21	15.18	10.33	11.05	12.10
MgO	0.76	0.50	0.30	0.34	0.28	5.64	4.77	11.93	6.31	6.37
CaO	2.86	2.68	1.67	2.05	1.41	8.87	10.42	11.39	10.41	9.22
Na_2O	3.45	3.36	4.90	4.63	4.49	2.21	2.14	1.53	3.16	3.82
K_2O	2.19	2.14	1.24	2.01	1.85	0.04	0.03	0.05	0.04	0.03
MnO	0.10	0.08	0.06	0.08	0.04	0.20	0.19	0.19	0.17	0.21
P_2O_5	0.08	0.05	0.05	0.05	0.04	0.08	0.10	0.09	0.09	0.10
Loss	1.97	2.49	1.96	2.73	1.22	6.57	2.55	1.87	1.61	1.99
SUM	100.11	100.13	100.42	99.28	100.23	100.52	99.02	100.11	100.37	100.73
Sr	242	202	191	264	203	160	210	137	212	125
Rb	67	58	25	56	47	<1	<1	<1	5	7
Nb	11	11	13	16	12	16	17	22	11	11
Y	18	20	30	11	22	16	16	17	21	21
Zr	108	113	126	121	114	44	43	42	36	33
Ba	709	665	493	745	860	<10	<10	<20	<10	<10
V	57	46	38	31	33	392	362	214	244	291
Ni	6	6	3	4	4	28	22	181	44	79
Co	5	4	4	3	4	63	62	62	49	56
Cr	100	120	85	92	80	38	17	361	60	142
Pb	12	9	14	9	12	<1	<1	<1	<1	<1
Cu	8	13	6	7	7	68	51	51	49	36
Zn	36	30	31	22	13	92	89	86	86	98

1 - 5 fine-grained porphyritic trondhjemite; 6 fine-grained trondhjemite (a marginal phase of the coarse-grained trondhjemite); 7 - 14 coarse-grained trondhjemite; 15 - 19 gabbro

All elements were analysized by I. Romme and I. Vokes with PHILIPS PW1480 X-Ray Spectrometer in Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology, 1991

Table 4.1

Major (wt.%) and Trace (ppm) Element Chemistry of The Altered Felsic Volcanic Rocks

	1	2	3	4	5	6	7	8	9
	av.(8)	GS3-3	GS3-6	GS2-9-1	GS1-29	GS1-31	GS3-7	GS3-9	GS3-11
SiO_2	73.29	73.14	78.61	65.05	78.08	65.22	74.54	57.16	51.39
TiO_2	0.31	0.38	0.21	0.33	0.19	0.31	0.30	0.47	0.19
Al_2O_3	12.66	11.37	9.65	14.61	9.35	13.36	12.62	15.31	7.51
*FeO	5.03	6.89	5.05	6.31	3.40	10.52	3.44	15.23	24.61
MgO	0.71	2.31	1.34	1.63	0.03	2.78	2.90	0.11	0.44
CaO	0.78	0.06	0.70	2.09	2.68	0.95	0.12	0.02	0.02
Na_2O	5.90	3.80	3.48	6.31	5.09	4.88	2.11	1.22	0.41
K_2O	0.36	0.29	0.21	0.92	0.27	0.63	1.12	2.71	1.49
MnO	0.07	0.06	0.11	0.13	0.28	0.16	0.98	0.03	0.03
P_2O_5	0.04	0.04	0.03	0.05	0.04	0.05	0.05	0.03	0.02
Loss	0.81	2.10	1.11	1.96	0.81	3.02	2.81	8.69	12.84
SUM	99.96	100.44	100.50	99.39	100.22	101.88	100.99	100.98	98.95
Zr	121	109	98	110	77	96	122	121	61
Nb	14	10	16	17	17	22	23	24	21
Y	59	67	48	66	31	57	88	74	23
Sr	90	80	89	110	83	52	94	85	23
Rb	3	<1	<1	11	0	4	12	26	14
Ba	63	<10	<10	476	<10	31	605	657	334
V	33	51	38	18	17	107	7	31	18
Ni	7	5	11	2	6	4	3	3	1
Co	5	5	8	2	3	6	1	5	13
Cr	63	38	73	38	45	29	54	73	75
Pb	5	3	2	1464	72	27	12	48	<1
Zn	62	77	54	7154	189	502	113	1271	413
Cu	17	56	205	36	13	462	1	172	873

1 unaltered rocks (an average of 8 samples); 2 - 3 weak altered rocks; 4 6 intermediate altered rocks associated with obvious veining mineralization; 7 intense altered rock associated with weak mineralization; 8 - 9 intense altered rocks associated with intense dense disseminated mineralization

All elements analyzed by Ivar Romme with PHILIOPS PW1480 X-Ray Spectrometer, Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology, 1991

Table 4.4 Comparison of the Gjersvik deposits with the Kuroko-type deposits

	Gjersvik deposits	Kuroko deposits in Japan
Age	Early Palaeozoic	Miocene
metamorphism	greenschist facies	zeolite facies
deformation	strong	very weak
tectonic environments	intra-ocean rifting environment	intra-arc extensional environment
continental crust	complete absence	presence
development of the volcanic arcs	immature or primitive	mature
magma series	tholeiitic	calc-alkaline
volcanic rock assemblage	well-defined bimodal basalt-rhyolite volcanic assemblages that essentially lack andesites	basalt, andesite, dacite and rhyolite assemblages
dominant types of volcanites constituting volcanic arcs	tholeiites	andesite, dacite and rhoylite
chemistry of the host volcanic rocks	Na-richment	K-richment
sedimentary rocks associated with the volcanic succession	only small exhalative sediments	sandstone, mudstone
intrusive rocks associated with the the volcanic arc	major trondhjemite plus small gabbro	quartz-diorite, granitoids
tendency of ore bodies in occurrence	cluster	cluster
orebody morphology	massive sulphides horizon underlying directly a stringer mineralization	massive sulphides horizon underlying directly a stringer ore

Table 4.4 continue

	Gjersvik deposits	Kuroko deposits in Japan
ore-associated volcanics	keratophyric pyroclastic complexes of rhyolitic composition	dacite, rhyolite
rocks hosting the feeder zone	felsic pyroclastic complexes	rhyolitic dome
major alterations related to mineralization	silicification sericitization carbonitization	silicification sericitization montmorillonite
major ore textures	compact, massive	compact, massive
major metal mineral assemblages	pyrite, chalcopyrite, pyrrhotite	pyrite, galena, sphalerite,
minor metal mineral assemblages	sphalerite magnetite	chalcopyrite, barite, tetrahedrite, tennantite
major gangue mineral assemblages	quartz, carbonate (calcite)	quartz
minor gangue mineral assemblages	chlorite	barite, gypsum, anhydrite
sulphates associated with the ores	none	barite, gypsum, anhydrite
major ore-forming element association	Cu-Zn	Pb-Zn
minor ore-forming element association	none	Ba, Cu

The Kuroko deposits are referenced mainly from Matsukuma & Horikoshi, 1970; and Franklin et. al., 1981

GEOLOGY OF THE VOLCANOGENIC MASSIVE Cu-Zn SULPHIDE DEPOSITS IN GJERSVIK AREA, CENTRAL NORWAY

SUN HAITIAN

1991

NTH
UNIVERSITETET I TRONDHEIM
NORGES TEKNISKE HØGSKOLE
Bergavdelingen
Institutt for geologi og bergteknikk

GEOLOGY OF THE VOLCANOGENIC MASSIVE Cu-Zn SULPHIDE DEPOSITS IN GJERSVIK AREA, CENTRAL NORWAY

SUN HAITIAN

1991

UNIVERSITETET I TRONDHEIM NORGES TEKNISKE HOGSKOLE
INSTITUTT FOR GEOLOGI OG BERGTEKNIKK

(UNIVERSITY OF TRONDHEIM NORWEGIAN INSTITUTE OF TECHNOLOGY
DEPARTMENT OF GEOLOGY AND MINERAL RESOURCES ENGINEERING)

Contents

Section 1: Introduction

pages

Section 2: Regional geology

Section 3: Metavolcanic and meta-intrusive rocks constituting the Gjersvik volcanic arc

3.2 Metavolcanic rocks

3.2.2 Description of lithologies

3.2.3 Chemistry of metavolcanic rocks

3.3 Meta-intrusive rocks

3.3.4 Chemistry of the rocks

3.4 Relationships among different types of the rocks

3.5 Petrogenetic and paleotectonic model

3.5.3 Major evidences reconstructing paleotectonic environment of the Gjersvik volcanic arc

Section 4: Massive sulphide mineralization

4.1 Introduction

4.3 Hydrothermal alterations

4.4 Zonation of the deposit and chemistry of the ores

4.5 Origin of the deposits

Section 5: Summary and conclusions

5.3 Metavolcanic rocks and their plutonic infrastructures constituting the Gjersvik volcanic arc

5.3.2 Lithologies

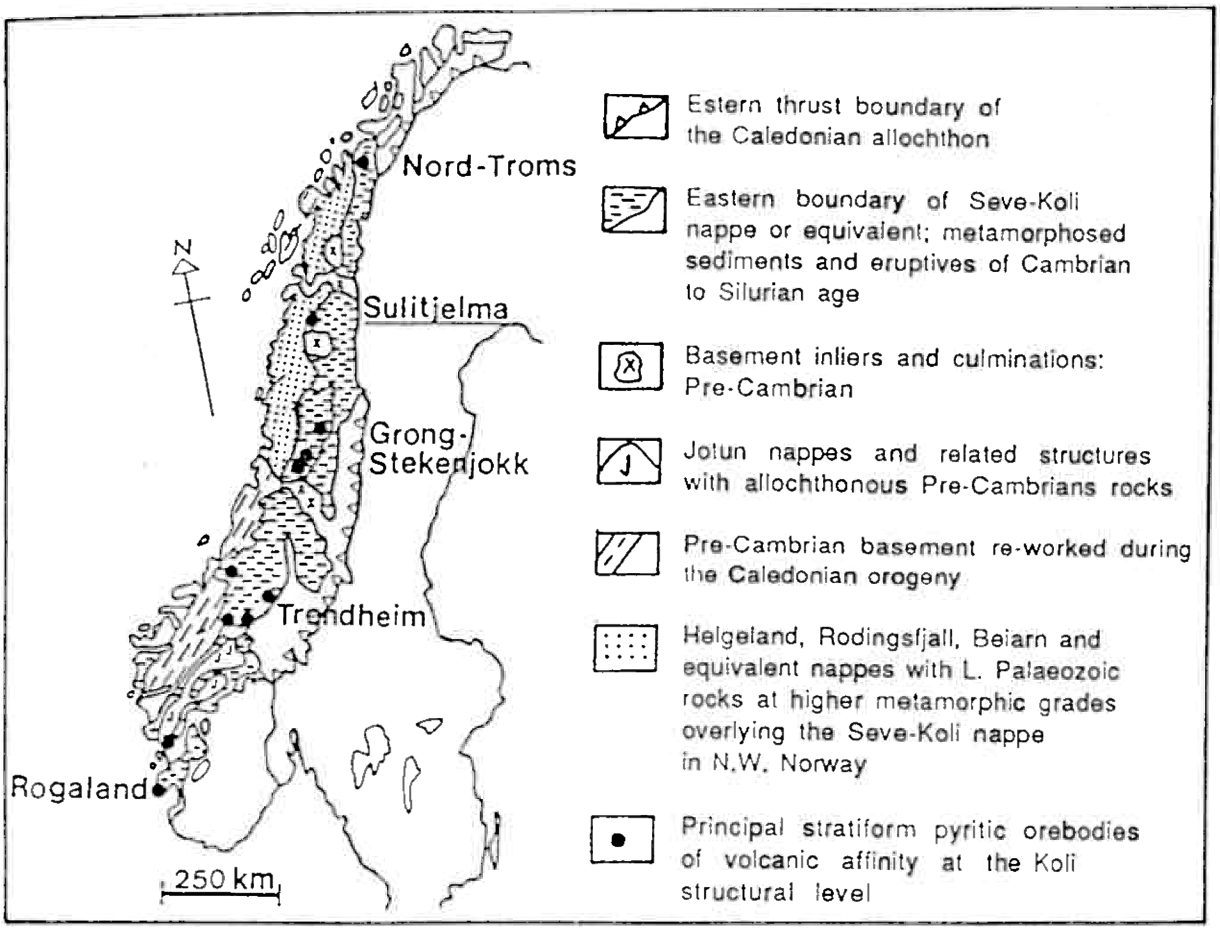
5.3.3 Chemistry of the magmatic complexes

5.4 Massive sulphide mineralization

Section 1: Introduction

1.1 Location

The Scandinavian Caledonides, a belt of Lower Palaeozoic metamorphosed and deformated volcanic and sedimentary rocks, extends about 2000 km from Regaland in the southwestern Norway to Nord Trøms along the western margin of the Scandinavian peninsula (Stephens et al., 1985), within which occur the various groups of the important stratiform and stratabound massive sulphide mineralization. Five main regions of the massive sulphide mineralizations within this complex metallogenic belt have been recognized and described by Vokes (1968): Rogaland in south-western Norway; the Trondheim district; Grong-Stekenjøkk district; Sulitjelma, and the Nord-Trøms districts. The geographic location of the Grong-Stekenjøkk district and its position within the Caledonites are shown in Figure 1.1. The host rocks consist predominantly of a varied assemblage of supracrustal volcanic and sedimentary rocks with closely associated plutonic masses of ultrabasic, basic and acid compositions. The conspicuous quantity of basaltic to andesitic volcanites in the supracrustal sequences, taken together with their deformed and metamorphosed condition, ranging in grade from lower greenschist to almandine amphibolites facies, has led to the familiar use of the terms greenschist and greenstone in descriptions of the stratigraphy of various districts (Strand, 1960). It is generally recognized that the massive sulphide mineralization have close genetic relationship to the volcanic rocks with which they are associated (Vokes, 1973). The stratigraphic sequence hosting the massive sulphide mineralization has been proposed to be chiefly of Ordovician age (Halls, et. al., 1977). However, the windows of the underlying Precambrian basement have produced the segmentation of the allochthon on which the division into separate districts is broadly based. It is clear that the separate districts that comprise the Ordovician massive sulphide mineralization lie at a broadly comparable structural level in the Caledonian allochthon of the Scandinavian peninsula, but there are significant differences in the paleotectonic environments, the stratigraphy and metamorphic grade of the host rocks from district to district. The genetic process that relates to the ores and host rocks has been masked by the effects of metamorphic recrystallization and polyphase deformation, which affected both



Estern thrust boundary of the Caledonian allochthon

Eastern boundary of Seve-Koli nappe or equivalent; metamorphosed sediments and eruptives of Cambrian to Silurian age

Basement inliers and culminations: Pre-Cambrian

Jotun nappes and related structures with allochthonous Pre-Cambrians rocks

Pre-Cambrian basement re-worked during the Caledonian orogeny

Helgeland, Rodingsfjall, Beiarn and equivalent nappes with L. Palaeozoic rocks at higher metamorphic grades overlying the Seve-Koli nappe in N.W. Norway

● Principal stratiform pyritic orebodies of volcanic affinity at the Koli structural level

Fig. 1.1 Simplified tectono-stratigraphic map of the Scandinavian Caledonides showing the five main areas of volcanogenic massive sulphide deposits at Koli structural level, after Vokes (1968) ores and host rocks during the process of allochthonous tectonic emplacement consequent upon collision of the Scandinavian and Lauzentian craton during Middle Silurian times.

The Grong-stekenjøkk district is located in the central Scandinavian Caledonides in where some of important massive sulphide deposits have been well known to occur in the metavolcano-stratigraphic sequences belonging to the Køli structural level of the Upper Allochthon, the Upper structural unit of the Seve-Køli Nappe in the central Scandinavian Caledonides, representatives of them being Skorovas, Gjersvik, Joma, and Stekenjøkk (Fig.1.2).

The Gjersvik and Skorovas ore deposits can be comparative in stratigraphic sequence and geology of the ore bodies. They are both located within a thick metavolcanic succession of the greenstones plus subordinate metafelsic volcanic rocks in the Gjersvik Nappe defined by Halls et. al., (1977). The Skorovas orebody, situated in the south of the Gjersvik Nappe, is the biggest one of a series of the massive Cu-Zn sulphide mineralization known so far in the area. The deposit consists of approximately 10 m.t. of massive and disseminated predominantly pyritic ore with an approximate average grade of 1.3 % Zn and 1.0 % Cu, together with trace amounts of Pb, As and Ag. Sufficiently detailed studies in regionally geological setting and geology of the ore body were carried out by Halls, et. al., (1977) and by Reinsbakken (1980). The Gjersvik ore deposit, located in the northern part of the Gjersvik Nappe, consists of approximately 1.6 m. t. of ores with an average of 31 % S, 1.6 % Cu and 0.9 % Zn with very few amounts of Pb and precious metals.

Geographically, the Gjersvik area is situated in north and northwest of the Limingen Lake, northeastern part of the Grong district of the Nord-Trøndelag in central Norway. The Gjersvik ore deposit as one of the most potentially economic value in this area is located in the northern shore of the Limingen Lake, about 800 m east of the cross-road at the Gjersvik village, along the Gjersvik-Røyrvik road.

Geologically, the Gjersvik massive Cu-Zn sulphide ore body lies in a thick, bimodal metamorphosed volcanic succession, taken together with closely associated intrusive masses. The metavolcanites consist predominantly of the greenstones of tholeiitic composition plus subordinate keratophyric pyroclastic rocks of rhyolitic composition. The massive sulphide

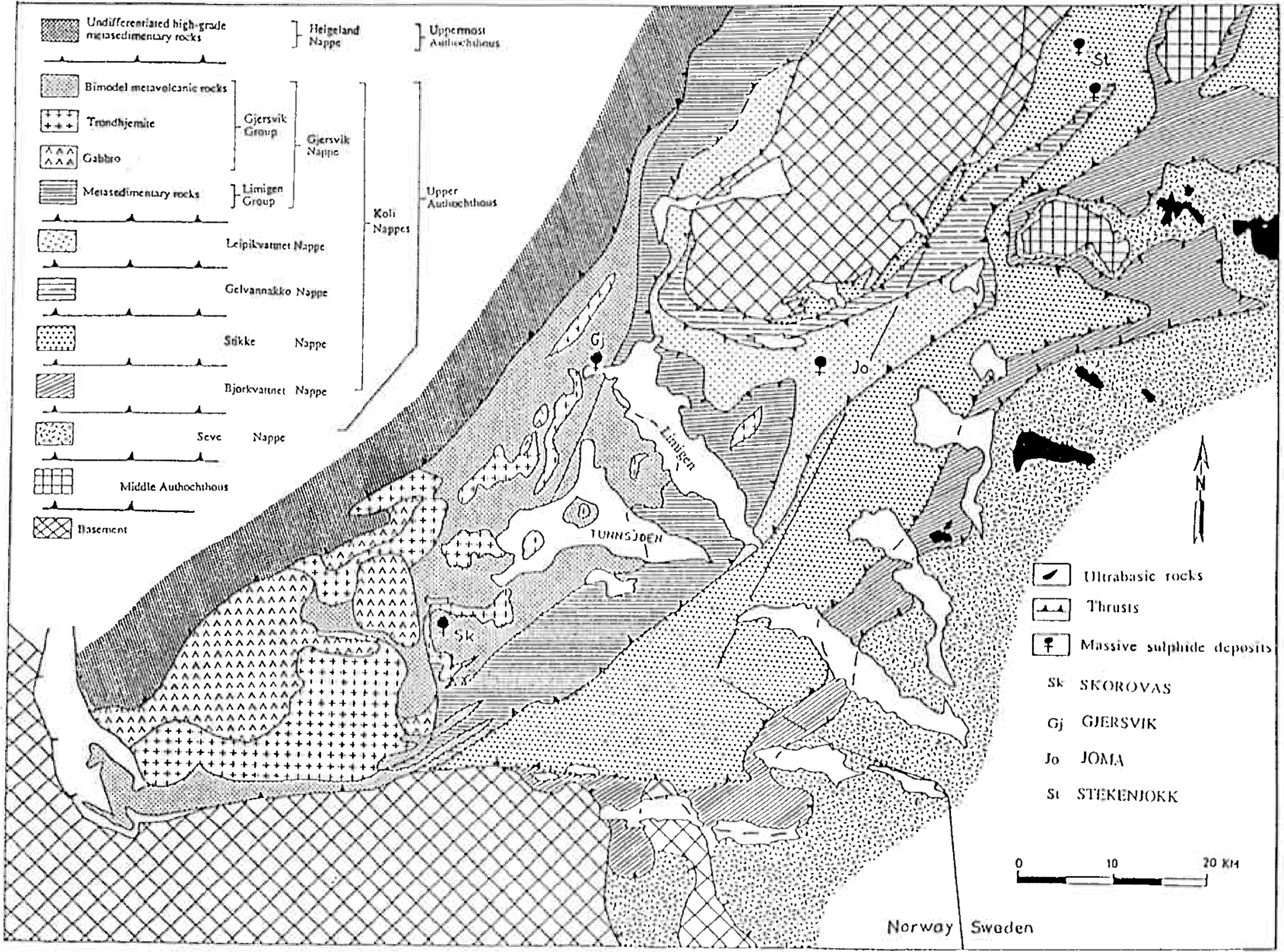


Fig. 1.2 map showing location of main ore deposits in Grong-Stekenjøkk district as well as main structural and stratigraphic units that can be distinguished within Køli Nappe, after Halls et. al., (1977) and Odling (1986)

mineralization are spatially associated mainly with the metafelsic, Na-rich, keratophyric pyroclastic complexes. The small iron-rich, exhalative chert are extensively present within the metavolcanic succession. The intrusive rocks associated closely with the metavolcanic succession comprise coarse-grained metatrondhjemite, fine-grained porphyritic metatrondhjemite and metagabbro.

1.2 Previous Research History

The Gjersvik deposit was discovered early in this century and was already planned for production as early as 1920s. However, it was never set into production because of disputes between the foreign shareholders and the Norwegian government. At present, remnants of the early elected workshops and offices can be seen along the Limingen Lake shore, near the entrance to the main exploration positions beneath the western limb of the ore horizon.

Early exploration of the deposit started with some preliminary drilling in 1912, and the ore reserves were first calculated by Steinar Foslie (1926) to be c. 1.4 m.t. The reserves have further been treated by Oftedahl (1958) and Pettersen (1972), respectively, to be c. 1.6 m.t. of ores (massive and disseminated) with an average of 31 % S, 1.6 % Cu and 0.9 % Zn with very few amounts of Pb and precious metals based on later complement drilling during the late 1950's and early 1960's.

Features of the major structural and stratigraphic units of the Gjersvik area were originally described by Steinar Foslie through the regional geological mapping work during the 1920's and 1930's. This work was published later by the Geological Survey of Norway in a series of 1:100000 map-sheets and synthesized by Oftedahl (1956) and Foslie & Strand (1956). More recent regional studies in geology, structure and lithology in the Grong-Gjersvik district were contributed by several authors (Halls et al., 1977; Kollung, 1979; and Lutro, 1977, 1979). Of them the detailed mapping on the scale of 1:50000 map-sheet in the Gjersvik area completed by Lutro in 1977 has been served as a basis for present detailed mapping and investigation of geology and ore deposits. The area around the Gjersvik orebody was mapped on the scale of 1:5,000 by Mellin (1979). The geological setting and genesis of the Gjersvik deposit were further discussed by Lutro (1979), Mellin (1979), Reinsbakken (1980) and Stephens & Reinsbakken (1981, 1986).

1.3 Outline of the present project

The present project was carried out while the author was in possession of a two year post-doctoral fellowship from N.T.N.F. (Royal Norwegian Council for Scientific and Industrial Research) from October 1, 1989 to December 31, 1991. The project was coorparatively organized by Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology, and Grong Gruber A/S, and was funded jointly by N.T.N.F., and Grong Gruber A/S. The research team consist mainly of Professor F. M. Vokes, Mr. A. Reinsbakken and Dr. Sun Haitian. The main aims of the project are to study the paleotectonic setting, volcanostratigraphic sequence, meta-igneous lithologies and geochemistry, and to study geological features of the ore bodies, structure and texture of the ores, ore compositions (chemistry and mineralogy), zoning, alteration and origin of the deposits, and to study relationship between volcanic processes and formation of the deposits, as well as to establish the advantageous targets for further evaluation and explosion of the massive base metal sulphide deposits in the Gjersvik area.

In order to establish the geological and stratigraphic relationship between meta-intrusive and meta-extrusive rocks as well as metafelsic and metamafic volcanic rocks and to investigate a potentiality finding of new massive sulphide bodies, the detailing surface mapping on the scale of 1:5,000 was carried out in the Gjersvikklumpen-Røyrvatnet area about 18 kilometers squares, located in the west of the Limigen Lake and the northeast of the Røyrvatnet Lake in the Gjersvik area. Two sheets of the geological map in the area were finished, which spent a total of nine weeks from 19th June to 24th August, 1990. However, it should be emphasized that complete mapping of the area was impossible due to the heavy cover and lack of good outcrop exposures on the surface in some places. Further regional surface mapping work on the scale of 1:20,000, combined with some detailing mapping of 1:5,000, was taken in the Gjersvik area in the summer from June to August of 1991 by Sun Haitian, Reinsbakken and Vokes. In addition, the drill hole #4 about 370 m in depth within the mapping area was logged.

A series of samples representative of different types of the rocks and the ores were collected from the massive sulphide orebodies, alteration zones, metavolcanic and meta-intrusive rocks in the mapping area and in the regional district. Among them, a total of 74 full silicate chemical analyses and trace elements analyses was performed on different types of the meta-intrusive and meta-extrusive rocks collected mostly from the surface and a few from drill hole. 8 specimen representative of different types of the altered rocks from the Gjersvik felsic complex were selected to make a full silicate chemical analyses and trace element analysis in order to study the alteration zoning. A total of 117 thin sections, 27 polished thin sections, and 26 polished sections have been determined, which they include mostly essential types of the rocks and the ores occurring within the Gjersvik intro-oceanic rifting volcanic arc. 14 specimen of the massive sulphide ores and 11 of the alteration zones were selected to make analysis in major ore metal elements such as Cu, Zn, Pb and Fe as well as precious element Ag, among which most of the ores and all of the altered samples were collected from the Gjersvik orebody, some of the ores being from exposure of the massive sulphide mineralization in the regional area.

During work of the research project, a series of the results related to the project was delivered to the Grong Gruber A\S. They include:

I Informal geological maps which cover the surface mapped area

(1) 5 sheets on the scale of 1:5,000 (Gjersvikruet DP 159-5-3, Vester-Gjersvikseteren DP 159-5-1, Gjersvik DP 160-5-3, Bjørkvatnet DO 160-5-4 and part of Kirma Dp 160-5-1,)

(2) 1 sheet on scale of 1:20,000 in the Gjersvik area.

II Reports

(1) Brief Summary of Mapping Work in The Gjersvikklumpen-Røyrvatnet Area of the Gjersvik, 1990

(2) Brief Summary for The Core Logging Bh 4, at RØRVATN, in Gjersvik Area

(3) Final Report

Section 2: Regional Geology

2.1 Regional geological setting

Thrust-emplaced terrains constitute the major structural styles of the central Scandinavian Caledonides shown in Figure 2.1. The Caledonian orogeny was proposed to have experienced one complete orogenic cycle, a so-called Wilson Cycle (Vokes, 1986). The events of the Caledonian cycle began in Vendian times (about 700 Ma ago) with marine transgression over the peneplaned surface of the Fennoscandian Shield and lasted until the end of the main period of Caledonian nappe development of allochthonous tectonic emplacement in the Late Silurian to Devonian time. Platformal and moigeosynclinal components of the Baltoscandian margin to the Baltica later Proterozoic-Silurian continent occur within the autochthonous cover sediments and within the thrust sheets of the Lower and Middle Allochthons consisting of the transported slabs of Proterozoic crystalline basement and Upper Proterozoic to Silurian sedimentary cover rocks. The overlying Seve Nappes (Upper Allochthon) are thought to have been derived from the rifted edge of Baltica and represent a continent-ocean transition zone. The higher thrust sheets, occurring in the Køli Nappes (Upper Allochthon) and Uppermost Allochthon, are far-transported slices of volcanic, intrusive and sedimentary rocks of ocean-floor, rifted arc, outer-arc basin, and back-arc marginal basin infill association, as well as ensialic fragments with abundant Lower Palaeozoic intrusions (Stephens, 1986). The Uppermost Allochthon was emphased to have a pre-tectonic spatial association with a western continent of the moigeosynclinal components, possible Laurentia (Stephen et. al., 1985).

The Gjersvik deposit is one of the chief stratiform massive base-metal sulphide deposits within the allochthonous meta-volcanic greenstone belt of the central Norwegian Caledonides. Existing knowledge of the major structural and stratigraphic units of the Grong-Stekenjøkk district indicate that the stratigraphic sequences containing the volcanogenic massive sulphide mineralization belong to the Køli Nappe, which is a structural unit of the Seve-Køli Nappe complex. Four divisions of the second-order tectonic units within the Køli level have been distinguished by Halls, et. al., (1977), which is shown in Figure 2.1. The first and upper-most of these is the Gjersvik Nappe, within which lie the Skorovas (Sk) and Gjersvik (Gj) ore bodies. Below this lies the Leipik Nappe, within which the Joma orebody (Jo) must occurs.

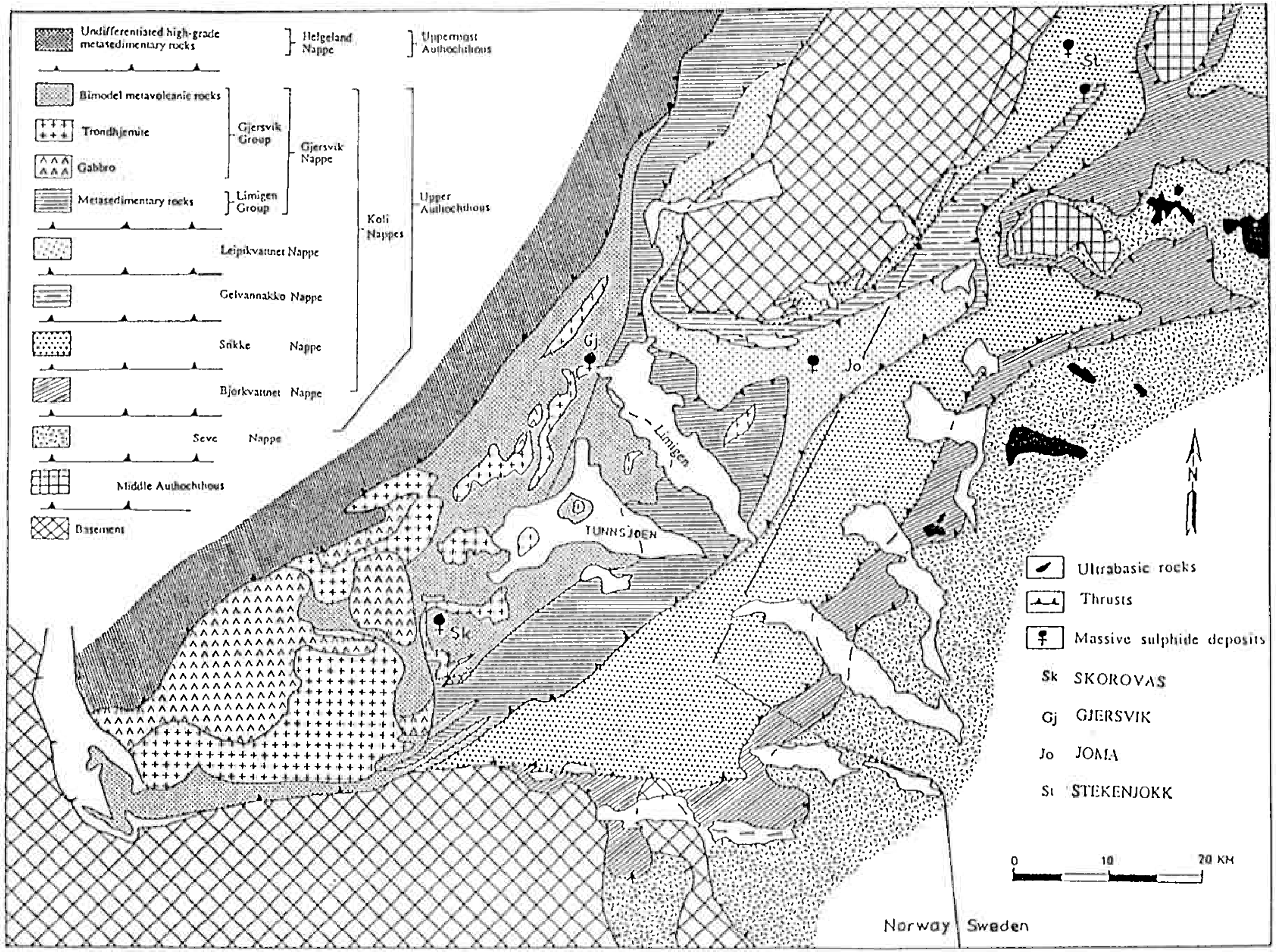


Fig. 2.1 map showing location of main ore deposits in Grong-Stekenjøkk district as well as main structural and stratigraphic units that can be distinguished within Koli Nappe, after Halls et. al., (1977) and Odling (1986)

Below this lies the Gelvernokko Nappe and, finally, the lower Køli Nappe unit, within which are situated the Stekenjøkk orebodies (St). The contact between the second-order tectonic units are dominated by thrusts and are taken, for the most part, to follow stratigraphic boundaries.

The present term, Gjersvik Nappe, has been defined by Halls et. al.(1977), which was suggested to use the name of the Limingen Nappe by Kollung (1979). It is structurally overlain and thrust to the west by the Helgeland Nappe (Ramberg, 1967) or the Helgeland Nappe Complex (Gustavson, 1975) consisting of a high-grade metamorphic sequences, which is of Cambrian age or older, which belongs to the Uppermost Allochthon. To the east, the Gjersvik Nappe is tectonic in contact with the Røyrvik Group of the Leipik Nappe consisting of intercalated layers of greenstone, quartzitic phyllite and graphitic phyllite, which is directly separated to the west from the overlying metasedimentary succession of the Limingen Group of the Gjersvik Nappe by major thrust (Halls et. al., 1977; Odling, 1986).

The Gjersvik Nappe has been subdivided into two groups by Halls et. al. (1977) and Lutro (1979), the Limingen Group, comprising predominantly a thick sequence of metasedimentary rocks of polymictic conglomerates and flysch-like sediments, and the Gjersvik Group, composed of meta-volcanic succession dominated by the greenstones of tholeiitic composition plus subordinate keratophyric pyroclastic rocks of rhyolitic composition, taken together with closely associated plutonic masses of trondhjemite with minor amounts of gabbro. The relationship between the Gjersvik and the Limingen Groups used to be proposed as a thrust contact by Foslie & Strand (1956) and Oftedahl (1956). In recent years, however, geological investigations have shown that the boundary between the two Groups is very probably of a primary nature (Halls, et. al., 1977; Lutro, 1979). The evidence is that the debris within the conglomerates in the Limingen Group can be matched directly with the magmatic complexes, i.e. trondhjemite, keratophyric pyroclastic complexes and greenstones of the Gjersvik Group. The Limingen Group has, thus, been interpreted as being stratigraphically younger than the Gjersvik Group and the sequence in the Gjersvik Nappe has been considered to be generally inverted. The relationship of the eruptive and sedimentary units in the Gjersvik Nappe can be interpreted in terms of the evolution of an ensimatic island arc which underwent uplift and erosion prior to emplacement on the Fennoseandian basement during the climatic stages of collision tectonism of the Caledonian orogeny in Silurian times (Halls, et. al., 1977).

Structural and stratigraphic correlations in chronology are made difficult by the structural complexity, by the sparsity of fossil remains and by the penetrative effects of tectonic deformation and regional metamorphism. Sufficiently detailed studies, however, based on the comparison of stratigraphy and structure in regional scale have made possible to support the age of the massive sulphide orebodies and their host stratigraphic sequences. The metavolcanic greenstones of the Gjersvik Group and of the Røyrvik Group, which host respectively the Gjersvik and Skorovas ore deposits as well as the Joma ore body, have generally been assumed to be Early to Middle Ordovician (Gale & Roberts 1974; Halls et. al. 1977; and Reinsbakken 1986). Further more, they were chronologically proposed by Gale and Pearce (1982) that the greenstone hosting the Joma orebody is stratigraphically younger than that containing the Gjersvik and the Skorovas ore deposits. The Stekenjøkk ore deposits were cited by the faunal fossil evidence to be a lower Silurian age (Zachrisson, 1971).

In recent years, some isotopic dating from the intrusive plutons associated closely with the Gjersvik volcanic arc made it possible to evaluate age of the magmatic complexes. Two U-Pb zircon ages of 483 +/- 4 Ma ana 456 +/- 2 Ma have been produced respectively from a foliated concordant trondhjemite body at the north of the Bjørvatnet about 2 km in the northern part of the Gjersvik Group by Kullerud et. al., (1988) and from the Møklevatnet granodiorite in the most southern part of the Gjersvik metavolcanic complex by Roberts and Tucker (1991). As the present state of knowledge, sufficient geological evidences have demonstrated that the Møklevatnet granodiorite has been proposed to be tectonostratigraphically highest part of and the youngest major pluton within the Gjersvik Nappe, and its crystallization age (456 +/- 2 Ma) can also be regarded as a maximum age for the oldest sediments of the unconformable overlying Limingen Group (Roberts and Tucker, 1991), while the 483 Ma trondhjemite is closely associated with the dark greenstone that has evidently proposed to be stratigraphically lower part of the Gjersvik metavolcanic succession on the basis of the detailing surface mapping. Thus, absolute dating have further confirmed the geological conclusion that age of the Gjersvik magmatic complex is most probably early to middle Ordovician. Meanwhile, they also contribute a considerable evidence that magmatic activity of the Gjersvik Nappe covered a time span of, at least, 25 to 30 million years. A previous Rb-Sr dating for the plutons, using 3 granodiorite samples together with one sample of assumed cogenetic gabbro yielded an isochron age of 433 +/- 1 Ma, which was interpreted as probably representing a deformational and low-grade metamorphic event (Raheim et. al., 1979).

2.2 Stratigraphic sequence of the Gjersvik Group

The present discussion is based on the surface mapping on the scale of 1:5,000 in the Røyrvetnet-Gjersvikklumpen area and on the scale of 1:20,000 in the Gjersvik area (Fig. 2.2), carried jointly out by the research team of Department of Geology and Mineral Resources Engineering, NTH., and Grong Gruber A\S during 1990 - 1991. The attention will focus on the metavolcanic succession rather than the metasediments of the Limingen Group. This was designed to re-examine the major structural and lithologic boundaries within the plutonic to volcanic sequence, to build up further stratigraphic successions, to establish relationship between meta-volcanic successions, between plutonic and eruptive rocks, and between lithologies and sulphide mineralization of the Gjersvik Group, and to make, as far as possible, a further interpretion of geology and paleotectonic environments as an extent of Foslie, Oftedahl and Lutro since they have affected the Gjersvik area.

The Gjersvik Group is mainly made up of a metamagmatic complex, which was previously called the Gjersvik Nappe (Oftedahl 1956, Foslie & Strand 1956) and the Skorovass Greenstone (Oftedahl 1974), but has been refined as a group, the Gjersvik Group (Halls et al. 1977; Lutro 1979). Outcrop of the succession from the Skorovas to the Gjersvik area is over a strike length of approximately 80 km along N.N.E. - S.S.W., with the widest up to about 20 km in the south, but thins out so quick from the Gjersvik village towards the north so as to become only about 100 m wide at the western part of the Sorvatnet in the north (Fig. 2.1). The stratigraphic trend is roughly along the N.N.E. - S.S.W.

The succession of the Gjersvik Group was originally subdivided into three Formations (Lutro, 1979) or into four major units (Reinsbakken, 1981). Due to the structural complexity and the penetrative effects of tectonics during regional deformation and metamorphism, contact between the meta-extrusive successions and between the meta-extrusive and meta-intrusive rocks are almost tectonic. This makes it difficult to recognize the original relationship for different geological bodies. On the basis of the detailing mapping,

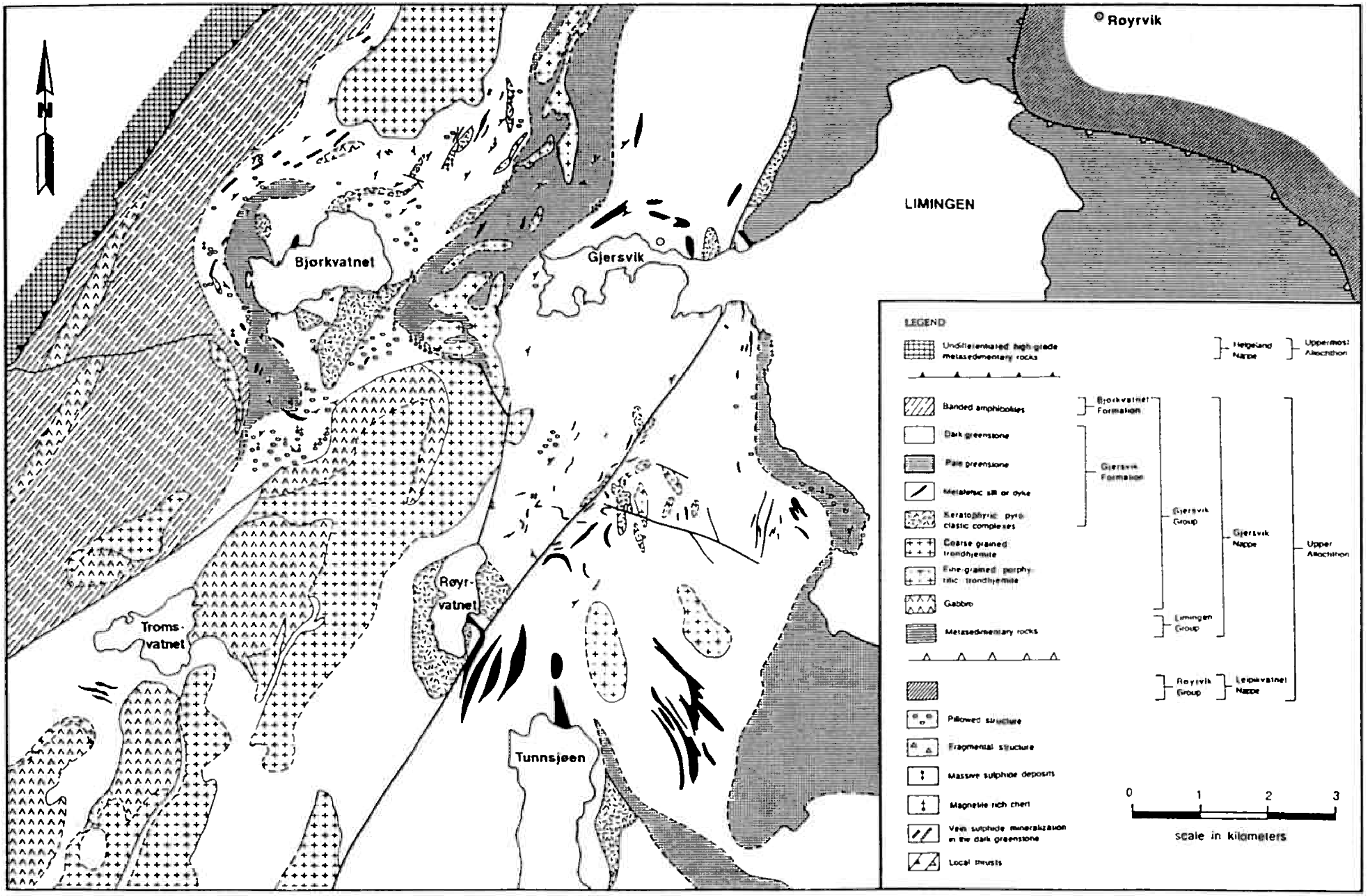


Fig. 2.2 Sketch geological map of the Gjersvik area

however, some geological features such as metamorphic grade, lithologies, rock associations, geochemistry of the rocks and relationship between rock-types and sulphide mineralization can be comprehensively used in determinating the stratigraphic succession. Present work by the author suggests that the metavolcanic succession of the Gjersvik Group is subdivided into two major Formations and several units:

Bjørkvatnet Formation: (oldest unit, including Kleiva and Bjorkvassklumpen formations of Lutro, 1979), comprising mainly massive amphibolites

Gjersvik Formation: which can be subdivided into three units:

Unit 1, (older unit) dark greenstones, consisting largely of massive, schistose and pillowed biotite-, stilpnomelane-,epidote-bearing and chloritic greenstones.

Unit 2, keratophyritic pyroclastic complexes, massive sulphide mineralization and exhalative sediments.

Unit 3, (youngest unit) pale greenstone.

Relations of the stratigraphic successions in the Gjersvik Group are schematically shown in the Figure 2.3.

Bjørkvatnet Formation: This Formation extending in a NE-SW direction is located in the west of the Bjørvatnet lake and occurs at the highest westernmost level of the Gjersvik Nappe directly beneath the high-grade metamorphic Helgeland Nappe Complex, which corresponds to the Kleiva and Bjørkvassklumpen Formations of Lutro (1979). The Formation is tectonicaly overthrust to the west by the Helgeland Nappe Complex and is structuraly in direct contact to the east with the greenstones of the Gjersvik Formation. It consists predominantly of dark, massive and banded amphibolites plus small fine-grained actinolite schists of metamorphosed grade up to amphibolite-greenschist facies, which is different from and distinct to the Gjersvik Formation the lower greenschist facies. Near the boundary to the

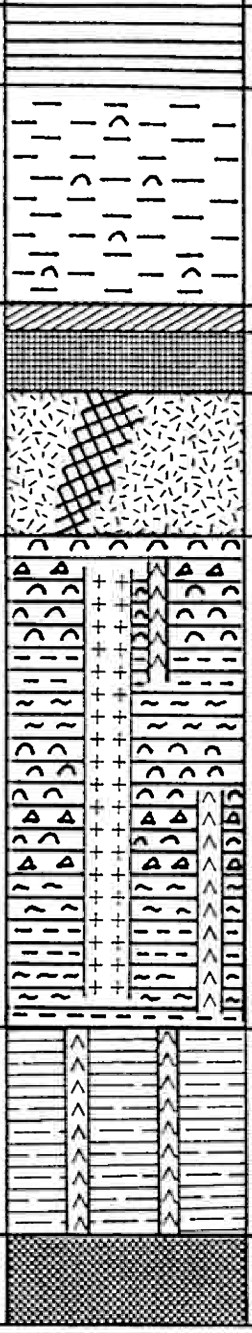
Group	Formation	Units	Stratigraphic column	Rock types
Limigen Group				younger metasedimentary rocks
Gjersvik Group	Gjersvik Formation Gjersvik intra-ocean rifting volcanic arc	D		pale, massive to schistose, Fe-poor, carbonate-rich, actinolite-bearing greenstone associated with a few pillowed structure
		C		exhalative sedimentary horizon massive sulphide ores keratophyric pyroclastic complex associated with the feeder zone characterized by intensive alterations and veinlet-type pyritic mineralization
		B		dark, massive to schistose, Fe-rich, pillowed, stilpnomelane-, biotite-, epidote-bearing and chloritic greenstone characterized by massive basaltic flow, breccia, tuff and pillowed lava, which were intruded by trondhjemite and gabbro
	Bjørkvatnet Formation the remnant of an ocean floor	A		dark, massive and banded amphibolites and schistose actinolite schists, which were intruded by gabbro-diorite complexes
Helgeland Nappe				older high-grade metamorphic rocks

Fig. 2.3 Schematic volcanostratigraphic column of the Gjersvik Group and its stratigraphic relationship to Helgeland Nappe and Limigen Group (not to scale)

Gjersvik Formations, the greenstone often becomes intensively schistose and steeply dipping, generally varying 60 - 80 degrees because of the extensively tectonic compression, and the greenstone also frequently occur as tectonic thin layers about several meters thick within the massive amphibolite body. It is obvious that a compressive tectonic belt exists between the Bjørvatnet and Gjersvik Formations and the massive amphibolite mass appears to thrust directly on the greenstone of the Gjersvik Formation.

The massive amphibolite comprises largely amphibole with minor albite, actinolite, chlorite and epidote. Amphibole is generally anhedron, blue-greenish in colour with associating two good cleavages at angle of the amphibole in the thin section. The amphibole is often strongly oriented along the schistosity. The actinolite schist consists predominantly of actinolite plus small amounts of chlorite and epidote. Sometimes, the disseminated sulphide mineralization associated with hydrothermal alterations are present as bands within the amphibolite succession. Occasionally, closely-packed pillow structure and thin magnetite bands or iron formation attest to the submarine origin of at least some of the amphibolites and actinolites. The amphibolites are intruded by gabbro-diorite complexes. Some petrochemical data show that the massive amphibolites have a MORB affinity, which is thought as the remnant of an ocean-floor based on which the Gjersvik volcanic arc was built (Reinsbakken, 1981). The Bjørkvatnet Formation is, thus, interpreted stratigraphically as the oldest unit of the Gjersvik Group.

Gjersvik Formation: This formation occurs in the major, eastern part of the Gjersvik Group and is initially in contact to the east with the metasedimentary succession of the Limingen Group. It lies structurally below and is generally sharp in contact to the western, older stratigraphic unit of the Bjørkvatnet Formation (Fig. 2.2).

The formation consists predominantly of a thick bimodal meta-volcanic suite in association with the plutonic infrastructures, which constitutes the Gjersvik volcanic arc. The bimodal feature is very obvious in both of the eruptive and intrusive complexes which are composed mainly of basic and acidic but essentially lack intermediate rocks (Fig. 2.4). The metavolcanic rocks are composed mainly of the tholeiitic greenstones and the keratophyric pyroclastic complexes of rhyolitic composition, while the meta-intrusive rocks comprise the trondhjemite and gabbro. No typical andesite and diorite have so far been found to occur within the Gjersvik

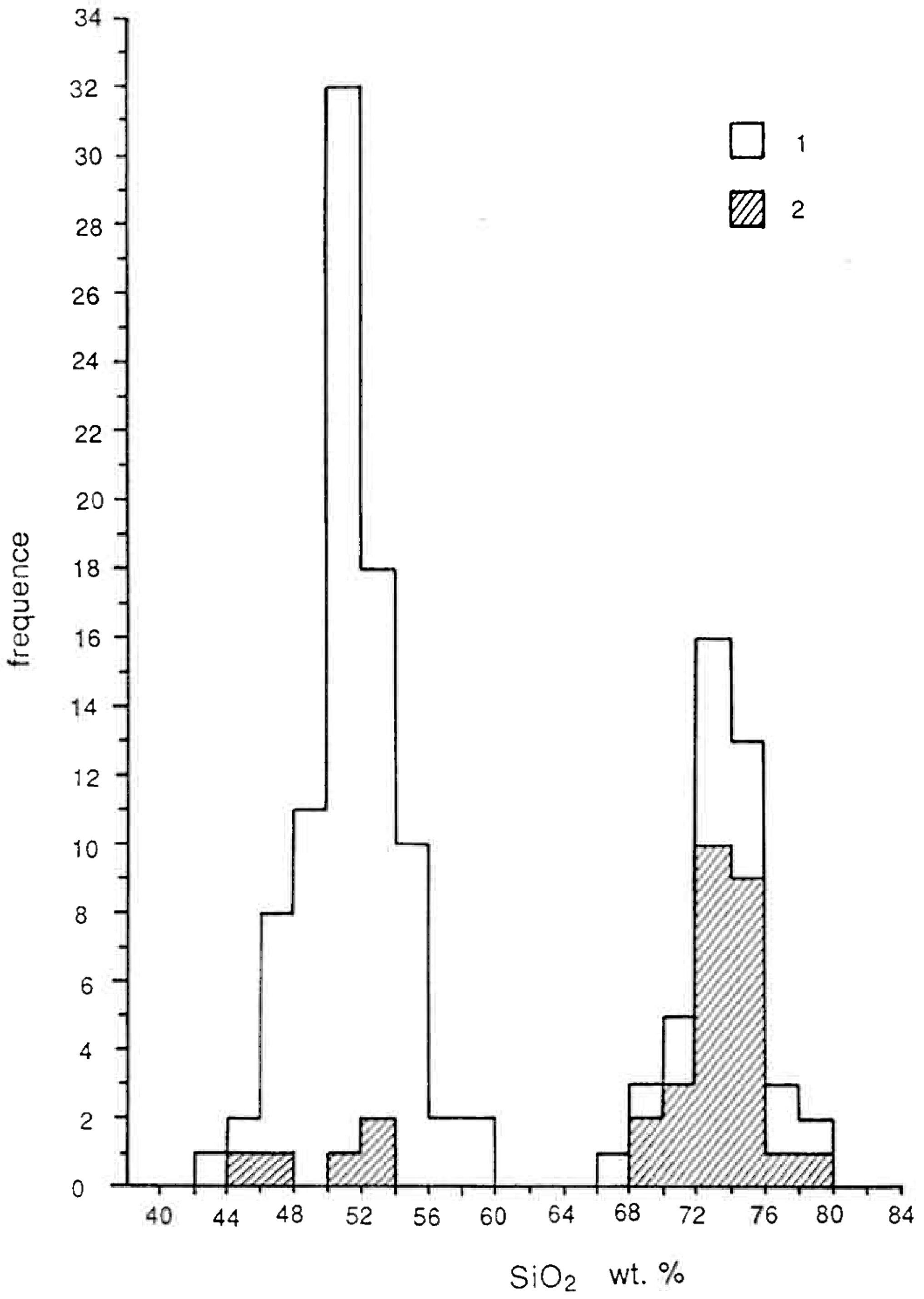


Fig. 2.4 Frequency ranges in SiO2 contents of the meta-extrusive and meta-intrusive rocks of the Gjersvik Formation

Total of 129 rock chemistry data, 56 of them quoted from Lutro (1979)

1 - meta-extrusive rocks; 2 - meta-intrusive rocks

Formation. It should be, however, emphasized that the metavolcanic rocks are dominated by the mafic metavolcanic greenstones plus minor amounts of the felsic keratophyric pyroclastic complexes. On the basis of the detailing surface mapping work, it is reasonable to make a fundamental estimation that the mafic metavolcanic rocks occupy at least two thirds of the total volcanic discharge even though it is, in fact, difficult to describe exactly proportion between the two. In contrast with this, the plutonic infrastructures are dominated by the trondhjemite in comparison to the gabbro.

The meta-volcanostratigraphic succession of the Gjersvik Formation has been proposed to be subdivided into three units: older unit of the dark greenstone, younger unit of the keratophyric pyroclastic rock, and youngest unit of the pale greenstone. The evidences for this subdivision result from that (1) these three stratigraphic units have a considerable scale for each one in their occurrences and distributions, and they can be apparently distinctive and separated to each other in a series of features in the field. The keratophyric pyroclastic complexes are pale to white in colour, very fine-grained, massive, very hard and compact, slight magnetic, and consist predominantly of acid volcanic lava, pyroclast, tuff and small dykes or sills that are generally clear in contact with the greenstones. The dark greenstone is generally dark green, massive or schistose, strong to slight magnetic, well developed pillowed in structure and associated in places with some special mineral assemblages such as biotite and stilpnomelane, while the pale greenstone is characterized by pale green colour, massive to schistose, and poorly developed pillowed structures, no-magnetism, carbonate-rich, and some distinct mineral assemblage such as actinolite; (2) contact between dark greenstone and pale greenstone is sharp but original, for the exhalative sediments often occur conformably just in junction between the two greenstones. More importantly, the dark and pale greenstones can be distinctly distinguished in geochemical properties, especially in trace element geochemistry, seeing discussion later; (3) the exhalative sedimentary horizon, such as magnetite-rich chert, related in some ways to an episode of the felsic volcanic activities occurring between the tholeiitic basalts at two stages occurs extensively between the dark and pale greenstone successions, which become a very useful stratigraphic mark: (4) The keratophyric pyroclastic complexes occur mainly between the dark and pale greenstones or are associated predominantly with the dark greenstone but very few with the pale greenstone. This relation appears to display the keratophyric pyroclastic rock was formed later than the dark greenstone but earlier than the pale greenstone. Thus, the keratophyric pyroclastic complexes have been interpreted to be related mainly to an episode of felsic magmatic activities between the basaltic magma processes at two stages; and (5) The hydrothermal alterations and sulphide mineralization are mainly associated with the keratophyric pyroclastic complexes or extensely occur within the dark greenstone but very few in the pale greenstone. It is evidently proposed that the major sulphide mineralization, including the mineralization within the dark greenstone, are predominantly related to an episode of the felsic volcanic processes between the basaltic magma processes at two stages.

These subdivided stratigraphic units will be described below in order from older to youngest one.

Unit 1: dark greenstone

The dark greenstone extends along N.N.E. - S.S.W. trend in strike and occupies in the most part of the metavolcanic rocks of the Gjersvik Formation (Fig. 2.2). It is generally characterized by dark green in color, Fe-rich, slight to strong magnetic property and massive to variable schistosity as well as developed pillowed structures in hand specimen and in the field outcrops. The magnetic property associated with the dark greenstone had been used as one of the most characteristic indications distinct from the pale greenstone during the surface mapping work. The experience of the mapping indicates that it can be confirmed as a subtype of the dark greenstone when the greenstone is associated with a testing magnetism with the magnet bar in the field outcrops, while the pale greenstone and the dark, altered greenstone are certainly not of magnetism. The dark greenstones are also extensively associated with some typical volcanic structures such as massive, pillowed, amygdaloidal and fragmental structures (Fig. 2.5, 2.6, 2.7), which appear to indicate that they were originally deposited as pyroclastic breccias and tuff, pillowed lava and massive flows. The pillowed structure indicates a submarine volcanic environment (Wilson 1960; MacDonald 1968). The amygdales are round in shape, and generally vary between 0.5 - 2 mm but occasionally up to 5 - 10 mm in diameter. They consist predominantly of epidote or epidote + quartz + carbonate assemblage, and are over in places 10 vol.% such as the dark greenstone revealed by the drilling core No.4. This feature appears to be important in determining the paleo-sedimentary environment because the study of a modern

Fig. 2.5 Dark, brecciated greenstone in the east of the Bjorkvatnet Lake about 600 m along the Gjersvik-Røyrvik road

Fig. 2.6 Amygdaloidal structure within the dark greenstone in the east of the Gjersvik ore body about 350 m along the Gjersvik-Røyrvik road

Fig. 2.7 Dark, pillowed greenstone in the east of the Bjørkvatnet Lake about 600 m along the Gjersvik-Røyrvik road

bimodal volcanic activity in back-arc rifting environment has indicated that basalts associated with 15-35% vesicles 0.25-5mm in diameter were erupted in depths of 1500-2500 m (Hochstaedter et. al. 1990) or the samples of basalts contain 10-50% vesicles, 1-10 mm in size despite an eruption depth of 2000 m (Urabe et.al. 1990).

On the basis of the main rock-forming mineral assemblages, several subtypes of the dark greenstone, i.e. stilpnomelane-, biotite-, epidote-bearing and chloritic greenstones, can be distinguished. The stilpnomelane- and biotite-bearing greenstones only occur locally in the dark greenstone succession and are mainly restricted in the vicinity of, especially in the eastern part of the major N.N.E. - S.S.W. trend fault although they were occasionally found in other places. The stilpnomelane- and biotite-bearing greenstones are characterized by more dark colour, massive to slight schistose structure and strong magnetism. The epidote is sometimes associated with this kind of the greenstone. The massive biotite- and stilpnomelane-bearing greenstone is generally not associated with pillowed, amygdoloidal and pyroclastic structure although the pillowed structure does occur in some places, for instance in the western shore of the Limingen lake. The presence of biotite and stilpnomelane in the dark greenstone has been interpreted mainly as a product of metamorphism in relation to the major fault deformation in the area. The evidences result from that (1) the stilpnomelane- and biotite-bearing greenstone are only present in local places in where they tend to be closely associated with the major faults; (2) the stilpnomelane and biotite occur not only in the greenstone, but also in the felsic pyroclastic complexes when they represent; and (3) study of the microscope indicates that the stilpnomelane crystal cut all of other rock-forming minerals constituting the greenstone and metafelsic volcanic rocks, which shows they are of the latest product of the mineral growth.

The epidote-bearing and chloritic greenstones are major subtypes of the dark greenstone. They are characterized by variable schistosity and apparently pillowed structure, which indicate a nature of the basaltic breccias, tuff and pillowed lava. The pillowed horizon appears, sometimes, to constitute the continue belts in occurrence, which often occur in near boundary to or are in contact with the pale greenstone. The pillowed dark greenstone belt is often associated with the keratophyric pyroclastic complexes and with the exhalative sediments. For example, the most important pillowed greenstone belt is mainly distributed along NE-SW trend in the west of the trondhjemite complex located in the south of Bjorkvatnet, via area surrounding the Bjorkvatnet, towards the north, extending about 7 km long with varying from several tens to hundreds meters in thickness. The horizon consists of thick, compact pillowed greenstone plus together some amygdaloidal and pyroclastic greenstone. This pillowed greenstone belt is directly in contact to the east with the pale greenstone, which is often separated by the distal exhalative sedimentary chert and magnetite layers.

Unit 2: keratophyric pyroclastic complexes and exhalative sediments

Keratophyric pyroclastic complexes

The keratophyric pyroclastic complexes are an important type of the metavolcanic rocks constituting the Gjersvik volcanic arc although they are subordinate in volume in comparison with the greenstone. They are extensively scattered throughout the metavolcanic pile and are characterized by irregular morphologies and variable sizes in occurrence (Fig.2.2) as rather thin dikes or small complexes ranging generally from several to a few tens, occasionally to hundreds of meters in thickness, and from tens to hundreds or thousand meters in length. The keratophyric pyroclastic complexes are light grey or brown in color, massive or lightly schistory in structure, very fine-grained, very hard and compact and slight magnetism.

According to lithologic association and occurrence, they can be subdivided into two groups. One is these being massive, homogeneous, very hard and fine-grained, small in size several to tens meters wide, tens to hundreds meters long, and occurring as dykes or sills (Fig. 2.8); Another is those occurring as the keratophyric pyroclastic complexes in relative larger scales consisting mainly of metafelsic pyroclastic rocks, mostly representative of recrystallized felsic pyroclastic rocks and tuff. For example, the biggest keratophyric pyroclastic complex in the Gjersvik area, located in the south of Bjorkvatnet, about 1800 m in length with varying 400 to 700 m wide, extending along NE - SW on the surface exposure, is apparently characteristic of the volcanic fragmental structure, and the felsic complexes associated with massive sulphide orebodies are also composed mainly of the keratophyric pyroclastic complexes such as the Gjersvik, Tjiermerjaevrieh and Annlifjellet (Fig. 2.2). This kind of the pyroclastic complexes consists of the felsic volcanic fragments, generally angular to subangular, about

Fig. 2.8 Typical felsic dykes or silles (f) and its contact relationship to the dark greenstone (d), in the west (upper) of and the east (low) of the Bjørkvatnet Lake

several mm to tens cm in size, setting in the matrix of felsic tuff (Fig. 2.9). It seems reasonable to suppose that the felsic dykes or sills probably represent a sub-volcanic phase of the extrusive pyroclastic complexes. What is important is that the massive sulphide deposits to have so far been found in the Gjersvik area are predominantly associated with the extrusive, keratophyric, pyroclastic complexes rather than the sills or dykes.

Exhalative sediments

The exhalative sediments consisting predominantly of thin, pyritic chert and magnetite-rich pyritic chert have been recognized to occur extensively within the greenstone succession, within which they have been found to distribute mainly either within dark, pillowed greenstone (Fig. 2.10) or in (or near) junction between dark and pale greenstones (Fig. 2.11, 2.12). Some of them can be evidently traced in connection with a volcanic episode of the keratophyric pyroclastic eruption occurring between two major basic magmatic activities of dark and pale greenstones during construction of the Gjersvik volcanic arc. For example, the thin exhalative pyritic chert and magnetite-rich pyritic chert extensively occur within the dark, pillowed greenstone or in boundary between the dark and the pale greenstone in the vicinity in the south and southeast of the biggest felsic pyroclastic complex in the south of the Bjørkvatnet Lake. Meanwhile, the proximal exhalative sedimentary massive sulphides and magnetite-rich cherts have also been recognized to be directly associated with the felsic pyroclastic complex and to occur between the felsic complex and the greenstone exposed in the southern shore of the Bjørkvatnet Lake. The proximal exhalative sediments within the greenstone can be traced as a lateral extension of the exhalative horizon of the massive sulphides and magnetite-rich cherts associated with the felsic pyroclastic complex.

The exhalative sediments seem to be mainly concentrated in two belts that are consistent with the distribution of the pillowed greenstone belts, even though they do also occur in other places outside these two belts. One belt is concentrated in the area from vicinity of the Sorvatnet, via the Bjørkvatnet extending towards the NE direction, another in the western shore of the Limingen Lake. The former occur mainly within the dark, pillowed greenstone or between dark and pale greenstones, while the latter are largely associated with the pale, pillowed greenstone or in junction between dark and pale greenstone. The exhalative sedimentary layers are thin,

Fig. 2.9 Fragmental structure in the keratophyric pyroclastic complexes in the northeast of the Bjørkvatnet Lake about 800 m

Fig. 2.10 Exhalative sedimentary chert within the pale, pillowed greenstone, at the western shore of the Limigen Lake

Fig. 2.11 Exhalative sedimentary, sheet-like magnetite-rich pyritic chert occurring between dark, massive-schistose greenstone (d) and pale, schistose greenstone (p), at the southeast of the Bjørkvatnet Lake about 900 m

Fig. 2.12 Contact relationship among the dark, massive greenstone (d), exhalative sedimentary, sheet-like magnetite-rich chert (e) and pale, schistose greenstone (p), at the northeast of the Bjørkvatnet Lake about 2000 m

Fig. 2.13 Inclusions of the gabbro within the coarse-grained trondhjemite, in the gabbro-trondhjemite complex at the west and northwest of the Rørvatnet Lake

generally less one meter but in places up to several meters thick, sheet-like or lens-like, very regular or folded, and completely concordant with their country rocks of the meta-volcanic succession. They can be in places discontinuously followed several hundred meters along an identifical stratigraphic horizon either within the dark, pillowed greenstone such as in the western shore of the Limingen Lake and vicinity of the Sorvatnet Lake, or in boundary between dark and pale greenstones such as in the south of the Bjørtvatnet Lake and in the northwest of the Gjersvik Lake.

Unit 3: pale greenstone

The pale greenstone with a N.E. - S.W. trend occurs mainly in the northwestern and southeastern parts of the area, respectively (Fig. 2.2). In the southeast, especially in the east of the Tunnsjoen Lake, the pale greenstone comes in direct contact to the east with the Limingen Group and is overlain to the west by the dark greenstone. The pale greenstone is mainly pale green in color, massive to variably schistose in structure, porphyritic in texture, Fe-poor and no magnetism, and carbonate-rich. Pillowed and fragmental structures are relatively poorly associated with the pale greenstone in comparison with the dark greenstone although they do occur in places. However, a belt with a good pillowed structures is present in the western shore of the Limingen Lake, within which the pale, pillowed greenstone is often associated with exhalative sediments. This belt is in contact to the west with the dark greenstone. It appears that the pale greenstone occurs dominantly as a massive basaltic flow.

The greenstones distributing in the areas both of the southeast and the northwest of the Bjørvatnet used to be considered as a subtype of the dark greenstone in the map on the scale of 1:50,000 by Lutro (1979), but they have been classified into the pale greenstones based on the surface mapping in combination with their geochemical natures. These greenstones are characterized by moderate green, varying, from slight to strong magnetism, very developed pillowed structure, associating with altered vein and disseminated sulphide mineralization, and very significant chemical compositions, including major and trace elements, which these features are consistent with the dark greenstone, but different and distinct from the pale greenstone. In addition, the exhalative sediments which were found often to occur between the dark and pale greenstones and within the pillowed greenstone in these area have been considered as one of the important stratigraphic market separating the dark and pale greenstones.

In comparison with the dark greenstone, only few felsic rocks have been found to be associated with the pale greenstone. This phenomena has also been proposed as an evidence that the pale greenstone was originally deposited later than the felsic volcanic processes. The primary contact between the dark and pale greenstones has in places been well observed when the exhalative sedimentary horizon occurs between them although this contact relationship is not always clear due to the tectonic affection. In the northwest of the Gjersvika Lake about 1400 m, for instance, there is a very good outcrop that displays a rather clear stratigraphic relationship among the exhalative horizon, dark and pale greenstones. The exhalative magnetite-rich chert, about 50 m long and varying 0.5 to 3 m thick, occurs conformably just in the junction between the dark, magnetite-rich greenstone (hanging wall) and the pale, no-magnetism greenstone (footwall) (Fig. 2.12). More significantly, the dark and pale greenstones occurring directly in each side of the exhalative sedimentary horizon, respectively, are very different and distinct to each other in the chemical compositions of major and trace elements. The magnetite-rich chert layer has been interpreted to be related to an episode of felsic volcanic activity occurring between the periods of two tholeiitic magmatic processes, the dark and pale greenstones being their metamorphosed equivalents, respectively. This kind of contact relationship among the dark, pale greenstones and exhalative sediments, in which the dark and pale greenstones are very characteristic and distinct in chemical compositions, was also observed on the outcrops in the southeast of the Bjørkvatnet.

2.3 Plutonic infrastructures within the Gjersvik volcanic arc

Metavolcanic stratigraphic sequence of the Gjersvik Formation was intruded by a series of plutonic infrastructure. The intrusives are also characterized by bimodal compositions, which can be correspond with the metavolcanic rocks within the Gjersvik volcanic arc. Three different types of the intrusive rocks have been recognized: metagabbro, coarse-grained metatrondhjemite and middle to fine-grained porphyritic metatrondhjemite. The gabbro and trondhjemite have been considered, respectively, to form the roots of contempeous, submarine volcanic sequences of tholeiitic and rhyolitic compositions.

In fact, the trondhjemite and gabbro are often closely associated spatially together and constitute the bimodal intrusive complexes (Fig. 2.2). It should be emphased, however, that contact between the trondhjemite and gabbro within the intrusive complexes is generally not clear but transitional. Enclusions of the gabbro, on the one hand, have locally been found to occur within coarse-grained trondhjemite as sub-angle to sub-round blocks varying from several centimeters to meters in size (Fig. 2.13), and some of them still remain the resorted rims (Fig. 2.14). The trondhjemites, on the other hand, occur sometimes within the gabbro as bands or lenses (Fig. 2.15). This phenomenon has been considered as two possibilities: One is that the gabbro blocks occur as xenoliths within the trondhjemite which indicates that intrusion of the trondhjemite is later than that of the gabbro; Another, most possibly, is that enclusions of the gabbro represent the remains of partial melting producing trondhjemite magma in gabbro or basaltic sources and that the intrusive complexes consisting of trondhjemite and gabbro represent the ascending masses of the tectonic emplacement from the deep crust in where the remains of gabbro and the trondhjemite produced by the partial melting coexist.

It is very difficult, in fact, impossible to observe the primary contact relationship between the plutonic complexes and metavolcanic rocks because of the tectonic destruction, especially affection of the penetrative structure. The present contact between the two is mostly tectonic, which has clearly been observed along boundary of the big plutonic complex located in the western and northwestern part of the Røyrvatnet. The intrusive complex apparently overthrusts on the dark greenstone with intermediate angle (Fig. 2.16). However, the contact between the fine-grained porphyry trondhjemite and the massive, dark, stilpnomelane- and biotite-bearing greenstones occurring in the Gjersvikklumpen area, east of the major NE - SW trend fault, appears to be more primary. On the basis of detailed mapping, it has been observed in the outcrop on the surface in the north of Røyrvatnet that the contact between the coarse- and fine-grained trondhjemites is gradual and transitional, which indicates that they probably belong to different deep-, and shallow-seated intrusive phases of contemporaneous magmatic processes.

2.4 Structure styles of the Gjersvik Group

The sequence of the Gjersvik Nappe has suffered a low-grade regional metamorphism and a

Fig. 2.14 Resorted rim of inclusions of the gabbro within the coarse-grained trondhjemite, in the gabbro- trondhjemite complex at the west and northwest of the Rørvatnet Lake

Fig. 2.15 Trondhjemite occurring as bands and longer lenses within the gabbro, in the gabbro- trondhjemite complex at the west and northwest of the Rørvatnet Lake

Fig. 2.16 Tectonic contact between the coarse-grained trondhjemite (t) and dark greenstone (d), at the northwest of the Rørvatnet Lake

Fig. 2.17 Fold with overlapping schistosity parallel the fold- axe place within the pale greenstone, at the western shore of the Limigen Lake

complex deformation history, at least, three or five major and minor phases of Caledonian deformation (Lutro, 1979; Mellin, 1979). The relationship among these phases of deformation was well elucidated in sequence of metasedimentary rocks of the Limingen Group (Lutro 1979), but is very difficult to be clearly distinguished each other within metavolcanic stratigraphic sequence of the Gjersvik Group. However, the surface mapping suggests that the strong deformation do occur and some of them have still been preserved in places within the metavolcanic stratigraphic sequence. The description of structures in follow is focused in the mapping area, but the further structure geology concerning the Gjersvik Nappe should be suggested to see the articles of Lutro (1979).

Fold

The folds can not be often observed on the outcrops in sequence of metamagmatic complexes in the Gjersvik Group because of an extensively schistose structures, generally, dipping NW trend with 40 - 50 dip angles. It appears that the folds have mainly been reserved in two styles: one is open structure with steeply approximately dipping NE -SW axial planes occurring in the deforming trondhjemites, metafelsic complexes and greenstones. Some fold was cut by the schistosity parallel the fold place (Fig. 2.17); another is more tightly structure with steeply dipping and different striking trends existing mainly in greenstones (Fig. 2.18). In the east of the Røyrvatnet the pillowed dark greenstone is obviously folded with dipping NW of about 40 dip angle. The axial planes are approximately parallel with the regional schistosity. In the Gjersvikklumpen area the strong fold of dark greenstone occurs between two blocks of the felsic rock which is steeply dipping SWW - NEE axial planes, in where the dark greenstone is associated with laminae of the obvious sulphide mineralization that are contemporaneously folded.

Thrusting

The main thrusts which separate the Nappes such as occurring as the boundaries between both of the Helgeland Nappe and the Gjersvik Nappe in the west of the Gjersvik area as well as the Gjersvik Nappe and the Røyrvik Group in the east have been described by Lutro (1979). The minor thrusts within the metavolcano-stratigraphic sequence of the Gjersvik Group are not often obvious because the earlier phase of thrusting is rather possibly eradicated by the effects

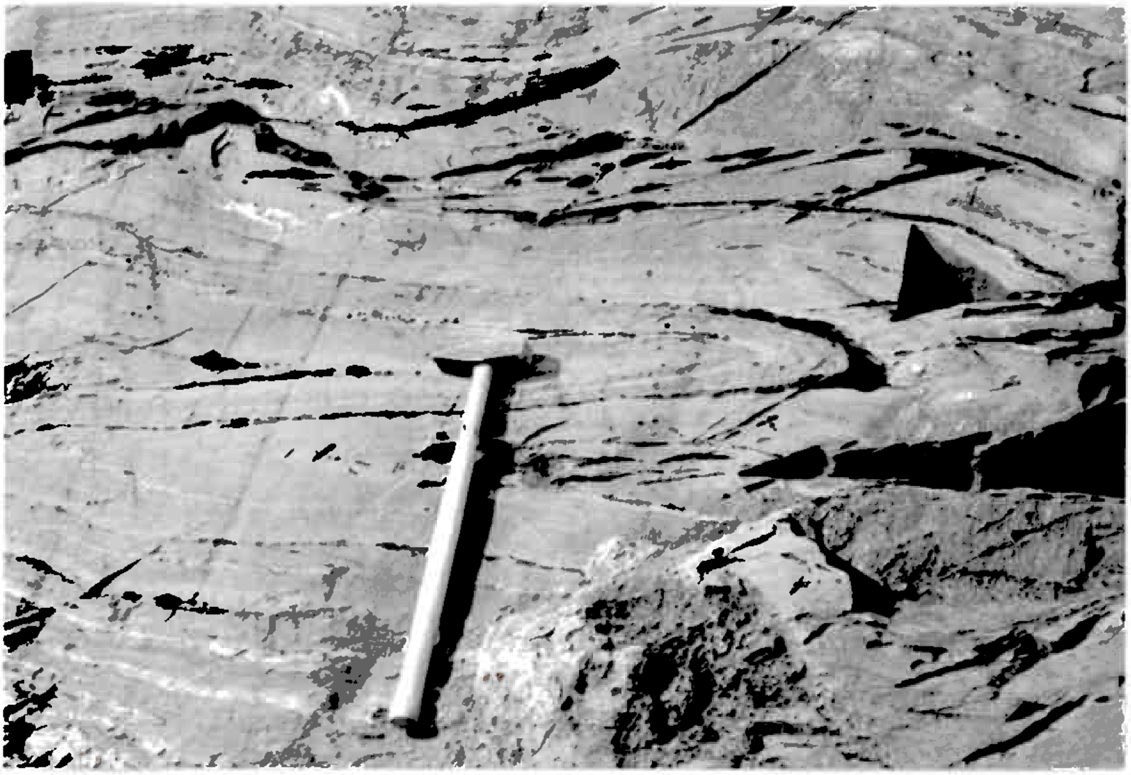


Fig. 2.18 Tight fold within the pale greenstone, at the western shore of the Limigen Lake

of later recrystallization and deformation of the volcanic rocks during metamorphism and tectonism. Geological investigation in the mapping area, however, indicates that the relative small thrusts do occur in places below the intrusive trondhjemite-gabbro complexes as boundaries between the intrusive complexes and greenstone, especially in the western area of the major NE - SW trend fault. These intrusive complexes are frequently bordered by minor thrusts and are characteristic of the penetrative structure.

In the north of Røyrvatnet, the contact between trondhjemites and dark greenstone is tectonic, which seems that the coarse-grained trondhjemite was brought to overlay or thrusts on the dark greenstone in several places. The contact plane generally dips deeply to the NW 320 - 350 (graduations of 400 degrees in the compass) with dipping angle ranging from 45 to 60. With associating the thrusting, the dark greenstone near the contact, on the one hand, is very schistose, and the coarse-grained trondhjemite itself, on the other hand, is intensively deformed along northeastern contact. The compression fissures and schistosity with a dominant NE - SW trend, essentially parallel or subparallel to the thrusting plane, occur extensively within intrusive of the coarse-grained trondhjemite. The dark greenstone has often been brought into planes of the compression fissures to occur as thin layers or lenses of structure filling, whereas quartz and feldspar tablets or rods in the outcrops of the course-grained trondhjemite are obviously orientated along schistose structure, which institutes the compression schistose zone within the coarse-grained trondhjemite. The same tectonic contact between the fine-grained porphyritic trondhjemite and the dark greenstone has also been found further to the north of Røyrvatnet.

Faulting

Brittle faulting appears to represent the latest event in the deformation history. Several minor faults and a series of fractures have been recognized in the mapping area. Among them relative larger faults have been distinguished as linear structures in the aerial photographs of the scale 1:10000 and generally very well marked topographically. These faults, however, are not often easily recognized on the surface.

A NE - SW major trend high-angle fault extending several tens kilometers passing from the east of Røyrvatnet to near western shore of the Limingen Lake is most important in the area. Lithologies occurring in each side of the fault are frequently different. In the north, the fault occurs mainly as the boundary separating metavolcanic sequence of the Gjersvik Group from metasedimental sequence of the Limingen Group, whereas in the south, the eastern and near part of the fault consists predominantly of dark, massive, stilpnomelane- and biotite-bearing greenstones, but the western part is largely composed of dark, varying schistory, epidote-bearing or chlorite-dominating greenstones of the Gjersvik Group mentioned just above. With associating the fault, strong compression zones occur frequently in the meta-extrusive and meta-intrusive rocks near two sides of the fault.

Other minor faults of different tends such as extending along N.W. - S.E., N.W.W. - S.E.E., and near N - S directions are common. These faults have in certain extent made the influence in the stratigraphic sequence. In the north of Røyrvatnet the coarse-grained trondhjemite is cut by and displaced up to several hundreds meters along the near NS trend fault of approximately 3 km strike extent. In the Gjersvikklumpen area the faults of extending N.W.W. - S.E.E. trend have cut and moved the metafelsic complex with obvious sulphide mineralization up to tens meters (Fig. 2.2).

Section 3: Metavolcanic and meta-intrusive rocks constituting the Gjersvik volcanic arc

3.1 Introduction

The Gjersvik volcanic arc comprises the magmatic complexes of the Gjersvik Formation, which underwent the low-middle regional metamorphism up to greenschist phase and the extensive deformation. Generally, greenschist facies metamorphism is mainly isochemical, that is, phase transformations of the minerals are much more than changes of the mineral compositions during metamorphism although the latter does exist. For example, oceanic basalts during hydrothermal circulation at the mid-ocean ridge result in considerable major mineralogical transformations, such as plagioclase -->albite --> chlorite or --> albite + epidote; plagioclase + pyroxene --> chlorite + epidote; olivine --> chlorite (+pyrite); pyroxene --> actinolite; glassy matrix --> chlorite - actinolite intergrowth; and vein minerals include chlorite, actinolite, epidote, quartz, pyrite and occasionally Cu-Fe-Zn sulphides (Humphris,1978).

The magmatic complexes of the Gjersvik Formation are mainly composed of the metamorphosed mineral assemblages of chlorite, epidote, albite and sericite, which occur more ore less in almost every type of the rocks, especially in the metavolcanic rocks. However, a few original minerals and a lot of primitive textures and structures are still remained within them. For example, augite and gabbro texture representing primitive tholeiitic basalt have been recognized in the dark, pillowed greenstone, and pillowed, amygdaloidal and clastic structures related to marine volcanic processes are extensively associated with the metavolcanites. Thus, the regional metamorphism of the Gjersvik volcanic arc has been consided to be low, and to be mainly isochemical. This nature makes it possible to use geochemical data in determining property of the original rocks.

The succession of the Gjersvik volcanic arc consists predominantly of a thick bimodal metavolcanic suite in association with a bimodal plutonic complexes plus small distal exhalative sediments. The bimodal volcanic rocks comprise the dark and pale greenstones of tholeiitic composition and the keratophyric pyroclastic complexes of rhyolitic composition, while the bimodal intrusives are composed by the coarse-grained trondhjemite, fine-grained porphyritic trondhjemite and gabbro. These rock types are separated each other from colour, texture, mineral assemblages and contents, chemical compositions as well as their field relationship in occurrence.

3.2 Metavolcanic rocks

3.2.1 Classification

Three different types of the metavolcanic rocks, i.e., dark greenstone, keratophyric pyroclastic rocks and pale greenstone, have evidently been distinguished, which represent respectively the three stratigraphic units formed in different stages of magmatic processes during construction of the Gjersvik intra-ocean rifting volcanic arc. The greenstones are extensively associated with submarine sedimentary structures such as massive, pillowed, amygdaloidal and fragmental structures, whereas some of metafelsic volcanic rocks are often associated with metafelsic fragments and breccias. These features indicate that the greenstones were primitively formed mainly as basaltic flow, pillowed lava and clastic volcanic rocks, while the felsic rocks were deposited as the volcanic pyroclastic rocks in submarine environments.

Chemically, the dark and pale greenstones are similar in SiO2 contents to each other and they all fall in a field of the basaltic rocks, ranging from 47 to 53.5 wt. % SiO2, whereas the metafelsic volcanic rocks vary mainly from 71 to 75 wt.% SiO2, which is consistent to rhyolitic compositions (Tables 3.1, 3.2, 3.3).

Whether the greenstones of basaltic composition or metafelsic volcanic rocks of rhoylitic composition are all characterized by the Na-rick and K-poor features. For example, on the one hand, Na2O contents are very high but K2O much low in both of these two types of the rocks, ranging mainly from 4 to 6 wt.% Na2O and from 0.02 to 0.5 wt.% K2O in the greenstones, and varying between 5.5 - 7 wt.% Na2O and between 0.1 - 0.9 wt.% K2O in the felsic rocks, respectively (Tables 3.1, 3.2, 3.3), on the other hand, albite is one of the mostly dominate rock-forming minerals in these volcanic rocks but very few potassium feldspar has been

Table 3.1

Major (%) and Trace (ppm) Element Chemistry of the Dark Greenstones

	1	2	3	4	5	6	7	8
	RS4-1	RS4-2	RS4-8	RS4-3	DR4#	M16-32	M15-17	M15-23
SiO_2	53.43	49.83	49.81	51.07	53.19	53.53	52.15	51.03
TiO_2	1.65	1.20	2.04	1.35	1.33	1.67	1.40	1.43
Al_2O_3	14.31	15.11	13.61	14.92	14.33	13.97	14.95	14.47
*FeO	14.02	13.99	13.19	14.47	13.43	13.96	14.04	13.81
MgO	2.75	7.83	4.91	5.20	3.89	3.39	4.68	4.20
CaO	3.70	4.38	6.23	3.69	4.65	3.62	4.97	5.36
Na_2O	5.70	4.96	4.41	6.06	5.67	5.05	5.32	5.16
K_2O	0.06	0.09	0.02	0.19	0.13	0.05	0.61	0.45
MnO	0.27	0.27	0.16	0.19	0.22	0.29	0.22	0.22
P_2O_5	0.53	0.11	0.17	0.11	0.18	0.56	0.13	0.13
Loss	4.14	3.23	5.70	2.92	3.17	4.47	1.78	1.96
SUM	100.56	100.40	100.25	100.71	100.19	100.38	100.25	98.22
Sr	122	112	148	81	126	97	111	173
Rb	<1	<1	<1	1	<1	<1	5	4
Nb	18	18	17	19	8	20	20	15
Y	41	30	48	35	33	38	31	27
Zr	54	48	68	49	57	52	52	51
Ba	<10	<10	<10	<10	<10	<10	<10	<10
V	61	403	465	490	305	65	377	287
Ni	3	33	23	11	6	1	19	3
Co	28	55	42	56	41	24	55	48
Cr	13	27	30	17	16	9	33	14
Pb	<1	<1	<1	<1	2	<1	<1	<1
Cu	14	14	11	43	40	21	47	28
Zn	151	167	140	151	137	151	146	124

Table 3.1, continue 1

	9	10	11	12	13	14	15	16
	M20-23	911213-2	913108	913111	913112	913113	913103	913104
SiO_2	53.22	47.45	50.58	53.30	51.06	53.50	52.25	58.32
TiO_2	1.34	1.55	1.65	1.39	1.82	2.06	1.36	1.48
Al_2O_3	15.09	16.76	15.87	15.41	16.28	13.72	15.15	15.17
*FeO	13.72	16.40	13.98	12.91	14.65	15.15	14.64	14.02
MgO	4.15	5.69	5.47	5.70	4.92	5.35	4.63	2.67
CaO	7.54	7.17	6.65	6.34	6.75	5.22	8.98	3.22
Na_2O	2.09	4.25	4.34	4.73	4.41	3.49	3.85	5.28
K_2O	0.06	0.02	0.51	0.14	0.04	0.59	0.20	0.15
MnO	0.21	0.23	0.18	0.17	0.23	0.24	0.23	0.28
P_2O_5	0.13	0.14	0.14	0.11	0.17	0.16	0.13	0.46
Loss	2.83	7.39	2.15	2.07	2.13	2.28	2.00	2.63
SUM	100.38	99.66	99.37	100.20	100.15	99.48	101.42	101.05
Sr	246	82	130	95	148	99	181	132
Rb	2	5	12	7	6	16	7	9
Nb	18	12	12	11	13	13	11	13
Y	32	31	32	29	34	39	22	40
Zr	56	39	47	40	48	57	34	44
Ba	39	<10	<10	<10	<10	<10	<10	<10
V	382	452	354	316	416	403	368	33
Ni	13	22	20	18	19	14	14	9
Co	54	69	60	45	64	33	56	22
Cr	23	21	19	17	23	19	18	14
Pb	<1	<1	<1	<1	<1	<1	<1	<1
Cu	46	54	54	19	18	32	17	19
Zn	85	151	43	132	137	188	103	188

Table 3.1, continue 2

	17	18	19	20	21	22	23	24
	913105	913106	913107	913506-2	913606	913701	913702	913703
SiO_2	53.20	54.30	54.09	52.68	54.34	61.48	54.30	54.95
TiO_2	1.43	1.30	1.20	1.68	1.21	1.07	1.90	1.27
Al_2O	15.14	15.39	14.67	14.75	15.54	14.15	13.87	15.86
*FeO	15.07	12.16	14.34	15.25	14.36	9.94	14.62	13.29
MgO	7.11	5.20	4.09	4.78	4.36	3.48	4.24	4.51
CaO	3.63	6.67	6.38	5.84	5.56	6.10	7.19	6.49
Na_2O	4.49	4.96	4.89	3.87	4.57	4.49	3.70	4.09
K_2O	<0.03	0.06	0.23	<0.03	0.03	0.50	<0.03	0.30
MnO	0.24	0.27	0.23	0.29	0.21	0.15	0.24	0.18
P_2O_5	0.11	0.12	0.10	0.25	0.12	0.27	0.16	0.12
Loss	3.12	4.97	1.81	5.51	5.41	5.39	4.34	6.21
SUM	100.42	100.43	100.22	99.39	100.30	101.63	100.23	101.06
Sr	72	120	167	47	90	103	115	107
Rb	6	7	11	7	<2	9	<1	3
Nb	13	11	12	13	15	18	18	17
Y	26	26	20	22	31	39	39	35
Zr	31	38	32	29	50	60	63	58
Ba	<10	<10	<10	<10	<10	<10	<10	<10
V	455	343	350	257	379	197	345	331
Ni	11	19	9	9	8	28	24	18
Co	51	29	48	54	56	28	45	49
Cr	16	24	17	15	21	52	34	28
Pb	<1	<1	<1	<1	<1	<1	<1	<1
Cu	3	37	21	20	23	29	54	50
Zn	154	76	131	161	140	87	134	135

7 - 9 massive stilpnomelane- and biotite-bearing greenstone

All elements analysized by I. Romme and I. Vokes, with PHILIPS PW1480 X-Ray Spectrometer in Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology, 1991

Table 3.2

Major (%) and Trace (ppm) Element Chemistry of the Pale Greenstones

	1	2	3	4	5	6	7	8
	RS441	RS442	RS451	RS452	RS491	RS492	RS4-7	911509
SiO_2	50.07	51.10	48.40	47.55	47.30	47.04	50.80	51.54
TiO_2	0.62	0.63	0.76	0.81	0.52	0.52	0.87	0.54
Al_2O_3	15.50	15.70	15.63	15.35	13.75	13.65	13.93	14.66
*FeO	9.09	9.30	9.79	10.30	9.24	9.22	10.83	10.57
MgO	7.35	7.55	8.03	7.97	11.46	11.62	6.00	8.42
CaO	7.22	6.72	7.46	7.17	8.45	8.39	6.27	8.85
Na_2O	4.76	4.90	4.63	4.51	3.11	3.05	5.73	4.14
K_2O	0.53	0.52	0.44	0.42	0.52	0.52	0.07	0.63
MnO	0.15	0.14	0.18	0.19	0.17	0.17	0.18	0.18
P_2O_5	0.11	0.11	0.11	0.13	0.06	0.06	0.10	0.08
Loss	4.53	4.11	5.78	5.72	6.78	6.76	3.99	5.99
SUM	100.11	100.78	101.21	100.12	101.36	101.00	98.77	99.61
Sr	103	101	137	153	61	60	86	75
Rb	6	2	<1	3	8	8	<1	13
Nb	17	15	16	17	17	17	17	11
Y	19	17	21	22	15	17	23	11
Zr	46	44	51	53	38	39	47	21
Ba	<10	<10	<10	<10	25	35	<10	14
V	253	254	226	230	195	197	277	266
Ni	82	82	96	95	222	226	76	106
Co	43	42	52	53	63	63	47	45
Cr	153	159	164	162	246	249	129	187
Pb	1	<1	9	11	<1	<1	<1	<1
Cu	69	64	69	74	18	11	7	63
Zn	76	74	91	91	94	97	105	81

Table 3.2, continue 1

	9 911611	10 911906	11 910612	12 911213-1	13 910609-1	14 910609-2	15 910204
SiO_2	51.86	49.61	52.93	50.46	50.68	50.32	53.71
TiO_2	0.60	0.89	1.09	0.80	1.24	1.02	0.94
Al_2O_3	14.99	16.12	15.39	15.23	15.92	16.41	15.68
*FeO	11.30	12.69	11.39	10.23	11.22	10.77	9.08
MgO	8.97	8.60	6.43	10.55	7.53	7.39	7.93
CaO	8.89	6.89	8.14	9.01	9.08	9.78	7.59
Na_2O	2.79	3.70	4.79	3.72	2.96	2.90	4.73
K_2O	0.29	0.55	0.23	0.03	<0.03	1.41	0.24
MnO	0.17	0.20	0.19	0.21	0.19	0.25	0.14
P_2O_5	0.08	0.07	0.12	0.08	0.13	0.12	0.13
Loss	5.18	6.05	4.85	8.21	4.21	9.73	3.91
SUM	99.94	99.32	100.70	100.32	98.95	100.37	100.17
Sr	144	88	118	129	337	72	109
Rb	11	14	8	5	6	28	9
Nb	11	11	11	11	12	11	11
Y	12	18	20	16	24	20	16
Zr	25	31	33	32	54	40	39
Ba	<10	61	<10	<10	<10	135	<10
V	258	320	279	217	262	264	202
Ni	112	106	78	194	72	73	145
Co	54	60	46	59	47	46	49
Cr	226	183	127	288	132	157	209
Pb	<1	<1	<1	<1	<1	4	<1
Cu	65	52	37	38	64	32	68
Zn	89	125	99	76	99	96	74

Table 3.2, continue 2

	16	17	18	19	20	21	22
	910323-1	910323-2	913114	913506-1	913601	913602	913603
SiO_2	48.34	51.88	55.03	49.69	54.28	51.28	52.31
TiO_2	1.06	1.11	0.74	0.82	0.73	0.72	0.56
Al_2O_3	17.69	16.70	14.79	17.75	15.39	14.59	14.97
*FeO	8.40	8.75	9.89	12.37	10.47	9.13	9.83
MgO	5.24	6.06	7.64	7.85	7.31	5.32	7.21
CaO	14.50	12.05	7.60	8.11	8.07	14.02	10.73
Na_2O	3.87	3.94	4.38	2.78	3.66	4.57	3.24
K_2O	0.17	<0.03	0.08	<0.03	0.46	0.47	0.66
MnO	0.12	0.15	0.21	0.31	0.17	0.17	0.17
P_2O_5	0.22	0.21	0.06	0.08	0.10	0.14	0.08
Loss	7.81	4.75	2.08	4.61	2.96	7.14	3.48
SUM	99.61	100.86	100.42	99.76	100.64	100.41	99.76
Sr	102	353	190	198	181	131	152
Rb	9	6	6	5	13	6	6
Nb	9	11	11	12	11	15	16
Y	21	20	16	19	17	18	14
Zr	39	57	31	32	44	44	47
Ba	<10	<10	<10	<10	<10	<10	<10
V	246	226	235	234	243	218	244
Ni	119	89	74	66	96	115	107
Co	57	30	44	67	45	45	47
Cr	200	189	146	119	205	140	190
Pb	<1	<1	3	<1	<1	<1	<1
Cu	45	25	<1	44	49	21	62
Zn	90	68	125	102	84	62	74

All elements analysized by I. Romme and I. Vokes, with PHILIPS PW1480 X-Ray Spectrometer in Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology, 1991

Table 3.3

Major (%) and trace (ppm) element chemistry of the keratophyric pyroclastic complexes

	1	2	3	4	5	6	7	8
	M22-7-1	M22-7-2	M15-13-1	M15-13-2	M17-26	GS3-12	913102	913109
SiO_2	75.20	75.05	72.78	72.40	66.73	71.28	75.23	77.67
TiO_2	0.21	0.22	0.37	0.37	0.54	0.35	0.25	0.19
Al_2O_3	11.90	12.00	12.95	12.77	14.24	12.94	13.01	11.46
*FeO	4.33	4.46	5.04	5.28	8.53	5.05	4.10	3.41
MgO	0.64	0.73	0.62	0.68	1.21	0.96	0.22	0.67
CaO	0.73	0.75	0.80	0.83	0.51	0.23	1.92	0.55
Na_2O	6.07	6.02	5.51	5.57	7.28	6.47	5.27	5.03
K_2O	0.27	0.27	0.96	0.79	0.04	0.14	0.19	0.20
MnO	0.06	0.06	0.11	0.11	0.10	0.05	0.10	0.04
P_2O_5	0.03	0.03	0.06	0.07	0.07	0.06	0.04	0.02
Loss	0.56	0.60	1.22	1.28	0.85	0.90	0.43	0.66
SUM	100.00	100.19	100.42	100.15	100.10	98.43	100.33	99.24
Sr	131	135	64	70	31	56	165	66
Rb	<1	<1	3	4	<1	<1	7	6
Nb	14	20	15	19	13	18	8	5
Y	60	63	67	69	58	68	39	44
Zr	133	138	137	135	94	118	114	100
Ba	<10	<10	248	164	<10	<10	45	<10
V	29	27	34	34	69	36	19	18
Ni	9	7	5	5	10	5	8	9
Co	5	3	4	3	11	6	3	2
Cr	75	58	69	70	40	39	61	90
Pb	10	<1	<1	<1	4	4	14	3
Cu	36	39	15	8	10	13	3	10
Zn	45	52	133	127	113	31	46	69

All elements were analysized by I. Romme and I. Vokes with PHILIPS PW1480 X-Ray Spectrometer, Department of Geology and Mineral Resources Engineering, University of Trondheim- Norwegian Institute of Technology, 1991 distinguished under microscope until now.

Plots of the greenstones of basaltic composition and of the metafelsic volcanic rocks of rhyolitic composition in Hughes' igneous spectrum (1972) indicate that almost greenstones and all metafelsic volcanic rocks fall outside in the normal igneous spectrum on the Na-enriched side but concentrate on field of the spilite and keratophyre (Fig. 3.1). The Na-enriched nature of the metavolcanic rocks was emphasized as a result of the spilitization of post-eruptive processes on the ocean floor by Stephens (1980). Thus, the original rocks of the greenstones and metafelsic volcanic rocks have been referred as the spilitized basalts and the keratophyric pyroclastic rocks of rhyolitic composition, respectively.

3.2.2 Description of lithologies

(1) Dark Greenstone

The dark greenstone constitutes one of the most dominate rock-types in the Gjersvik volcanic arc. It is exposed about 7 - 10 km thick on the surface in the west and southwest of the Limingen Lake, but thins out towards the north so rapid that the succession of the dark greenstone only becomes about 100 m thick in the northwest. The succession of the dark greenstone tends to extend roughly along the N.N.E. - S.S.W. trend although the intensive tectonic deformation and metamorphic reconstruction makes it difficult to erect a meaningful volcano-stratigraphy.

The dark greenstone is characterized by dark green in colour, massive to varying schistosity, fine grain, rarely visibly porphyritic crystals, Fe-rich and slight-magnetism in hand specimen and field outcrops. It consists mainly of chlorite and albite with considerable, but variable amounts of epidote, stilpnomelane, biotite, muscovite, sericite, quartz and carbonate. Magnetite and pyrite are common accessory minerals occurring as fine-grained anhedral or euhedral, with lessly abundant sphene. The essential mineral assemblages of the dark greenstone correspond to those of the greenschist facies, which obviously results from the regional low - middle grade metamorphism. Due to a considerable variety on some major mineral assemblages, several subtypes of the dark greenstone can be subdivided, i.e., stilpnomelane- and biotite-

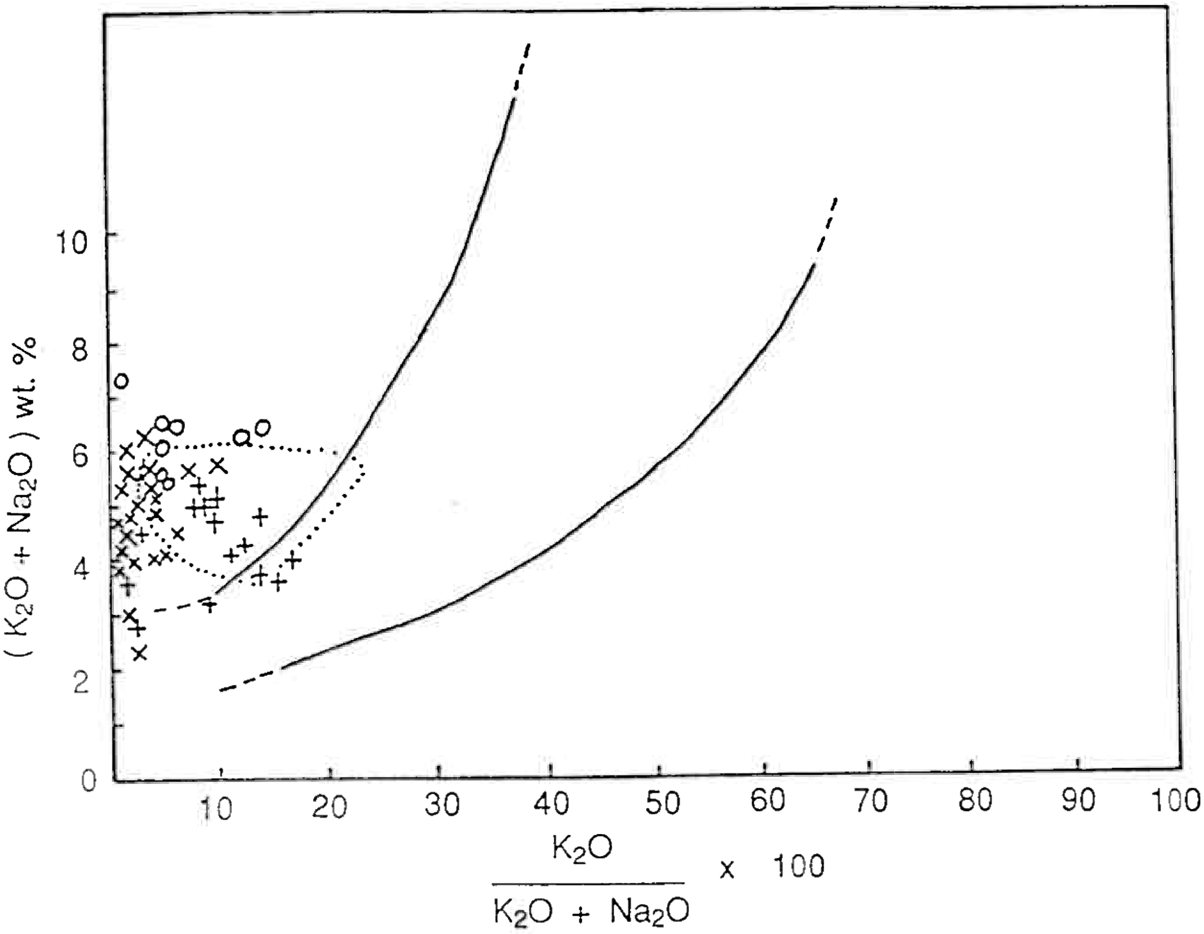


Fig. 3.1 Plots of greenstones and felsic volcanic rocks in the igneous spectrum of Hughes (1972)

x dark greenstone; + pale greenstone; o felsic volcanic rocks

◌ field of spilite and keratophyre

// field of normal igneous rocks

bearing, epidote-rich and chloritic greenstones. Mineralogical differences among these subtypes result largely from differences in relative proportions of the essential minerals.

Stilpnomelane- and biotite-bearing greenstone

The dark, stilpnomelane- and biotite-bearing greenstone are characterized by even darker in colour, stronger magnetism, massive to slight schistory with few pillowed structure, which appear to indicate that they were mainly deposited by massive basaltic flows. The surface mapping have revealed that the dark, stilpnomelane- and biotite-bearing greenstones tend to be associated with the fault zones and occur mainly in the eastern and near part of the major N.N.E. - S.S.W. trending fault in the area, even though they are also occasionally present in other places. They are intercalated with the epidote-bearing and chloritic greenstones in occurrence but there are no clear contacts among them. In fact, it is, perhaps, only difference of the stilpnomelane- and biotite-bearing greenstones to other subtypes of the dark greenstones that is appearance of the stilpnomelane, sometimes, and biotite.

The stilpnomelane- and biotite-bearing greenstones are mainly composed of albite, chlorite, epidote, stilpnomelane and biotite with small amounts of quartz and carbonate. Magnetite as a common accessory mineral seems to become richer in the stilpnomelane- and biotite-bearing greenstone than other subtypes of the dark greenstones. The contents of felsic and mafic minerals are approximately equal. The felsic minerals are dominated by albite, but the mafic minerals vary among their proportions each other, especially epidote, stilpnomelane and biotite. The epidote is about few to 30 percent, whereas the stilpnomelane and biotite range usually from n to 10 or more percent in contents, respectively. Stilpnomelane and biotite can coexist together in the dark greenstone such as in the Royrvatnet-Gjersvikklumpen area (Fig. 3.2), but also occur respectively in different horizons of the dark greenstone, for example in the Lillefjell area (Mellin 1979). It is often difficult to distinguish biotite from stilnomelane in hand specimen and field outcrops but they can be distinctive to each other in thin section.

Stilpnomelane is brown or dark brown in colour under thin section and occurs as long lath and needle crystals about 0.2 - 1 mm in length and 0.01 - 0.05 mm wide, frequently showing radiating aggregates of the needle crystals. The stilpnomelane laths tend to occur without

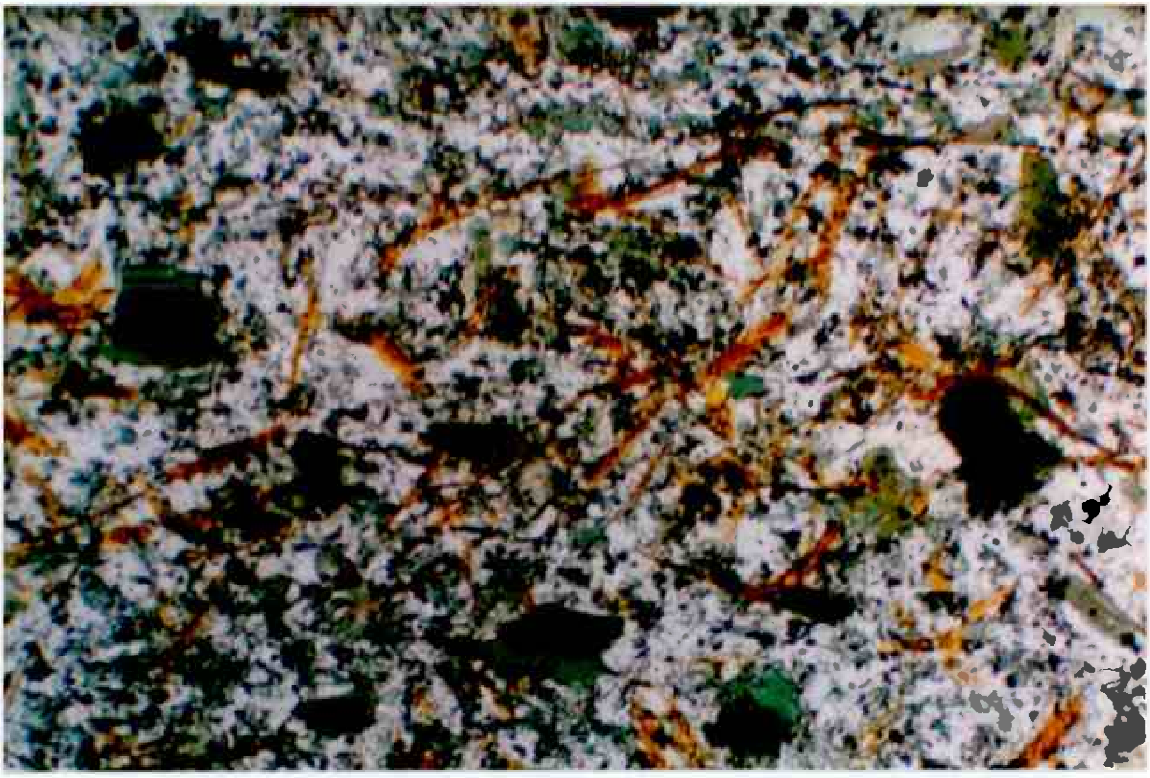


Fig. 3.2 Coexistence of stilpnomelane (brown in colour) and biotite (dark green) in the dark greenstone " - " 4 x 3.2 x 1.25

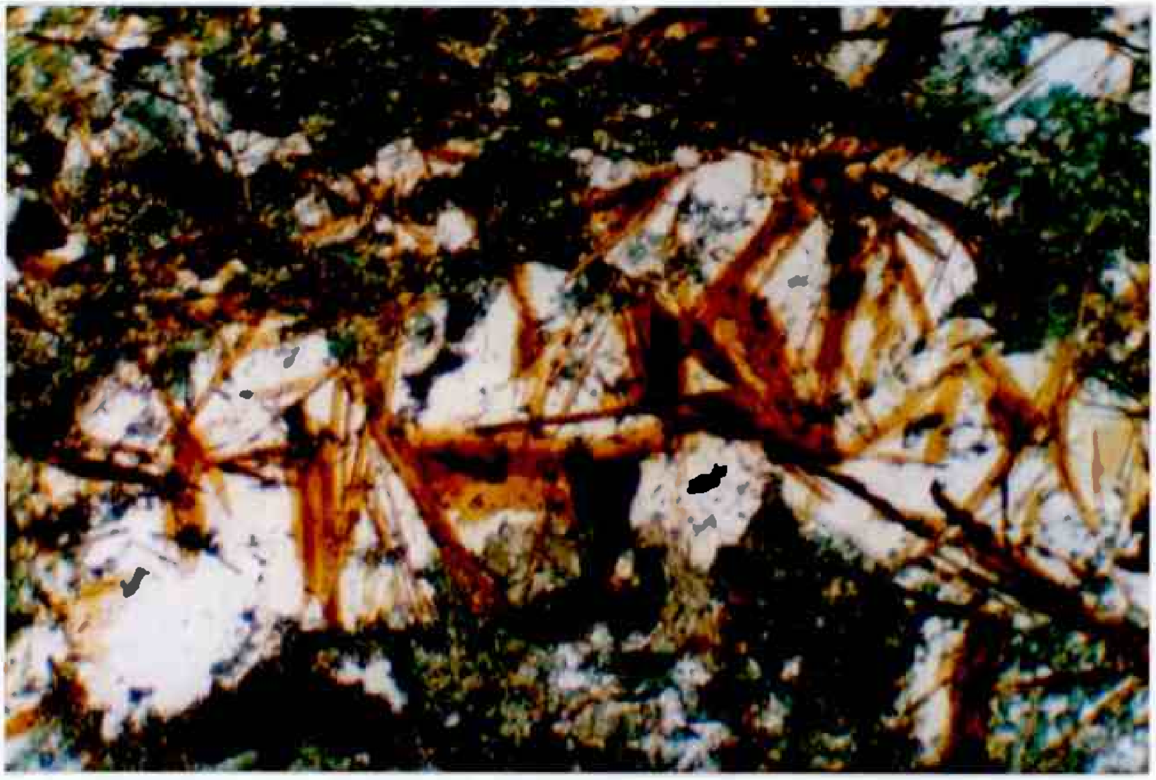


Fig. 3.3 Stilpnomelane (brown in colour) cutting a quartz vein and all existed fabrics in dark greenstone " - " 4 x 3.2 x 1.25

preferred orientation and to cut all existing textures and fabrics, including hydrothermal quartz and carbonate veins (Fig. 3.3). This suggests that the growth of stilpnomelane was probably remained or started after formation of the tectonic fabrics and has strong crystalloblastic tendencies. Stilpnomelane can be not only limited to occur within the dark greenstone and but also be associated with the keratophyric pyroclastic rocks (Fig. 3.4). These features demonstrate that the stilpnomelane is not a primary. Biotite associating with the stilpnomelane in the Royrvatnet-Gjersvikklumpen area is of distinctive green in colour under thin section. It usually occurs as hypidiomorphic platy porphyritic crystals with perfect cleavage, about 0.1 - 0.2 mm in size. It is significant that the stilpnomelane often cuts or replaces the biotite along its edges, which indicates that they appear to have existed as two unequilibrium phases.

These features of the stilpnomelane described above such as limited distribution in occurrence, close association with the fault zones, appearance in both types of dark greenstone and keratophyric pyroclastic rocks, and cutting all fabric textures and other minerals, appears to point out that formation of the stilpnomelane is in some ways related to late fault tectonic activities after the regional low-grade metamorphism.

Epidote-bearing and chloritic greenstones

The epidote-bearing and chloritic greenstones are major subtypes of the dark greenstone. They are dark to moderate green, massive to very schistose in structure, and varying magnetism. The chlorite always occurs as one of the major rock-forming minerals, whereas the epidote in the greenstone varies from very few to over 50 percent in content.

In comparison with the stilpnomelane- and biotite-bearing greenstones, they are only associated with few biotite and stilpnomelane, but obviously with pillowed, clastic and amygdaloidal structures. The pillows are generally flattened or irregular and round to somewhat flatted in cross section, ranging from several cm to 1.5 m in diameters. The interiors of the pillows comprise mainly either chlorite or epidote. The former is generally dark, massive, Fe-rich and slightly magnetic, and contains a few vesicles, and is often associated with chilled margins marked by a 0.5 to 2 cm thick zone rich in epidote (Fig. 3.5). The chilled margins are

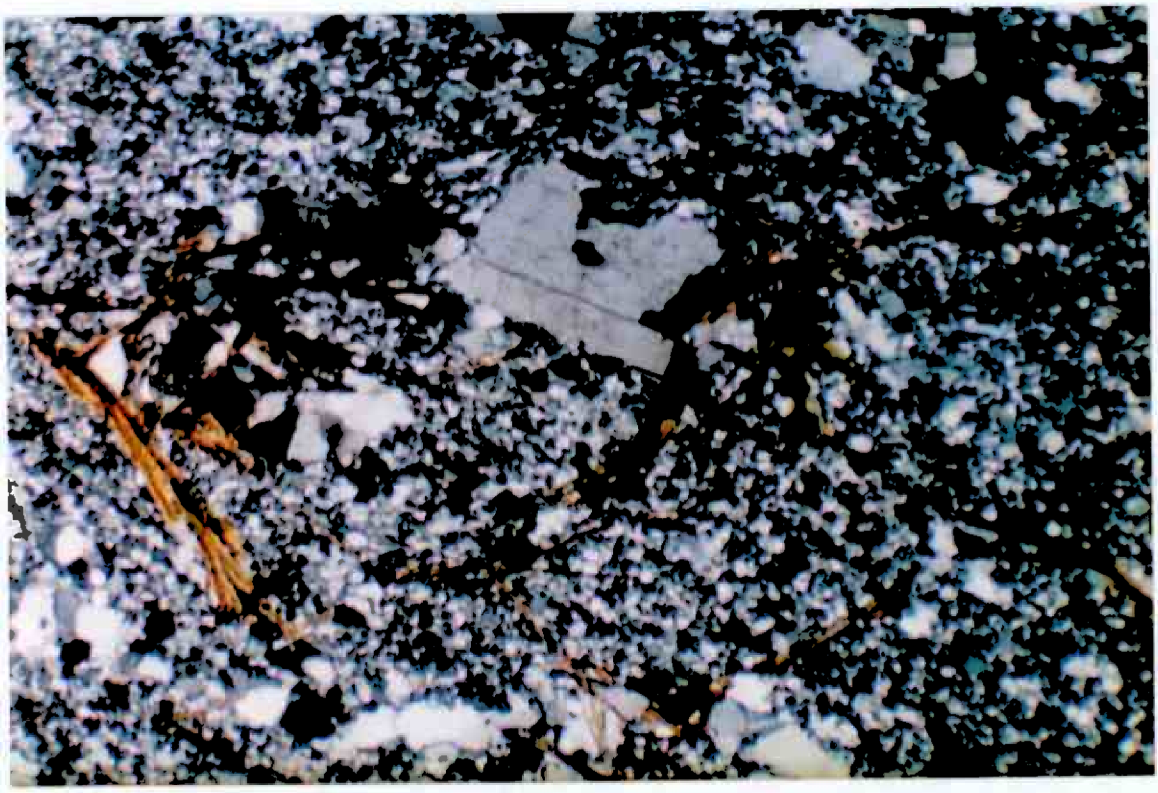


Fig. 3.4 Stilpnomelane (brown in colour) occurring within the keratophyric pyroclastic rocks " + " 2.5 x 3.2 x 1.25

Fig. 3.5 Chloritic pillows with epidote-rich rims in the dark greenstone on the new road near the western shore of the Limigen Lake

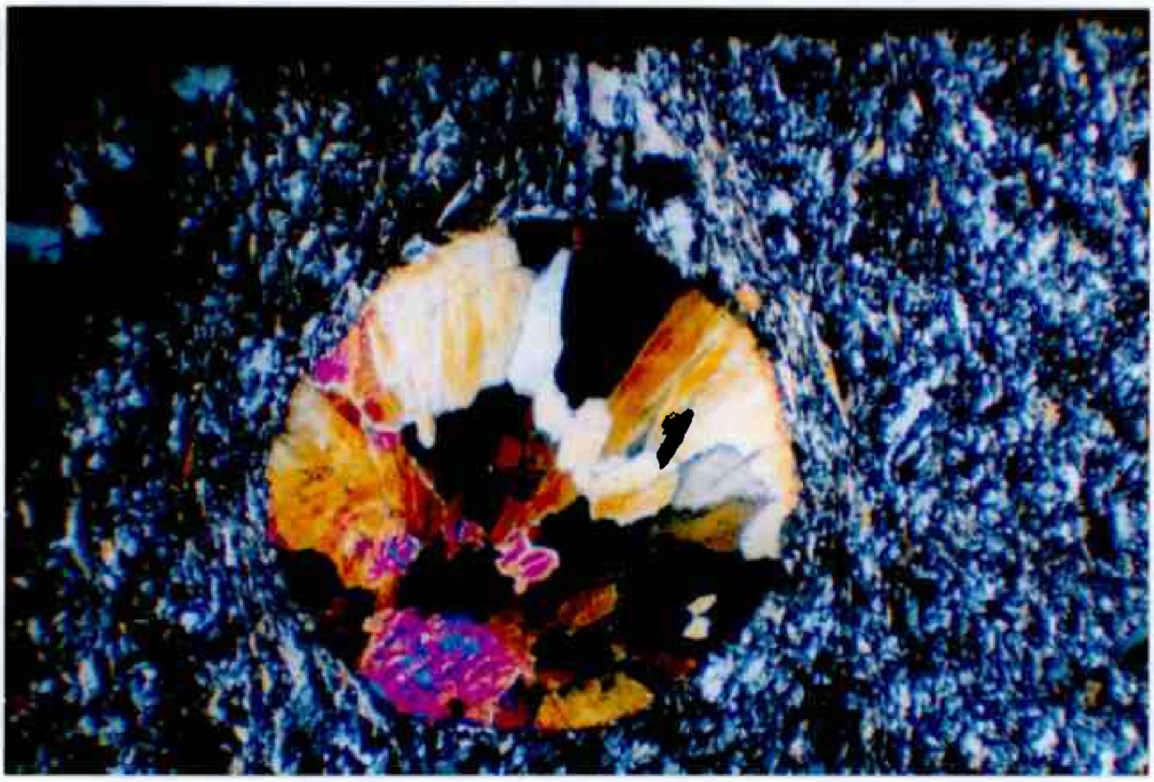


Fig. 3.6 A epidote amygdale surrounded by schistosity in the dark greenstone

" + " 4 x 3.2 x 1.25

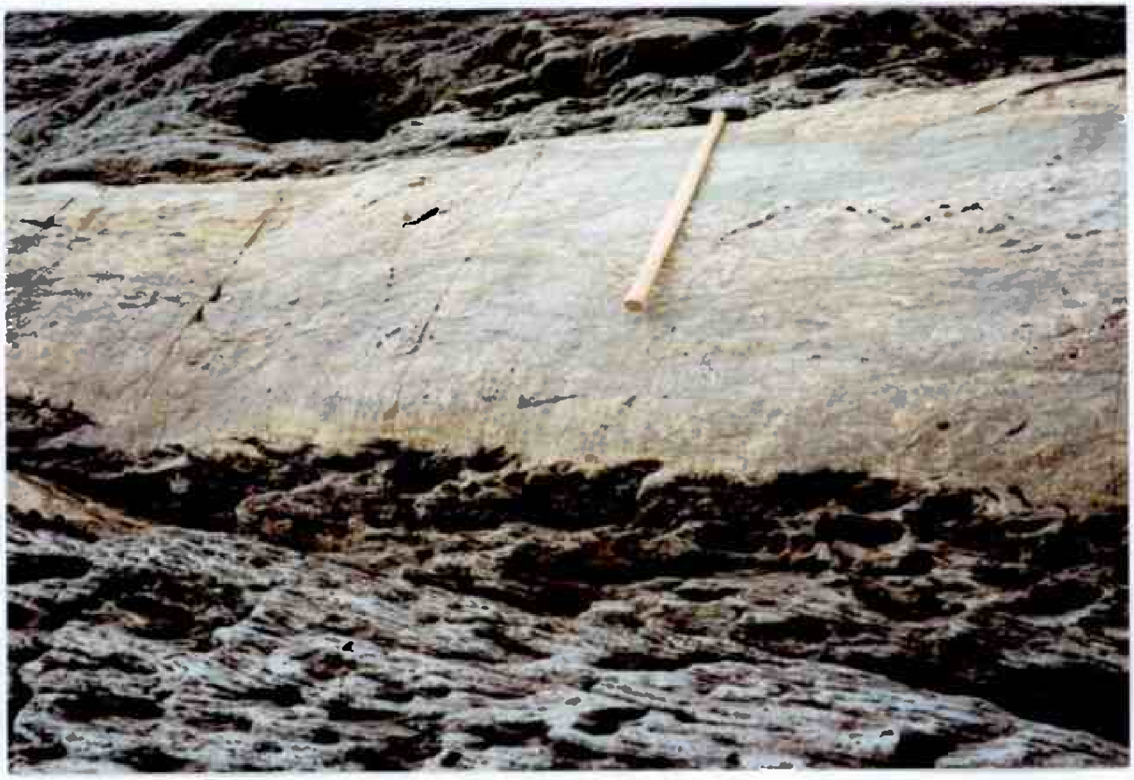


Fig. 3.7 A epidote-rich band occurring within the dark, pillowed, and chloritic greenstone in the western shore of the Limigen Lake

frequently associated with obvious pyrite mineralization. This kind of pillowed greenstone layer generally occurs with less deformation and remains in some ways the originally sedimentary features, which are valuable in determining stratigraphic succession, for example, the pillowed greenstone layer in the eastern and northeastern parts of the Bjorkvatnet. The latter is usually moderate green, massive, Fe-poor, and associated with the chilled margins rich in dark chlorite such as the pillowed belt in the western shore of the Limingen Lake. The stratigraphic layer associated with the epidote pillowed geenstones is generally deformed so strong that it is impossible to distinguish any original sedimentary features. These pillows were formed either by the replacement or by the filling of epidote with quartz and carbonate during extrusion on the ocean floor. The fragment-bearing greenstones characterized by pyroclastic sedimentary origin are often associated with or occur near horizon of the pillowed greenstones. They comprise fragments of the dark greenstone setting in the matrix consisting mainly of chlorite. The fragments are usually irregular, elongated, about several to hundreds cm long and several mm to tens cm width, and roughly oriented. The layers of the fragment-bearing dark greenstone are often very schistory.

The greenstones are frequently vesicular in both recognizable pillowed and unpillowed successions, which are often infilled by a variety of secondary minerals to form an amygdaloidal structure. The amygdales are generally rather round, ranging from 0.1 mm to tens cm in maximum dimension and surround by the schistosity (Fig. 3.6). These amygdales are local in occurrence but can concentrate sometimes over 10 percent in content. The amygdaloidal layers tend to occur in certain horizons of the succession of the epidote-bearing and chlorite-dominating greenstones. For instance, three, at least, different levels which concentrate amygdales have been recognized to occur in the drilling core #4. The amygdales consist mainly of crystalline individual or aggregate of the epidote (Fig. 3.6), lessly importantly of mineral assemblages of epidote + quartz or epidote + chlorite + quartz. Some relative larger amygdales are often associated with obvious interior structures composed of quartz and\or carbonate surround by epidote. Thus, the succession of epidote-bearing and chloritic greenstones was originally deposited mainly by the pillowed lava and volcanic clastic material with abundant volatile components in the submarine environment, and probably represent stratigraphically an upper level of sequence of the dark greenstone.

The epidote-bearing and chlorite-dominating greenstones consist mainly of albite, chlorite and epidote with small amounts of quartz, carbonate and biotite. Occasionally, augite has been recognized to occur within interior of the pillows with relative low-grade metamorphism and deformation such as pillowed greenstone in the north of the Bjorvatnet (thin section No. RS 4-7). The proportion of felsic and mafic minerals are approximately equal. The felsic minerals are dominated by albite but the proportions of the mafic minerals are variable, most of the greenstones being very chloritic with only minor amount of epidote, whereas others very epidote-rich with lesser chlorite. In fact, epidote is very variable and local in occurrence, and present mainly as very irregular granular individual crystal or aggregates or as the filling material in the vesiculas and some of the pillows. For example, the epidote can reaches over 50 percent and is present mainly as local epidote-rich bands and filling material of the pillows within the pillowed, chloritic greenstone succession (Fig. 3.7). Thus, the epidote has been considered to be mainly related to hydrothermal processes after the eruption on the ocean floor, especially those being as bands and as infillng of the vesiculas and pillows, or to the regional metamorphism such as some individual crystal or aggregates of the epidote. Albite is the most dominant forming-rock mineral, ranging generally from 40 to 50 percent in content. It is anhedron granular or euhedron laths about 0.05 to 0.5 mm in size, and often associated with obvious twinning of albite. The refractive index of the euhedron laths is lower than that of the jaffaite. Chlorite is tabular or scaly, very irregular but often orientated to constitute the schistory, which is obviously a major product of the metamorphism. Biotite occurs mainly as porphyroblastic crystals, being generally flakes with one perfect basal cleavage. Carbonate and quartz are mainly secondary minerals, and variable in content, ranging generally from 1 to 5 percent. Augite is subeuhedrol, granular or tabular, and cleavage length fast, which was only found to be reserved in some of the pillowed lava. Augite crystals are sometimes associated with two cleavages, one good and another imperfect, at near 90. It appears to represent a residue mineral phase of the tholeiitic basalt before regional metamorphism.

The dark greenstones are characterized by holocrystalline-porphyritic and holocrystalline-homogeneous textures. The former tends to occur in the schistose greenstones, whereas the latter is mainly associated with massive and pillowed greenstones. The porphyritic texture is mainly composed of lath-shaped albite, ranging generally from 0.1 to 0.5 mm, setting in matrix consisting largely of felsic minerals, chlorite and epidote, usually being less 0.05 mm in size. Content of the porphyritic minerals ranges generally from 15 to 25 percent. Almost all porphyritic crystals of the albite are orientated and surrounded by schistory. These features indicate that the porphyritic greenstones appear to be originally deposited by lava or crystal tuff. The relics of typical metagabbro textures has been recognized to be associated with the homogeneous greenstones, that is, the chlorite, epidote and augite tend to occupy within a space between laths of albite which has no obvious orientation, even though the intergranular texture was mostly destroyed by the second hydrothermal processes, metamorphism and deformation. This kind of the primary texture shows that the massive and pillowed greenstones were originally deposited by basaltic lava.

(2) Pale greenstone

Pale greenstone occurs mainly in the northwestern and southeastern parts of the area. The contact between pale and dark greenstones is sharp, especially when the exhalative sedimentary layers occur just in junction between them although this contact relationship is not always clear in the outcrops. The pale greenstone is light green in colour, fine-grained, massive to schistose, Fe-poor and without magnetism, and carbonate-rich. In comparison with the dark greenstones, pillowed and plastic structures are lessly associated with the pale greenstone although they do occur in local places, which appears to indicate an origin of the major massive basaltic flow.

The pale greenstone is mainly holocrystalline-homogeneous and porphyritic in textures and its main mineral assemblage is similar to that in the dark greenstones, which consists predominantly of chlorite, epidote and albite, but is characterized by higher property of carbonate in content and present of iron-poor actinolite. Carbonate ranges generally from 10 to 15 percent, whereas actinolite varies among 0 to 20 percent in content. Felsic minerals range from 20 to 40 percent in content, and are usually too fine in grain about or less 0.05 mm in size to be recognized. Some of them, however, are associated with an obvious twinning of albite. Sometimes, biotite occurs as the euhedron and flake-shaped porphyroblastic crystals, about 0.05 -0.3 mm in size. It is often associated with veins consisting of quartz and carbonate, which seems to show that it is related with secondary process.

(3) keratophyric pyroclastic complexes

The keratophyric pyroclastic complexes scatter extensively as rather thin complexes within the dark greenstone, which used to be called keratophyres (Oftedahl 1956) and trondhjemites (Foslie & Strand 1956). They are white to light grey or to light rose in color, very fine-grained, much hard and dense with at times associating recognizable free quartz in hand specimen. The felsic extrusive rocks are characterized by their small scales in size and very irregular morphologies in shape. The relative large felsic extrusive bodies which are usually several tens meters in width and hundreds meters long but generally less one kilometer square in scale consist apparently of felsic volcanic pyroclastic rocks. The fragments are generally angular to subangular, ranging from several to tens cm across, and less 30 percent in contents, which set within the felsic volcanic rocks with similar components. This feature indicates that the keratophyric pyroclastic complexes of the relative large scales were formed as an extrusive sedimentary process of the felsic volcanic pyroclastic rocks and tuff rather than as an origin of the felsic lava. More importantly, the massive sulphide deposits known so far in the Gjersvik area are mainly associated with this kind of the complexes. For example, the Gjersvik massive sulphide body and other massive sulphide deposits such as Annlifjellet, Tjiermajaevrieh and Gjersvikklumpen are all associated with the keratophyric pyroclastic complexes, and the biggest keratophyric pyroclastic body in the southern shore of the Bjorkvatnet is also associated with the massive sulphide mineralization. The smaller scale felsic bodies are only several to tens meters in width and length, respectively, and are often homogeneous in texture and structure of the rocks. They exhibit, in places, a distinct intrusive contact relation to their wall rocks. These smaller scale felsic rocks are often associated with obvious porphyritic texture consisting of quartz and albite porphyritic crystal setting in the matrix of felsic minerals plus minor chlorite and sericite. They have thus been interpreted as dykes, sills or subvolcanic rocks.

The keratophyric pyroclastic complexes of rhyolitic composition are characterized by albite-rich, less mafic minerals in content and very few recognizable potash feldspar. They consist of albite, quartz with small amounts of sericite, carbonate, chlorite, epidote and biotite, among which the felsic minerals dominated by albite are most abundant, ranging usually from 80 to 95 percent in content. Magnetite and pyrite are main accessory minerals, being subanhedron to anhedron fine grained, about 2 percent in content, whereas apatite and sphene are lessly important, being euhedron fine-grained.

The felsic extrusive rocks are characterized by holocrystaline-porphyritic textures consisting of phenocrysts setting in a very fine-grained, usually less 0.05 mm in size, matrix of quartz and albite with subordinate chlorite and epidote (Fig. 3.8). Content of the phenocrysts is generally less 20 percent. The phenocrysts are mainly composed of euhedron to subeuhedron tabular albite with obvious twinning of albite or Carsbad, ranging generally from 0.1 to 0.6 mm in size, which occur as either individual crystal or aggregates. A few roundish quartz and subeuhedron biotite phenocrysts also frequently occur. The biotite phenocrysts associated with one perfect cleavage are often locally or wholly replaced by chloride. All phenocrysts are in certain extent oriented and surrounded by schistory. Some of phenocrysts are associated with flow texture.

3.2.3 Chemistry of metavolcanic rocks

(1) Sample selections and analytical techniques

A total of 74 samples including 22 pale greenstones, 24 dark greenstones, 8 felsic volcanic rocks, 8 coarse-grained trondhjemites, 6 fine-grained porphyritic trondhjemites and 5 gabbros, representative of different types of the metavolcanic and meta-intrusive rocks in the Gjersvik colcanic arc were collected from the Gjersvik Formation in the Gjersvik area for chemical analysis of major and trace elements. The dark greenstone was further chosen from different subtypes, that is, massive and schistose chloritic greenstones, massive stilpnomelane- and biotite-bearing greenstones, and pillowed chloritic greenstone. All samples were collected from the surface outcrops but only one (DR4) from drilling core Bh4 in the mapping area. The analysized results are shown in Tables 3.1, 3.2, and 3.3.

Due to the fact that the all rocks within the Gjersvik Formation underwent affections of the regional low-grade metamorphism and, especially, the local replacement of the ocean-floor hydrothermal system within the volcanic piles, some of the metavolcanic rocks were changed in their primary compositions during the second geological processes. Thus, it is necessary to

Fig. 3.8 Typical porphyritic texture in the felsic volcanic rocks, albite porphyrocrystals are replaced, showing original crystals

" + " 2.5 x 3.2 x 1.25

make carefully an essay for the collected samples in order to certify if they are fresh enough to be used. The samples were first carefully selected in outcrops or drilling core in the field, each of them must then be identified under microscope. The results have shown that all collected samples but only one (913704) have a minimum or a negligible affection in their chemical compositions from the second geological processes. The results are believable and available in determining the natures of the primitive rocks. The sample (913704) is not good enough to be used because it was greatly effected by the hydrothermal alterations.

Major and trace elements were analyzed by an instrumental method with PHILIPS PW1480 X-Ray Spectrometer, made by Ivar Romme and I. Vokes, at laboratory of Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology.

(2) Metavolcanic rock series

Study of the recent volcanic activity and volcano-petrology has shown that different magma series tend to be associated with distinct tectonic settings or to occur in different stage during a volcanic island arc (Wilson, 1989). It has, however, be emphasized that the results from the major elements must be combined with a consideration of those from the trace elements when they are used to determine magma series because all kinds of the rocks in the Gjersvik volcanic arc have suffered affections both of ocean floor weathering process (spilitization) and regional low-grade metamorphism, during which some mobile elements such as sodium and potassium have probably been changed in comparison with their original compositions. Affection of the ocean floor weathering process is perhaps more than that of the regional low-grade metamorphism in compositions of the rocks, since regional metamorphism up to or under low-grade greenschist facies is generally isochemical, which has no or few affection in chemical compositions of the rocks.

Generally, volcanic rocks can be classified into two magma series, i.e. alkaline, and sub-alkaline or low-K sub-alkaline series (Middlemost 1975). Plots of the greenstones of basaltic composition in the Gjersvik volcanic arc in the diagram of wt % K2O versus wt % SiO2 indicate that they all concentrate on field within the low-K sub-alkaline and sub-alkaline magma series

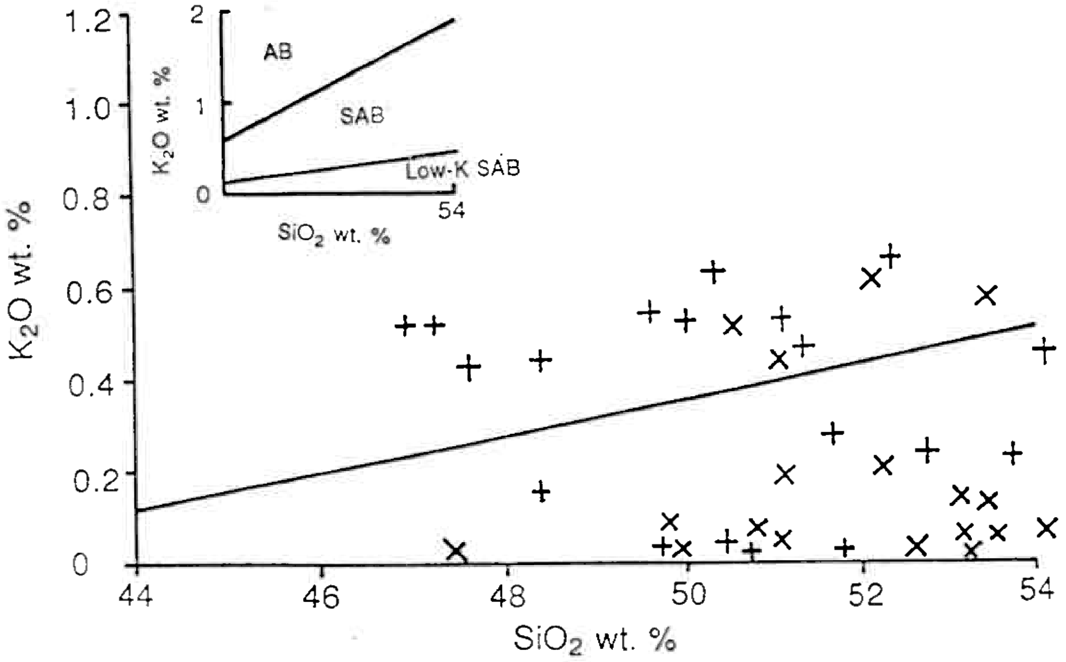


Fig. 3.9 Plots of the greenstones in diagram distinguishing alkaline and sub-alkaline basalts in terms of wt. % K2O versus wt. % SiO2 (after Middlemost, 1975)

x dark greenstone; + pale greenstone

(Fig. 3.9).

The sub-alkaline magma series, including both of sub-alkaline and low-K sub-alkaline magma series, can be subdivided into a low-K tholeiitic and a high alumina or calc-alkaline series. One of the most prominent differences in chemical compositions between the more basic end-members of typical tholeiitic and calc-alkaline series is in their $Al2O3$ content: calc-alkaline basalts and andesites generally vary between 16-20 wt.% $Al2O3$, whereas their tholeiitic counterparts contain only 12 - 16 wt.% $Al2O3$ (Wilson, 1989). $Al2O3$ contents of the greenstones are generally less 16 wt.%, ranging from 13.5 to 16.5 percent (Tables 3.1, 3.2). This feature relative low $Al2O3$ is also well exhibited in diagram of Alkali Index (A.I.) versus wt.% $Al2O3$, in which the greenstones almost plot within field of tholeiitic basalt (Fig. 3.10).

Another important difference between tholeiitic and calc-alkaline basalts is that they have two different differatiation trends called iron-depletion and iron-enrichment trends of the calc-alkaline and tholeiitic series, respectively. In the triangular diagram F-M-A (MgO-FeO*-(Na2O+K2O)), typical tholeiitic series shows trends approximately parallel to the M-F side in their early and middle stages of fractional crystallization, whereas typical calc-alkaline series shows trends approximately normal the M-F side (Akiho Miyashiro, 1974). Plots of the greenstones and the metafelsic rocks in the diagram F-M-A show an apparent tholeiitic trend (Fig. 3.11).

In addition, the TiO2 content decreases with increase FeO/MgO in calc-alkaline magma series, whereas it increases first and then decreases in typical tholeiitic magma series (Akiho Miyashiro 1974). In diagram of FeO*/MgO versus wt % TiO2, plots of the greenstones are consistent with the trend of a typical tholeiitic series, but distinct to a calc-alkaline series (Fig. 3.12).

In a short word, chemical compositions described above have demonstrated that the metavolcanic rocks constituting the Gjersvik volcanic arc are most probably tholeiitic in magma series. It is significant when this conclusion combines with the geological fact that the Gjersvik volcanic arc is dominated by the greenstones of tholeiitic composition, occupying about

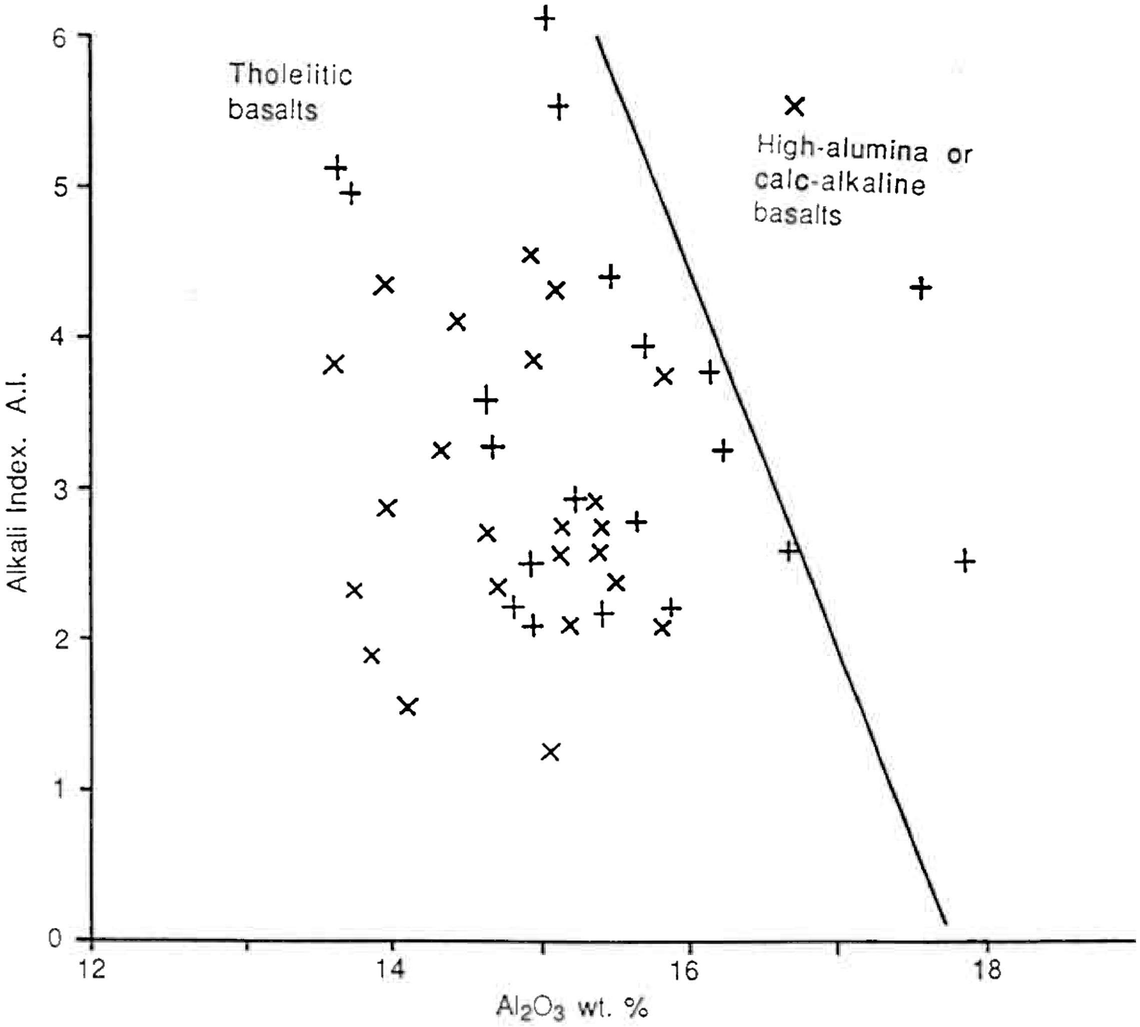


Fig. 3.10 Plots of the greenstones in diagram of Alkali Index (A.I.) versus wt. % Al2O3 distinguishing the tholeiitic and high-alumina or calc-alkaline basalts (after Middlemost, 1975)

x dark greenstone; + pale greenstone

$$A.I. = \frac{Na2O + K2O}{(SiO2 - 43) \times 0.17}$$

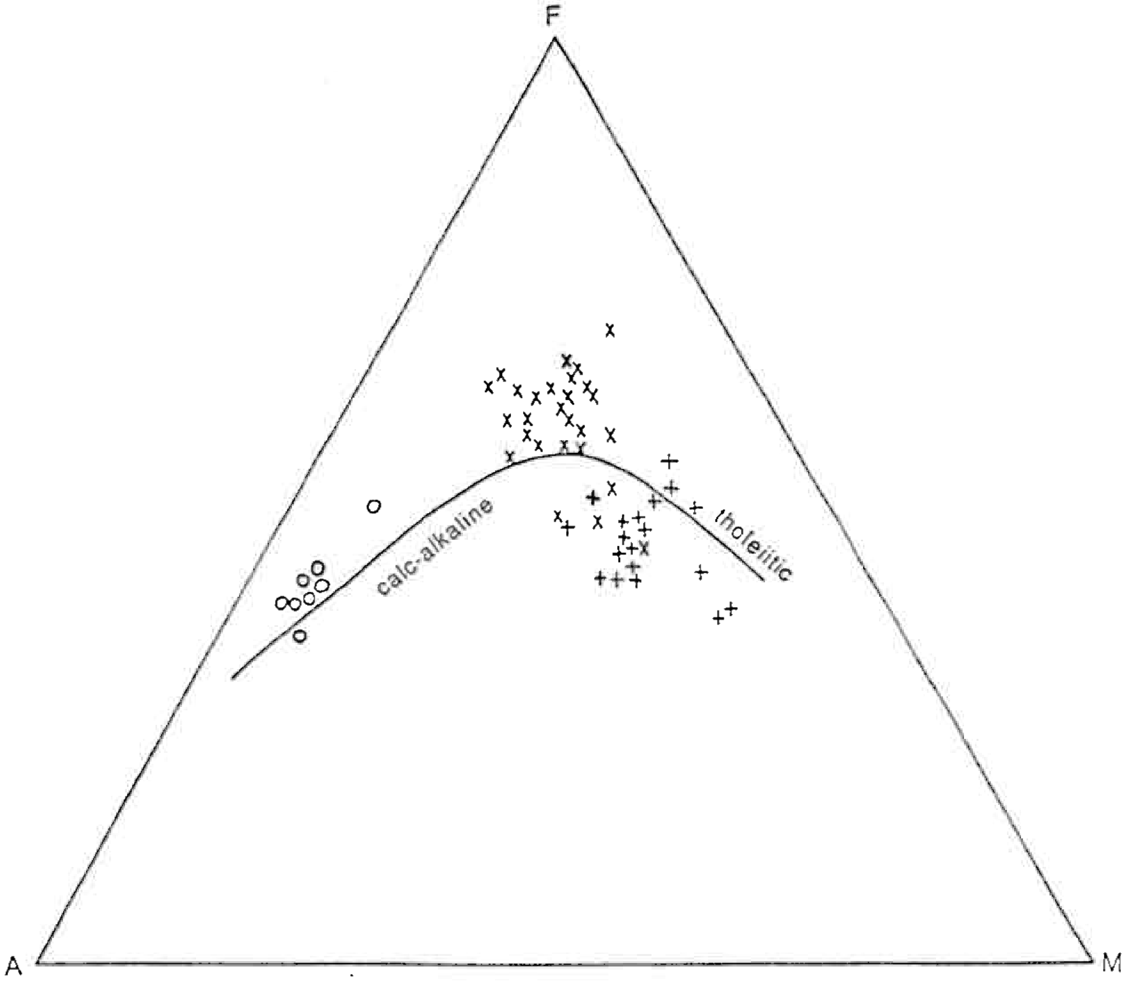


Fig. 3.11 Plots of the metavolcanic rocks in triangular FMA diagram indicating typical tholeiitic and calc-alkaline differentiation trends

A - Na2O + K2O; F - FeO + Fe2O3; M - MgO

x dark greenstone; + pale greenstone; o felsic volcanic rocks

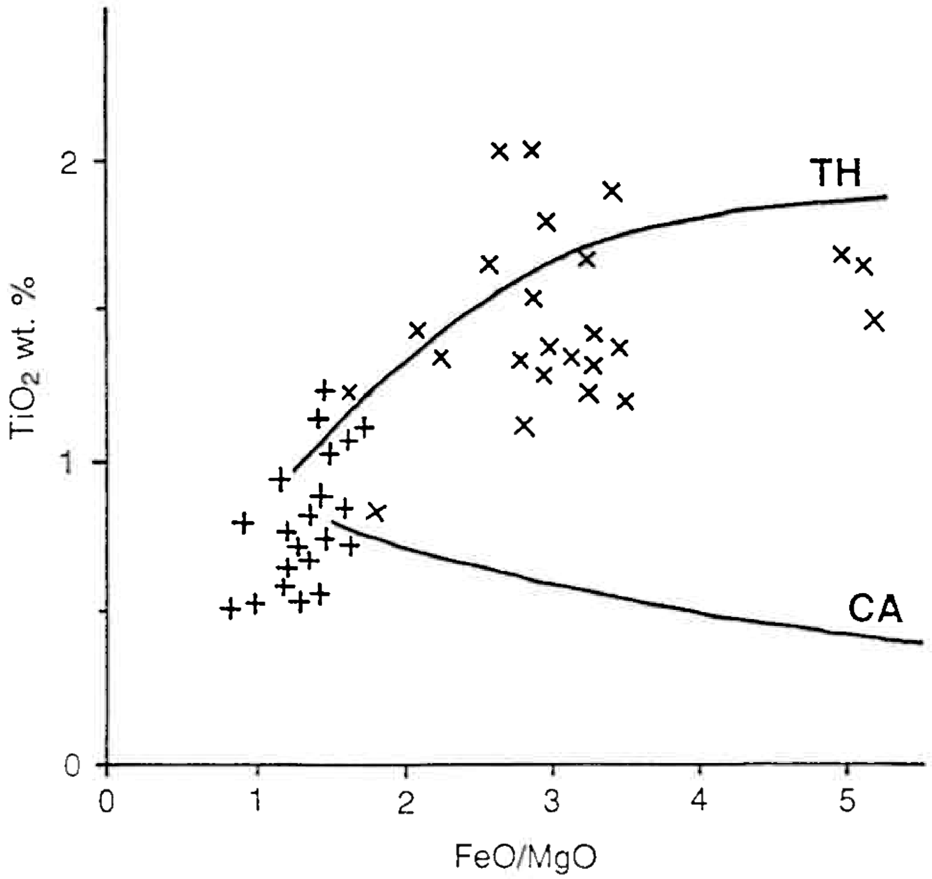


Fig. 3.12 Plots of the greenstones in diagram distinguishing the tholeiitic and calc-alkaline basalts in terms of the different trends of variations of TiO2 versus FeO/MgO (after Miyashiro, 1974)

TH - tholeiitic trend of the island arc
CA - calc-alkaline trend of the island arc

x dark greenstone; + pale greenstone

80 per cent in volume, plus only small amounts of felsic volcanic rocks. It hence is concluded that the Gjersvik volcanic arc was mainly made up by tholeiitic basalts. More importantly, the immature island arcs are usually made up of basaltic rocks of the tholeiitic series, whereas calc-alkaline magmas are typical of more mature arcs and active continental margins (Wilson, 1989).

(3) Major elements

Bimodal feature

The Gjersvik volcanic arc is characteristic of a typical bimodal compositions of the metavolcanic rocks, especially in SiO2 contents. The greenstones concentrate mainly on the range of 50 - 52 percent in SiO2 content and vary among 46 to 56 percent, whereas the keratophyric pyroclastic rocks concentrate largely on 72 - 76 percent and ranges from 70 to 78 percent (Fig. 3.13). This feature is also distinctive in the field, for two kinds of the metavolcanic rocks can be easily distinguished on rock outcrops during the surface mapping. The greenstones of tholeiitic composition are characterized by pale or dark green, whereas the keratophyric pyroclastic complexes of rhyolitic composition are typical of pale- and grey-white in colour. No typical volcanic rocks of andesitic composition have so far been found within the Gjersvik Formation in the mapping area. It should mentions that it is possible that some greenstones contain a relative high SiO2 in content. However, they result mainly from the affection of hydrothermal alteration of silicification, not from transformation of the volcanic rock types based on the determination under microscope.

In recent review of magmatism and tectonic settings throughout the world, Martin and Piwinskii (1972) noted that two kinds of magmatism in orogenic and nonorogenic belts are associated with two tectonic settings, compressional and tensional (rifting) environments. The prominent igneous rock associations in orogenic belts are predominantly calc-alkaline or hypersthenic in magma series, consisting of andesitic volcanogenic sequences predominantly of andesite, high-alumina basalt, and dacite with fragmental volcanoclastic strata and of quartz monzonite, granodiorite, and quartz diorite with minor granite, diorite, and gabbro in batholithic belts, which the latter is considered to be the plutonic equivalents of the andesitic

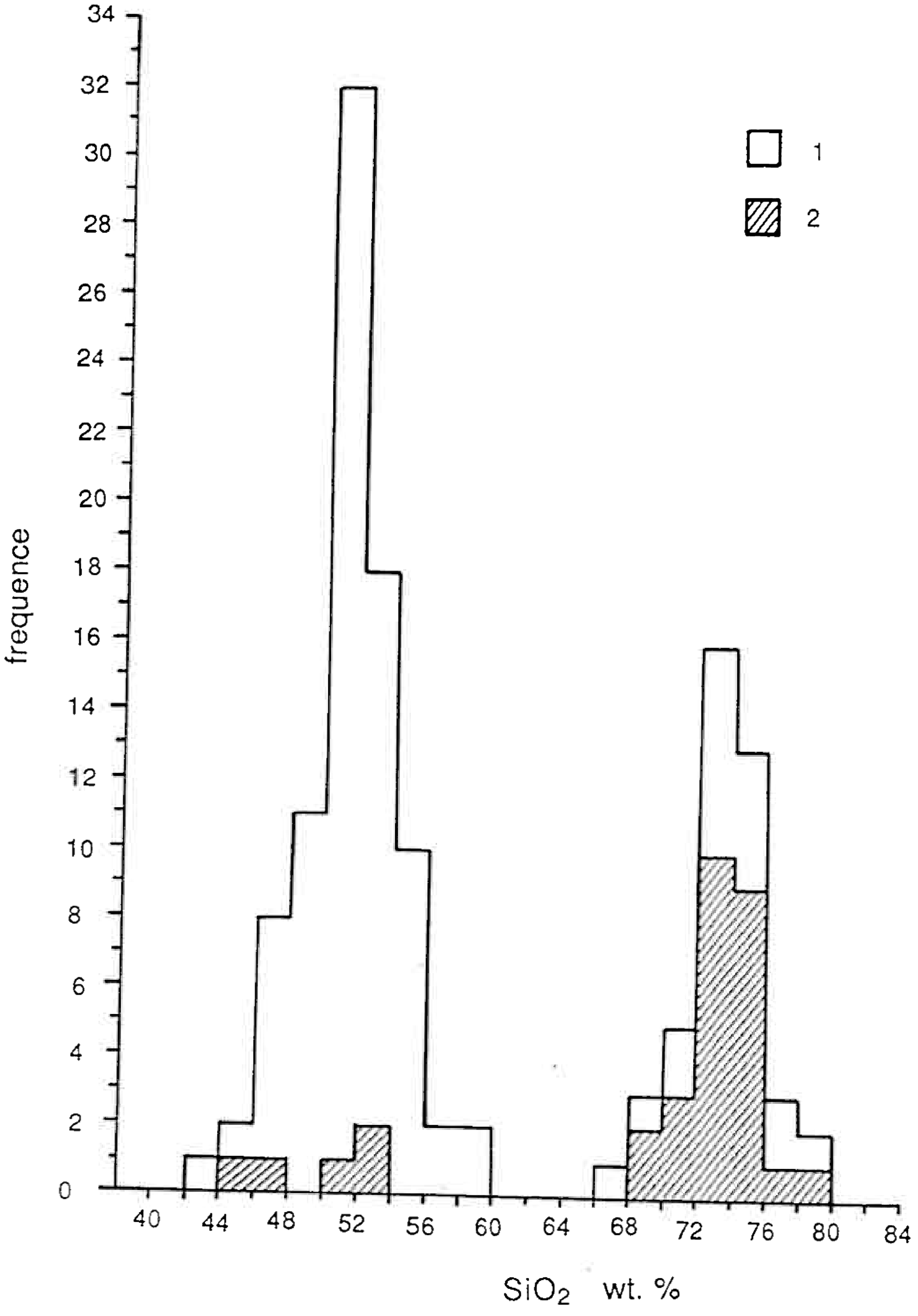


Fig. 3.13 Frequency ranges in SiO2 content of meta-extrusive and meta-intrusive rocks of the Gjersvik Formation

Total of 129 rock chemistry data, 56 of them quoted from Lutro (1979)

1 - meta-extrusive rocks; 2 - meta-intrusive rocks

sequences. In contrast, the igneous rock associations occurring in tensional environments are characterized by obvious bimodal basalt-rhyolite volcanic assemblages that are essentially lack or volumetrically insignificant andesites. Otherwise, the recent researches have pointed out that the igneous rock associations within the back-arc environments throughout the world are also characterized by bimodal tholeiitic basalt-rhyolite assemblages (Sinton et. al, 1987; Hochstaedter et. al, 1990; Smith et. al, 1990;).

It is very significant to make a comparison of the bimodal volcanic assemblage constituting the Gjersvik volcanic arc with those of recent igneous associations in different tectonic environments. The bimodal metavolcanic assemblage dominated by the greenstones of tholeiitic composition plus small keratophyric pyroclastic rocks of rhyolitic composition in the Gjersvik Formation is apparently different from those in well-developed island arcs with a thick continental-type crust consisting of andesites and dacites of the tholeiitic and calc-alkaline series, and from those in continental margins characterized by andesites, dacites, and rhyolites of the calc-alkaline series (Wilson, 1989). They are also in some ways distinct from those in oceanic island, mid-oceanic ridges and intracontinental rifts although they all undoubtedly belong to tensional or rifting environments. The reason is that the bimodal volcanic assemblages in intro-plate tectonic settings such as oceanic islands and intracontinental plate rifts are predominantly associated with or dominated by alkali basalts and their differentiates, such as alkalic basalt, rhyolitic, trachytic, phonolitic differentiates and their plutonic equivalents, and locally with important ultramafic, nephelinitic, and carbonatitic volcanic rocks, whereas those at mid-oceanic ridges are dominated by the abyssal tholeiitic basalt but not or seldom associated with evolved felsic volcanic rocks and their plutonic equivalents. The bimodal metavolcanic assemblage in the Gjersvik Formation, however, is probably comparable with those in the tensional back-arc and the immature, ensimatic island arcs environment formed directly on the ocean floor.

General feature

As the recent knowledge state, it has been known that most major elements are considered to be mobile and hence may be of limited use in petrogenetic interpretion. However, in some studies it has been assumed that certain major elements were not mobile and can be used to infer primary magmatic processes (e. g., MgO in the study of Barker et. al., 1989).

The general features of the dark and pale greenstones in major elements are presented in the variation diagrams of MgO versus Al2O3, CaO, TiO2, FeO, Na2O and K2O (Fig. 3.14), in which the greenstones are compared to the tholeiitic basalts occurring in typical but different tectonic environments such as MORB (Mid-ocean ridge basalts), HTB (Hawaiian tholeiitic basalts) and IATB (Island arc tholeiitic basalts). Generally, fields of major elements of the greenstones are not completely coincident with each of those of MORB, IATB and HTB, but they, especially Al2O3, TiO2 and FeO, tend to be concentrated between those of MORB and IATB. TiO2 and FeO decrease systematically but Al2O3 and CaO tend to increase with MgO increase in contents, while Na2O and K2O are mainly random (Fig. 3.14). Thus, MgO and TiO2 are assumed to be immobile and can be used in inferring primary magmatic processes, the FeO, CaO and Al2O3 are probably in certain levels mobile and can conditionally be used in petrogenetic interpretions, whereas Na2O and K2O are too mobile to be used in interpreting primary magmatic processes. However, Na2O and K2O are perhaps valuable in detremining the secondary geological processes such as ocean-floor weathering and regional metamorphism. It has been revealed that Na2O and K2O contents in the greenstone are probably determined mainly by ocean-floor spilitization, but not largely by the primary volcanic compositions (Fig. 3.1). It must be emphasized, however, that any petrogenetic interpretations for the metavolcanic rocks in terms of geochemistry must be based on the combination of the major with the trace elements of the rocks.

MgO contents appear to have different enriched trends in dark and pale greenstones, the former varying mainly from 2.5 to 7 percent, but the latter from 7 to 12 percent. This means that the dark greenstone is probably poor in MgO content relative to the pale greenstone in their primary magma compositions. Al2O3 contents of the pale and dark greenstones range from 13.5 to 15.5 percent that are mainly similar with those of MORB and HTB produced within ocean crust but relatively lower than those of the IATB. CaO contents appear to show a trend similar with that of IATB, i.e., CaO increases with increasing MgO contents, and they are generally lower than those in MORB and HTB. Field of TiO2 in the pale and dark greenstones falls between MORB and IATB, and are distinct from that in HTB. More significantly, the trend that TiO2 contents decrease systematically with MgO increase is consistent with that of the MORB but distinct with typical IATB. The same trend also reflects in the FeO against MgO changes. In addition, the dark

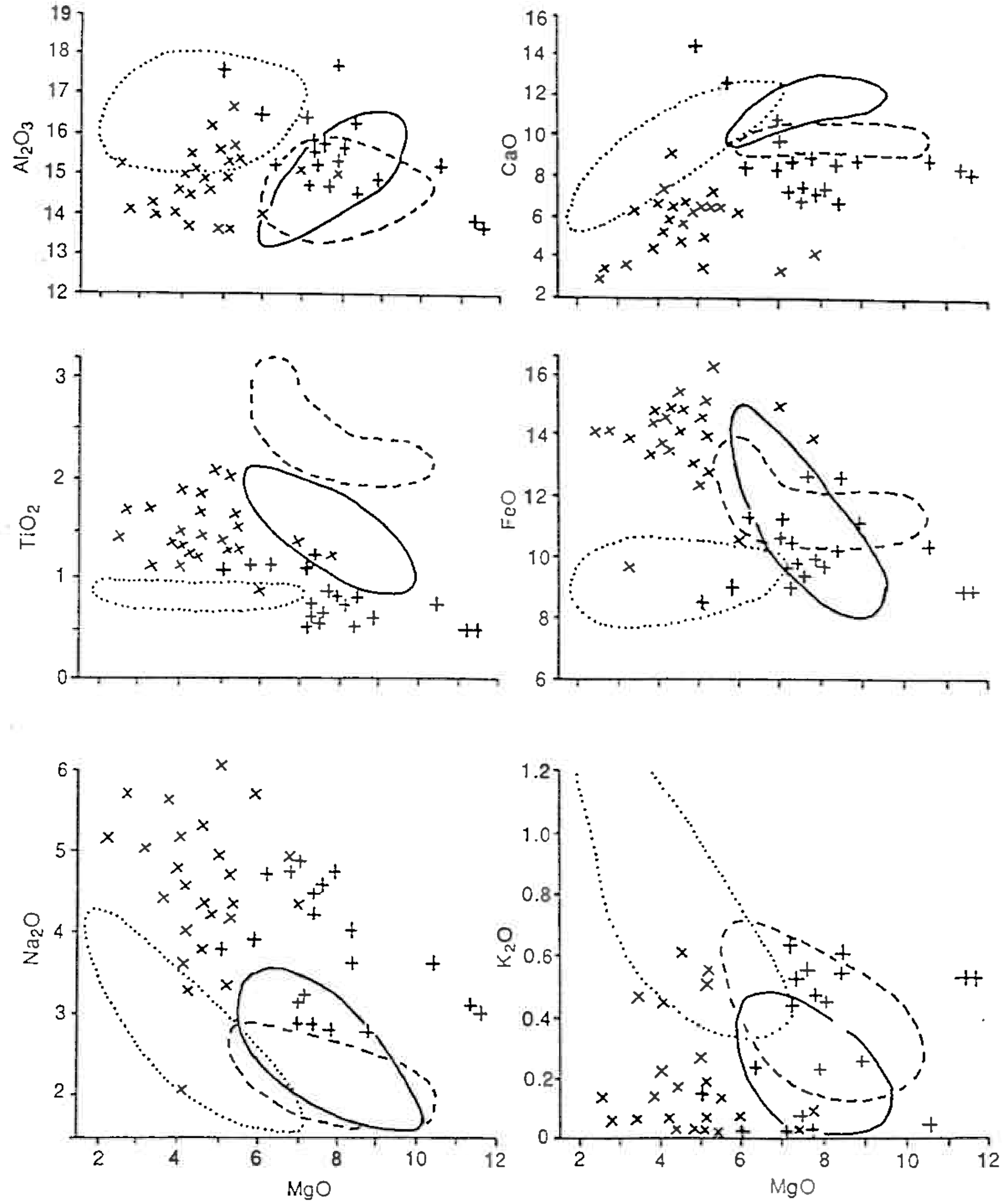


Fig. 3.14 Major element variation diagrams showing trends for the dark and pale greenstones of tholeiitic composition and making a comparison of the greenstones with MORB, HTB and IATB representive of typical but different tectonic environments

x dark greenstone; + pale greenstone

◌ field for the island arc tholeiitic basalts (IATB) from Miyashiro (1974); ⬭ field for the Hawaiian tholeiitic basalts (HTB) from Carmichael et. al., (1974), Wilson (1989) and Hess (1989); ◯ field for mid-ocean ridge tholeiitic basalts (MORB) from Sun (1979) greenstone is characterized by high TiO2, ranging from 1 - 2 percent, and high FeO*, varying mainly from 12 to 15 percent in contents that are similar with those of MORB and HTB, whereas the pale greenstone is relative low both in TiO2, less 1 percent, and in FeO content, ranging from 8 to 12 percent that are similar with those of IATB. Differences between the dark and pale greenatones in TiO2 and FeO contents appear to be originic. The alkalic contents (Na2O and K2O) of the greenstones vary greatly and are inconsistent with those of MORB, HTB and IATB. Na2O contents in the greenstones are generally higher than that of MORB, HTB and IATB but in some of them are indeed low. K2O contents of some of the greenstones are very low but others relatively high. The reason leading Na2O and K2O considerable changes has been interpreted to be produced by secondary geological processes of ocean floor weathering.

In addition, the pale and dark greenstones appear to be clearly separated into two groups on the basis of some element contents such as MgO, TiO2 and FeO*. The pale greenstone is characterized by high magnesium but low iron and titanium, whereas the dark greenstone by relatively low magnesium but high iron and titanium in contents, which probably indicate an primary differences between the dark and the pale greenstones in their primary magma compositions.

(4) Trace Elements

Discussion

Petrogenetic interpretion of altered or metamorphosed igneous rocks is impaired by difficulties in discriminating between chemical characteristics produced by igneous processes and those superimposed during subsequent events such as sea-floor hydrothermal alteration, regional metamorphism, and exposure to hydrothermal fluids accompanying later plutonism. In the case of the Gjersvik volcanic arc, the latter is not considered as a factor since there is no later plutonism to be found in the area. And, the low-grade regional metamorphism is most probably isochemical and hence is also interpreted as a neglect factor. The hydrothermal alterations related to the mineralization and the ocean-floor weathering (spilitization), however, must be tested before chemical data of the samples are used in petrogenetic interpretion.

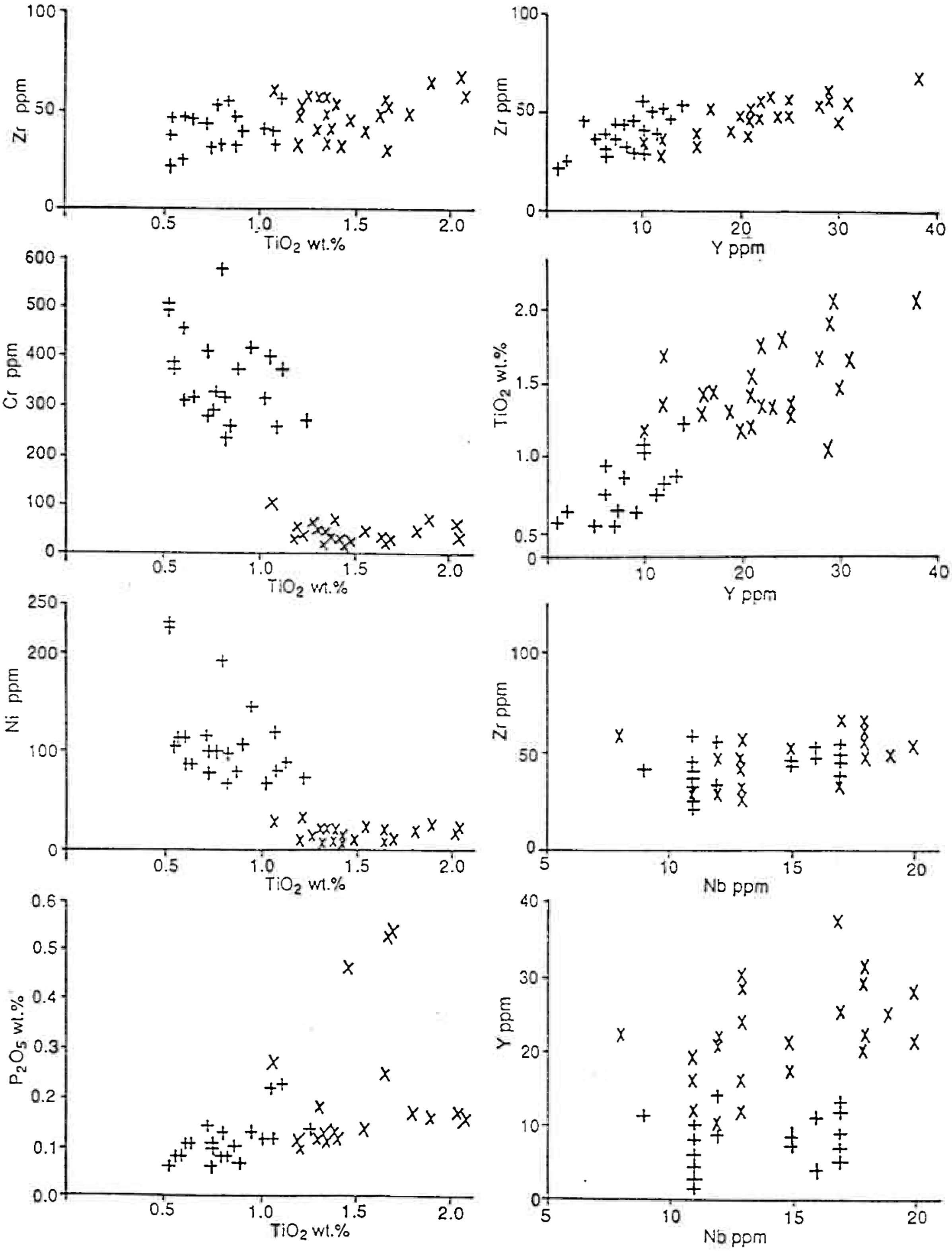


Fig. 3.15 Variation diagrams of immobile trace and minor elements in the dark and pale greenstones

+ pale greenstone; x dark greenstone

Some of trace elements were studied as immobile components in hydrothermal fluid such as Zr, Nb, Hf, Th, Ta, Ti, Cr, P, and Y (Humphris and Thompson 1978; Winchester and Floyd 1976; Floyd and Winchester 1975; Donato 1991) although many major and trace elements are considered to be mobile. In order to determine element behaviors, pairs of some trace and minor elements in the dark and pale greenstones are used to judge how immobile they are during the superimposed hydrothermal processes. Most of the pairs, such as TiO2 - Zr, TiO2 - Cr, TiO2 - Ni, TiO2 - Y, Zr - Y, and Nb - Zr exhibit strong systematic covariance, while others, including TiO2 - P2O5 and Y - Nb in great extent display the scattered correlations (Fig. 3.15). These patterns imply that affections of the post-magmatic alterations related to the mineralization and the ocean-floor weathering (spilitization) are minimal in the most trace and minor immobile elements and that the abundances of Ti, Zr, Cr, Ni and Y, most probably exhibit primary magmatic compositions, but the Nb and P, perhaps including some mobile elements such as Rb, Ba and Sr, were in certain extent changed.

General feature

Trace elements in different types of the metavolcanic rocks constituting the Gjersvik volcanic arc are shown in Table 3.1, 3.2 and 3.3.

Greenstones

The immobile elements in the pale and dark greenstones are very significant and distinct each other. The pale greenstone is characterized by apparent high Cr, Ni, as well as low Ti and Y in comparison with the dark greenstone. For example, the Ni contents vary among 66 - 221 ppm, average 107 ppm, the Cr among 119 - 529 ppm, average 240 ppm, the Ti among 3117 - 7434 ppm, average 4793 ppm, and the Y among 11 - 24 ppm, average 17.5 ppm in the pale greenstone, whereas the Ni contents range from 2 to 28 ppm, average 13 ppm, the Cr from 12 to 57 ppm, average 25 ppm, the Ti from 6414 to 12350 ppm, average 8940 ppm, and the Y from 20 to 40 ppm, average 31 ppm in the dark greenstone (Table 3.1, 3.2 and 3.4). In addition, the Co is slightly high but the Zr and the V are low in the pale greenstone (49 ppm Co, 40 ppm Zr, and V 250 ppm average values, respectively) relative to those in the dark

Table 3.4

Some trace elements and their ratios in the dark and pale greenstones of tholeiitic composition in comparison with those in the tholeiitic basalts in the recent identifical tectonic environments

	pale greenstone n = 22	dark greenstone n = 24	N-type[1] MORB	E-type[1] MORB	Back-arc[2] BATB	Arc[1] ATB
Zr	40	48	80	75	130	22
Ti	4793	8940	9300	8060	8753	3000
Y	18	32.5	29	22	30	12
Ni	110	14.5	173[3]	124[3]	59[4]	14[5]
Co	50	46	45[3]	51[3]	34[6]	33.5[7]
Cr	180	21.5	403[3]	324[3]	258[4]	100[5]
Cr/Ni	1.65	1.48	2.33	2.61	4.34	7.14
Ni/Co	2.20	0.32	3.84	2.43	1.73	0.41
Zr/Y	2.22	1.47	2.9	3.4	4.3	1.8
Ti/Zr	120	175	109.74	107.46	67.33	13.63

1 - Sun (1980); 2 - Hawkesworth et. al., (1977); 3 - Schilling et. al., (1983); 4 - Saunders & Tarney (1979); 5 - Luff (1982); 6 - Hawkwns (1990); 7 Dixon, (1979)

greenstone (42 ppm Co, 51 ppm Zr, and V 352 average values, respectively). This is significant in interpreting petrogenetic processes because systematic differences and changes of the trace element populations in the dark and pale greenstones reflect to originated magma compositions since the Ti, V, perhaps, and Zr show parallel behavior but Ni, Co, and Cr are similar during magmatic processes.

It has been demonstrated that the behaviors of some trace elements in the tholeiitic basalts are determined both by their primary background value, i.e. source material, and by magmatic processes. For example, high values (e.g. Ni = 250-300 ppm, Cr = 500-600 ppm) for these elements are good indicators of derivation of parental magmas from a peridotite mantle source because these trace elements are compatible in peridotite that are concentrated in minerals rather than the melt phase. The crystal-liquid distribution coefficient data indicates that Ni and Co will partition into olivine during partial melting and fractional crystallization processes, while Sc, Cr, and V will enter clinopyroxene, spinel and garnet. Thus, these trace elements should increase in mantle that has lost basaltic magma, and peridotites with the highest Mg value and MgO, NiO, and Cr2O3 content and the lowest CaO, Ti2O, and Al2O3 content are the most refractory (Hess, 1989). Thus, a comparable property both of high Cr and Ni concentrations and Mg-rich nature in the pale greenstones and of much low Cr and Ni contents in the dark greenstone exhibit they were originated from different magma sources.

In addition, the diagrams of MgO against Ni and Cr (Fig. 3.16) show that the Ni and Cr increase systematically with the increase MgO in the pale greenstone, while the Ni and Cr are not obviously variable with increase MgO in the dark greenstones. The different geochemical behaviors of the Cr, Ni and Mg in the dark and pale greenstones display the different evolved trends of magmatic processes. It has been revealed that the Ni abundances in MORS strongly controlled by olivine fractionation. Contents range from > 300 ppm in primary glass basalts to 25 ppm in highly evolved basalts, and correlate well with MgO content. Cr contents similarly show a marked reduction from 700 to 100 ppm with progressive fractionation (Wilson, 1989). Thus, apparently different trends of MgO against Ni and Cr point out that the pale and dark greenstones were originated from the more differentiated and undifferentiated tholeiitic basaltic magmas, respectively. Different differentiated trends of the dark and pale greenstones are further revealed in terms of V and Ti correlation. Diagram of V against TiO2 shows that V and Ti

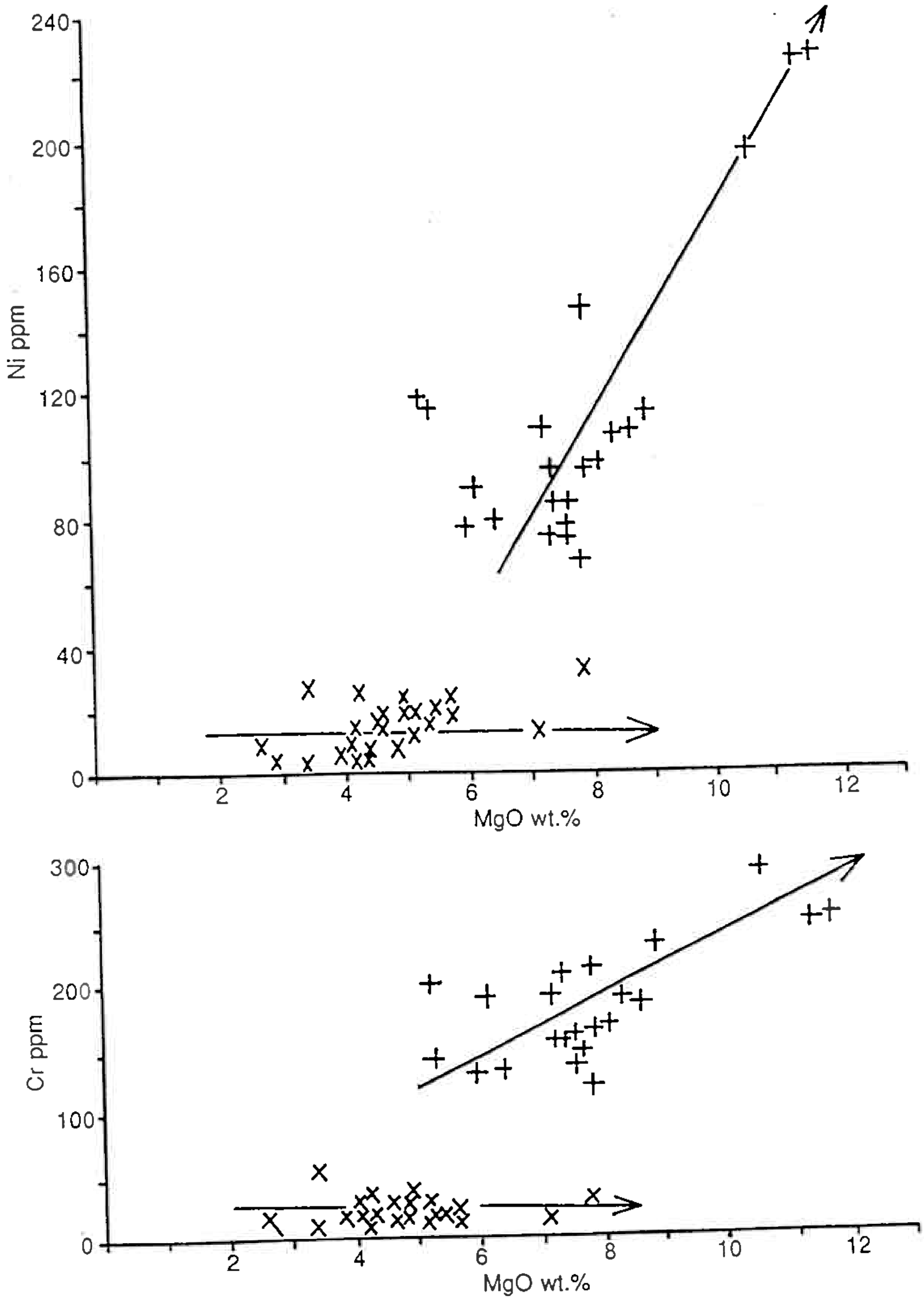


Fig. 3.16 Diagrams showing different evolved trends and relations between MgO against Cr and between MgO against Ni in the dark and pale greenstones

\+ pale greenstone; x dark greenstone

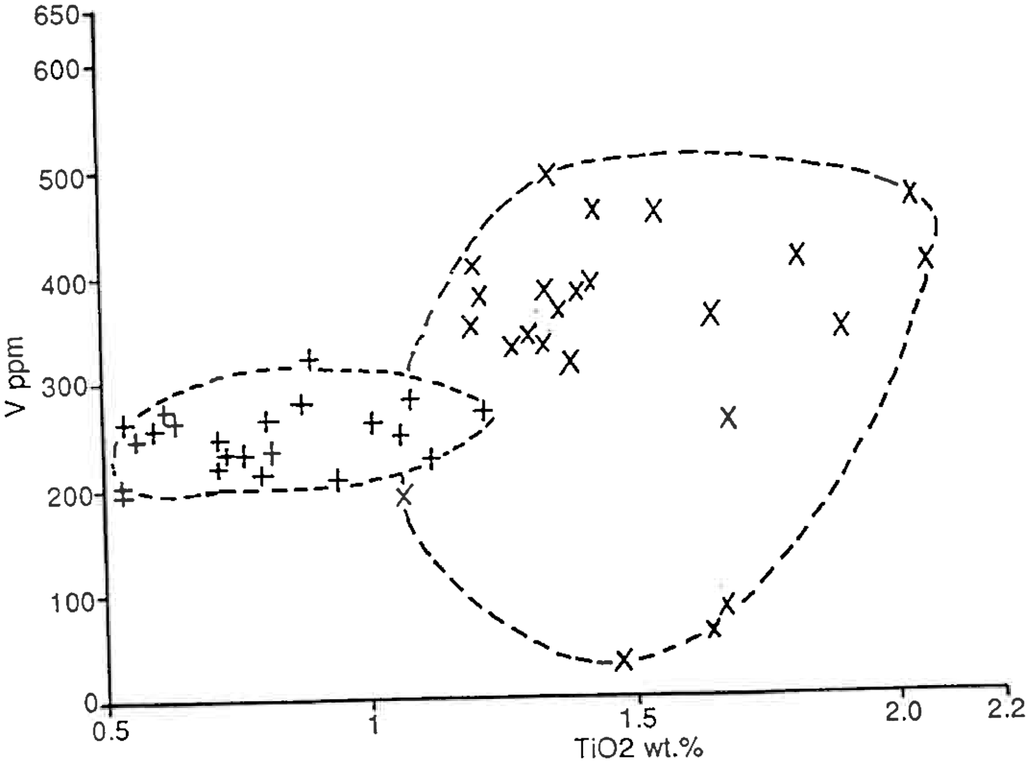


Fig. 3.17 Diagram showing different V and Ti behaviors in the dark and pale greenstones

\+ pale greenstone; x dark greenstone

have good linear correlation in the pale greenstone, i.e., V has no apparent variation with Ti increase, while V and Ti show obvious divergent behaviour in the dark greenstone (Fig. 3.17). Due to the fact that V and Ti should display parallel behaviour during melting and crystallization processes, the good linear correlation point out that the fraction of Fe-Ti oxides such as ilmenite and titanomagnetite play an important role during tholeiitic magma process leading formation of the pale greenstone, whereas V and Ti divergent behaviour in the dark greenstone probably indicates Ti substitution into some accessory phase such as sphene or rutile.

Paleotectonic environments evidenced from geochemistry of the greenstones

Study of the recent volcanic activities has well been revealed that the calc-alkaline magmas are apparently associated uniquely with subduction, while low-K tholleiitic basalts are the typical products of magma generation at constructive plate margins (Wilson, 1989). However, the tholleiitic basalts are present not only at mid-oceanic ridges, but also in back-arc basins, oceanic islands, island arcs, active continental and continental flood basalt provinces. The Gjersvik volcanic arc is composed of a bimodal volcanic suite, consisting predominantly of the greenstones of tholeiitic basaltic compositions plus small felsic volcanic rocks, and hence the question is led, i.e., what is paleotectonic environment generating the Gjersvik tholeiitic basaltic volcanic arc becomes important.

In general, the major element characteristics of primary mantle derived magmas are not particularly sensentive indicators of tectonic setting. Fortunately, it is now well established that distinctive trace elements are associated with different magma generation environments, although their petrogenetic interpretation in some instances remains ambiguous. It is useful to make a comparation of some immobile element populations and their ratios between the dark and pale greenstones and tholeiitic basalts generated in distinct tectonic environments (see Table 3.4). The compatible trace elements Ni and Co in the pale greenstone are correlated to those in the E-Type MORB, and the Cr to that in the Back-arc tholeiitic basalts (BATB), while the Cr/Ni and Ni/Co ratios (Cr/Ni, Ni/Co) are very closed those in the N-type MORB and the E-type MORB, respectively. In contrast to this, the Ni and Cr contents as well as the Ni/Co ratio in the dark greenstone are correlated to those in the Island-arc tholeiitic basalts (IATB) although the Co and Cr/Ni ration are comparable with those in the N-Type MORB. The incompatible trace

Table 3.5

Correlative analysis of the dark and pale greenstones to tholeiitic basalts occurring in distinct tectonic environments based on the immobile trace elements

		N - type MORB	E - type MORB	Back-Arc BATB	Island Arc IATB
Zr			x +		x +
Ti				+	x
Y			x	+	
Ni			x		+
Co		+	x		
Cr				x	+
Cr/Ni		x +			
Ni/Co			x		+
Zr/Y		x			+
Ti/Zr		x			
correlative coefficient	x	0.27	0.45	0.1	0.18
	+	0.2	0.1	0.2	0.5

x pale greenstone; + dark greenstone

elements Ti in the pale greenstone is comparable to that in the IATB, Y is correlated to that in E-type MORB, and Zr lies between those in the E-type MORB and the IATB, but their rations (Zr/Y, Ti/Zr) are all correlated to that in the N-type MORB. However, the Ti and Y in the dark greenstone are very closed those in the BATB, while the Zr and Zr/Y ratio are comparable to that in the IATB.

Simply, these relations of the pale and dark greenstones to other tholeiitic basalts in the distinct tectonic environments resulting directly from data of the compatible and incompatible elements are further treated on the basis of correlative analysis. Each of the trace elements or their ratios in the pale and dark greenstones is assumed as a factor, which is proposed to be correlative to that having the nearest content in each of the tholeiitic basalts representive of distinct tectonic environments. The result points out that the correlative coefficient of the pale greenstone to E-type MORB is 0.45, to N-type MORB 0.27, to IATB 0.18, and to BATB 0.1, whereas the dark greenstone to IATB 0.5, to BATB 0.2, to N-type MORB 0.2, and to E-type MORB 0.1 (Table 3.5). It appears that the immobile trace element compositions in the pale and dark greenstone are not completely identical to those in each of tholeiitic basalts occurring in distinct tectonic environments. However, the trends show that the pale greenstone can be compared mainly with the E-type MORB and in certain extent to the N-type MORB, while the dark greenstone is in great extent corrlated to the IATB and to, in some ways, the BATB. Thus, the pale greenstone was probably originated from source of the E-Type MORB mantle, but it was in certain extent mixed by some material of back-arc or island arc tholeiitic basalt, and that the dark greenstone was mainly generated in the back-arc or island arc environments.

The paleotectonic environments of the pale and dark greenstones would be further discussed in terms of some tectonomagmatic discrimination diagrams of trace elements, especially immobile elements, that are often used in determining tectonic environments. On the Cr - Ti diagram, the dark greenstone plot in field of the island arc tholeiitic basalt, while the pale greenstone exhibits a transitional nature from the island arc to the ocean ridge tholeiites (Fig. 3.18). In contrast to this, the pale greenstone plots in field of the island-arc tholeiitic basalts, but the dark greenstone in a transitional field from the island-arc tholeiites to the within-plate basalt affinities on the Cr - Y diagram (Fig. 3.19). On the Zr - Ti diagram, plots of the pale and dark greenstone mainly fall within or in outside A, B, and D fields, which indicate a trend

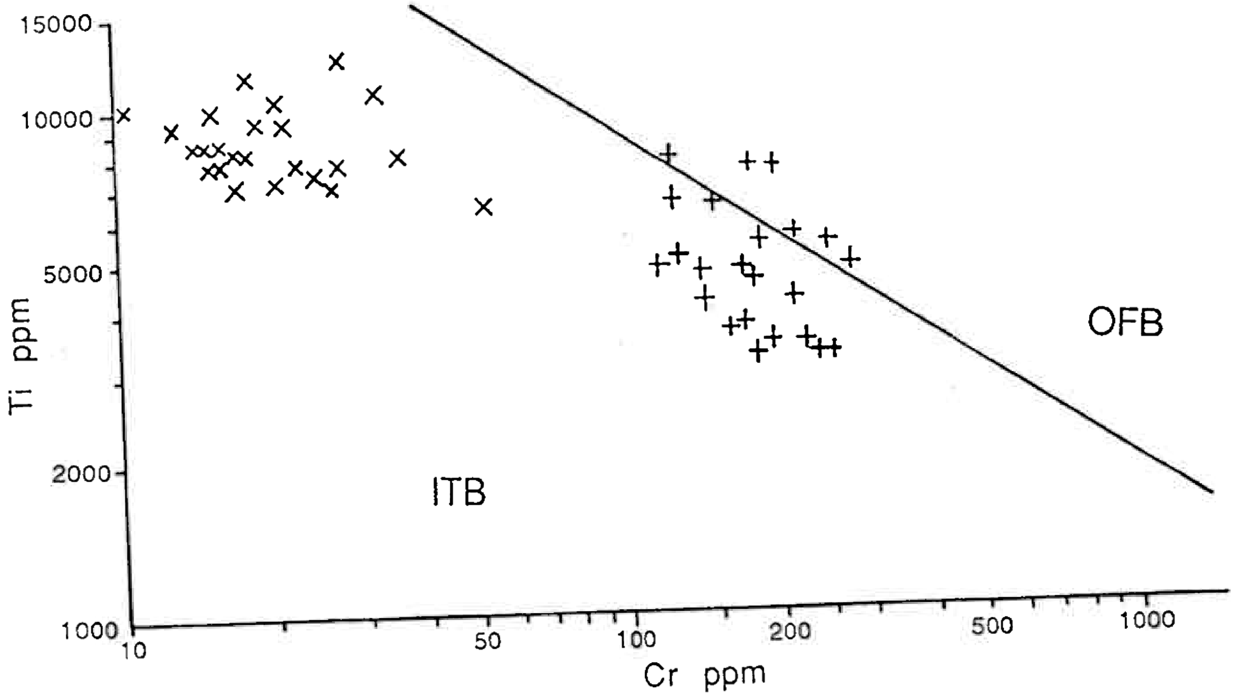


Fig. 3.18 Plots of the dark and pale greenstones in Cr - Ti tectonomagmatic discriminant diagram for basaltic rocks, distinguishing fields between the recent ocean-floor basalt (OFB) and island-arc tholeiitic basalt (ITB) affinities (after Pearce, 1975)

\+ pale greenstone; x dark greenstone;

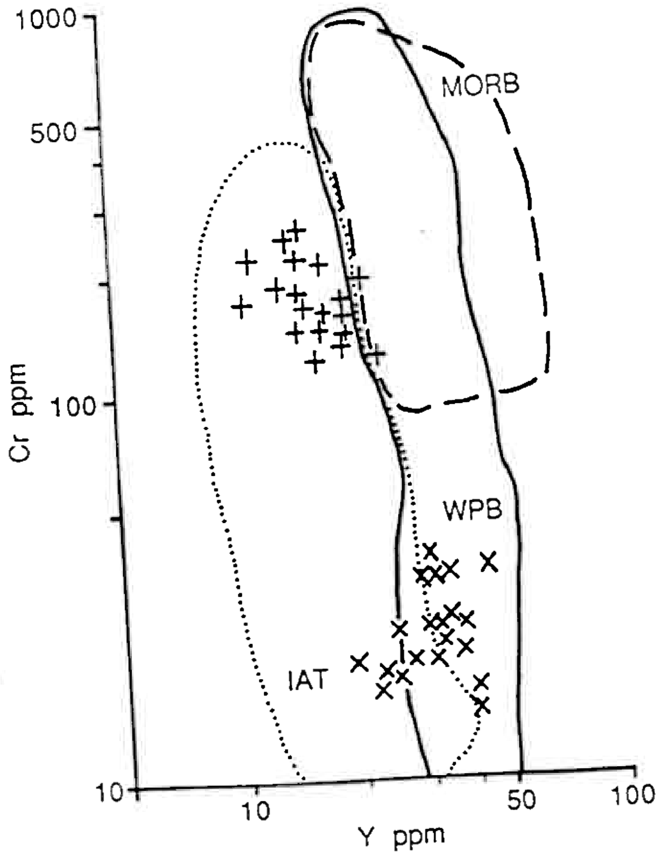


Fig. 3.19 Plots of the dark and pale greenstones in Cr - Y tectonomagmatic discriminant diagram for basaltic rocks, distinguishing fields among the recent mid-ocean ridge basalt (MORB), island-arc tholeiite (IAT), and within-plate basalt (WPB) affinities (after Gale and Pearce, 1982)

\+ pale greenstone; x dark greenstone;

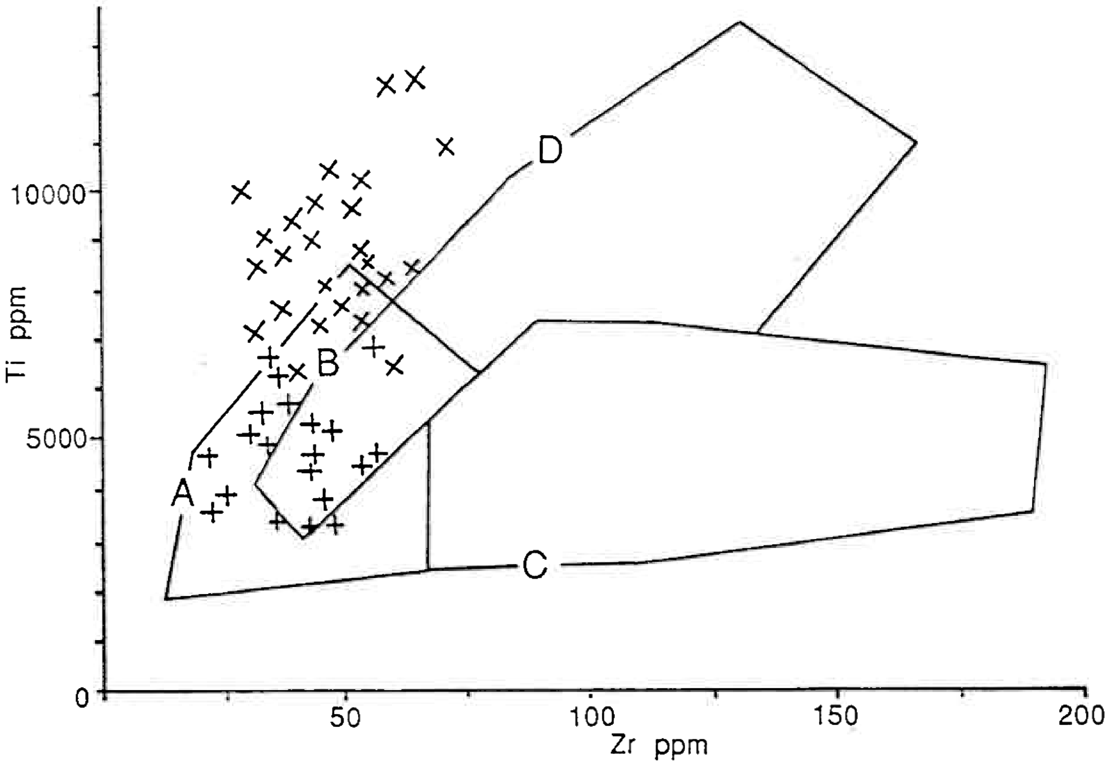


Fig. 3.20 Plots of the dark and pale greenstones in Ti - Zr tectonomagmatic discriminant diagram for basaltic rocks distinguishing the recent ocean-floor basalts in fields D and B; low-potassium tholeiites in fields A and B; and calc-alkaline basalts in fields C and B (after Pearce and Cann, 1973)

\+ pale greenstone; x dark greenstone;

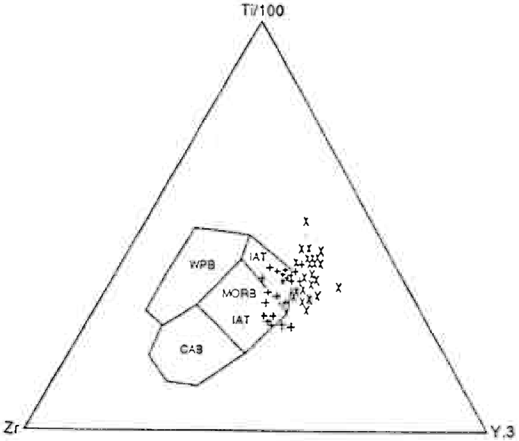


Fig. 3.21 Plots of the dark and pale greenstones in Ti/100-Zr-Y.3 tectonomagmatic discriminant diagram for basaltic rocks, distinguishing the recent within-plate basalts (WPB), island-arc tholeiites (IAT), calc-alkaline basalts (CAB), and mid-ocean ridge basalts (MORB) (after Pearce and Cann, 1973)

\+ pale greenstone; x dark greenstone;

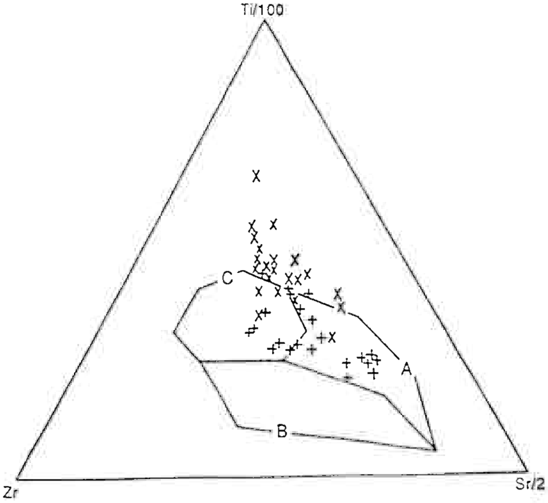


Fig. 3.22 Plots of the dark and pale greenstones in Ti/100-Zr-Sr/2 tectonomagmatic discriminant diagram for basaltic rocks, distinguishing the recent ocean-floor basalts in field C, calc-alkaline basalts in field B, and low-potassium tholeiites in field A (after Pearce and Cann, 1973)

\+ pale greenstone; x dark greenstone

parallel to ocean floor basalts and low-potassium tholeiites but different to calc-alkaline basalts (Fig. 3.20). The pale greenstone is concentrated mainly on field of the island-arc tholeiites in the triangular Ti/100 - Zr -Y.3 diagram (Fig. 3.21), but plots on field of the low-potassium tholeiites in the triangular Ti/100 - Zr - Sr/2 diagram (Fig. 3.22), while the dark greenstone fall mainly in field outside the basalts in the distinct tectonic environments.

These immobile element behaviors have well confirmed that the dark and pale greenstone are tholeiitic in magma series and they were not originated from the calc-alkaline basalts associated uniquely with subduction. However, it is not easy to make a direct comparison because each of the dark and pale greenstones is not completely coincident in the immobile trace element compositions with one of the basaltic rocks occurring in recent distinct tectonic environments. It appears that the dark and pale greenstones are of a transitional nature. For example, the dark greenstone tend to be correlated mainly to the IATB, but is also in certain extent related to the MORB and BATB, whereas the pale greenstone is comparable largely to the E-type MORB, and is also in some ways correlated to the N-type MORB, BATB and IATB in immobile trace element compositions and their behaviors.

Keratophyric pyroclastic rock

Mobile elements vary greatly in the keratophyric pyroclastic complexes such as Sr ranging from 12 to 165 ppm, Ba from < 10 to 342 ppm (see Table 3.3), which indicates they were greatly effected during later hydrothermal alterations and ocean-floor weathering. Compatible elements Co and Ni are low, generally less 5 ppm, but Cr is much high, ranging from 39 to 90 ppm, average 68.5 ppm in the keratophyric pyroclastic complexes.

3.3 Meta-intrusive rocks

3.3.1 Types of the intrusive rocks

Two main different types of the intrusive rocks, that is, trondhjemite and gabbro, have been recognized to be associated with the Gjersvik volcanic arc. The trondhjemite is subdivided into two subtypes of the fine-grained porphyritic trondhjemite and the coarse-grained trondhjemite.

The trondhjemite within the Gjersvik Formation was named as the granodiorite by Lutro (1979). What is different between trondhjemite and granodiorite is in their sodium and potassium relative contents. Trondhjemite is characterized by Na-rick and K-poor but granodiorite by relative K-rick and Na-poor. The name trondhjemite comes from the old spelling, " Trondhjem", of Trondheim, Norway. V. M. Goldschmidt originated the term in 1916 in his famous paper on the intrusives of the Trondheim-Oppdal region, in which he defined trondhjemite as " holocrystalline, leucocratic rock that consists largely of sodic plagioclase and quartz and contains only minor biotite and potassic feldspar, that biotite is the typical dark phase, and that amphibole or, rarely, diopsidic pyroxene may occur in place of biotite ".

An approximate definition of trondhjemite has also been given in terms of major elements by Barker (1979). The major-element contents of trondhjemites, either as limits or as typical concentrations are:

(1) SiO2 > ca. 68 percent, usually < 75 percent;
(2) AL2O3 typically > 15 percent when being 70 percent SiO2 and <14 percent 75 percent SiO2;
(3) (FeO* + MgO) < 3.4 percent, and FeO*:MgO commonly is 2 - 3;
(4) CaO ranges from 4.4 - 4.5 percent in calcic trondhjemite to typical values of 1.5 - 3.0 per cent;
(5) Na2O typically is 4.0 - 5.5 percent; and
(6) K2O < ca. 2.5 percent, and typically < 2 percent.

Further division was suggested that trondhjemite can be divided into low-Al2O3 and high-Al2O3 types at 15 percent AL2O3 at 70 percent SiO2 (Barker, 1979).

The coarse-grained and fine-grained porphyritic trondhjemites within the Gjersvik volcanic arc are all characterized by holocrystalline, leucocratic, greyish-white in colour, massive to slight schistory. These two kinds of the rocks are very similar in mineral components and chemical compositions but can be distinguished in the fine-grained porphyritic and the coarse-grained holocrystalline textures. They consist mainly of albite or oligoclase (about 60 percent in volume), quartz (about 30 per cent), biotite and chlorite (generally less 5 per cent), with small amounts of sericite but very few potassium feldspar. Major element compositions of the rocks illustrate that SiO2 contents are higher, ranging mainly from 72 to 75 per cent; Al2O3 from 12.8 to 14.8 per cent; CaO from 0.6 to 3 per cent; Na2O from 3.4 to 6.9 per cent; K2O from 0.3 to 2.2 per cent; (FeO* + MgO) from 1.6 to 4.2 per cent, and FeO*:MgO is mainly 5 - 8 (Table 3.6). The mineral assemblages and chemical compositions of the felsic intrusive rocks discribed above are comparable with the definition of the trondhjemite by Goldschmidt (1916) and Barker (1979), but are distinct from normal granodiorite.

In addition, the felsic intrusives have further been confirmed as trondhjemite in terms of a normative An-Ab-Or classification diagram for common siliceous igneous rocks proposed by O'Connor (1965). Plots of the felsic intrusive rocks lie mainly within a field of the typical trondhjemite composition (Fig. 3.23). Thus, it is concluded that the felsic intrusives associated with the Gjersvik volcanic arc can be reasonably named as a subtype of low-Al2O3 trondhjemite.

3.3.2 Morphylogies, occurrences and sizes of the intrusive bodies

The intrusives within the Gjersvik volcanic arc consist predominantly of trondhjemite or gabbro. They are generally associated with the dark greenstone but a few with pale greenstone. However, a kind of gabbro that often occur as small dykes, generally less 5 m in width, within the meta-volcanic sequence apparently intrude into and cut every type of the meta-volcanic rock such as felsic volcanic rocks, dark and pale greenstones. This type of the gabbro has been proposed to represent, perhaps, the latest magmatic process in the Gjersvik volcanic arc. The intrusives are various in scale, generally among several hundreds meters to kilometer squares, some of big bodies being up to ten kilometers squares, and are apparently small in comparison with the batholiths in the continental environment in scale. The small intrusives are generally irregular, while the relative large bodies are in certain extent similar with ellipse in shape.

The relative large bodies are characteristic of the intrusive complexes composed predominantly of the trondhjemite plus minor gabbro. For example, the biggest intrusive body

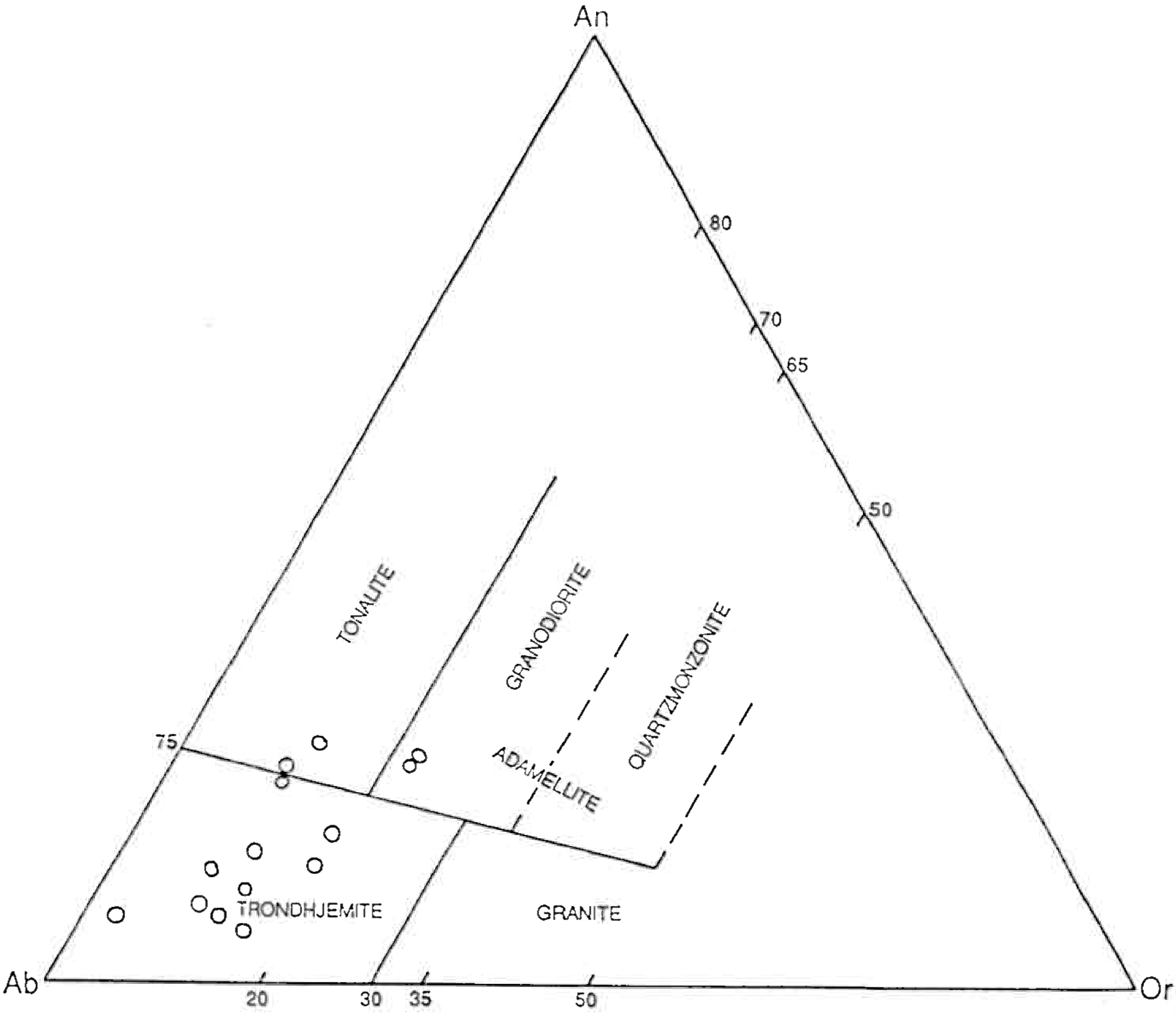


Fig. 3.23 Normative feldspar compositions of the felsic intrusive rocks in the Gjersvik Formation in the system Ab-Or-An of a classification of the felsic intrusive rocks. Field boundaries from O'Connor (1965)

in the Gjersvik area, located in the west and northwest of the Rorvatnet Lake, is an intrusive complex consisting of an association of the coarse-grained trondhjemite plus gabbro. Two contact relations between trondhjemite and gabbro within the complex have been observed. Gabbro, on the one hand, often occur as xenoliths or big blocks within the coarse-grained trondhjemite. The xenoliths are irregular to subrounded, about several cm to meters in diameters. Some of them are associated with a resorting rim, but others are clear in contact to the trondhjemite. On the other hand, the trondhjemite occur as irregular veins, blocks or as bands filling along the fissures within big block of the gabbro. The relationships between trondhjemite and gabbro appear to indicate that the gabbro probably represent a plutonic cognate residual enclusion derived from the basaltic or gabbroic source producing the trondhjemite magma through the partial melting processes.

The fine-grained porphyritic trondhjemite are generally small in scale and not associated with the gabbro. They are very similar in mineral assemblages and chemical compositions with, but can be distinct in textures to the coarse-grained trondhjemite. The relationship between the coarse-grained and fine-grained porphyritic trondhjemites has been revealed on the basis of detailing surface mapping. For example, in the north of Rorvatnet Lake about 1.5 km the coarse-grained trondhejmite is immediately transitional into the fine-grained porphyritic trondhjemite and no clear and direct contact boundary exists between the two. Thus, the fine-grained porphyritic trondhejmite and coarse-grained trondhejmite have been interpreted to represent a shallow-seated and deep-seated phase of co-magmatic processes, respectively.

Contacts between the intrusive bodies and the greenstones are almostly tectonic and no clear primary contact relations have so far been observed. The intrusive complexes, including coarse-grained and fine-grained porphyritic trondhjemites, frequently overthrust on the greenstone. Near the boundaries the greenstone are often characterized by intensive schistosity and small tight fold as well as very deeply dipping, varying generally from 60 to 80 degrees. The thrust in the regional often exists in the boundary between the intrusive bodies and the greenstones. In the northern and northeastern part of the Royrvatnet, for example, the coarse-grained and fine-grained porphyritic trondhjemites are structurely overlain on the dark greenstone (Fig. 2.18), which seems to show that the coarse-grained and fine-grained porphyritic trondhjemites were brought to thrust over the greenstones. In addition, the bodies of the trondhjemites themselv are associated with the intensive foliation zone parallel or subparallel to the contact, emphasized by obvious oriention of the albite and quartz tablets which must be related to regional tectonics rather than primary emplacement of the pluton. The fine-grained porphyritic trondhjemite associated with the pale greenstone in the northwest of the Gjersvika Lake was also revealed to be tectonic in contact to the pale greenstone on the basis of the surface mapping. Thus, the tectonic contacts between the intrusives and greenstones within the Gjersvik Formation results apparently from penetrated structural emplacement of the rigidity massive intrusive bodies into the lower intensity mafic basalts during tectonic processes.

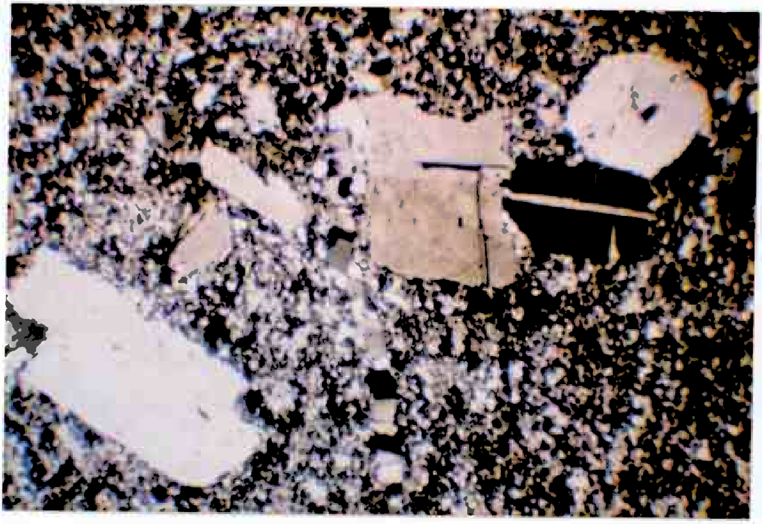
3.3.3 Description of lithologies

The coarse-grained and fine-grained porphyritic trondhjemites underwent the regional low-grade metamorphism, which leads to the secondary mineral assemblages such as chlorite, epidote, muscovite, sericite and carbonate associated with the trondhjemites.

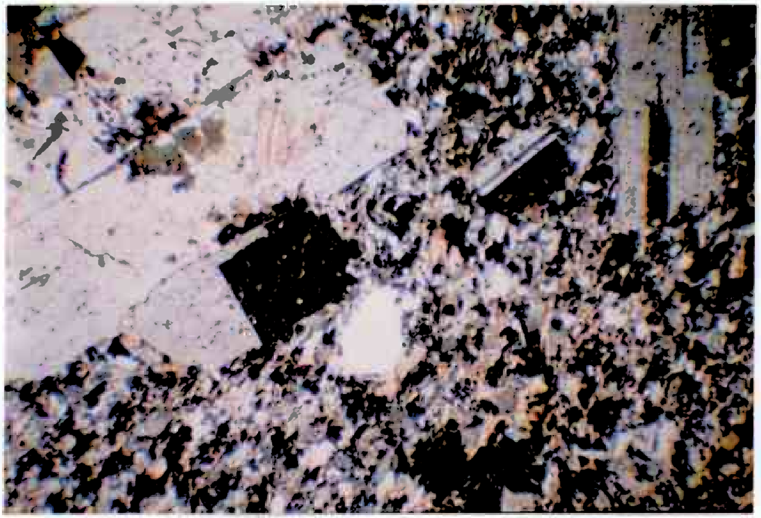
It is very difficult to be distinguished between the coarse-grained and the fine-grained porphyritic trondhjemites on the hand specimen and field outcrops because they are all holocrystalline, leucocratic, greyish in colour, massive to slight schistose. And, the coarse-grained and fine-grained porphyritic metatrondhjemites have similar mineral assemblages. Only distinction, perhaps, between the two is in their grained size and texture. The fine-grained porphyritic trondhjemite is frequently characterized by relative fine grain and porphyritic texture, whereas the coarse-grained trondhjemite generally by holocrystalline and coarse-grained textures. In fact, difference between the felsic extrusives and intrusives in the Gjersvik volcanic arc is also in their textures but not in mineral assemblages (Fig. 3.24).

The intrusive bodies of the coarse-grained trondhjemite, such as in the north of Royrvatnet Lake, are often associated with a narrow zone, about meters in width, of fine-grained porphyritic marginal facies near the contact between the greenstone and trondhjemite. It transfers towards the big intrusive body in grain size, but is similar in mineral assemblage, which has been interpretated as a chilling marginal zone formed during the intrusive processes. It is probably significant to mention that the chilling zone is in some ways similar in mineral assemblages and texture with the fine-grained porphyritic trondhjemite.

(a)



(b)



(c)

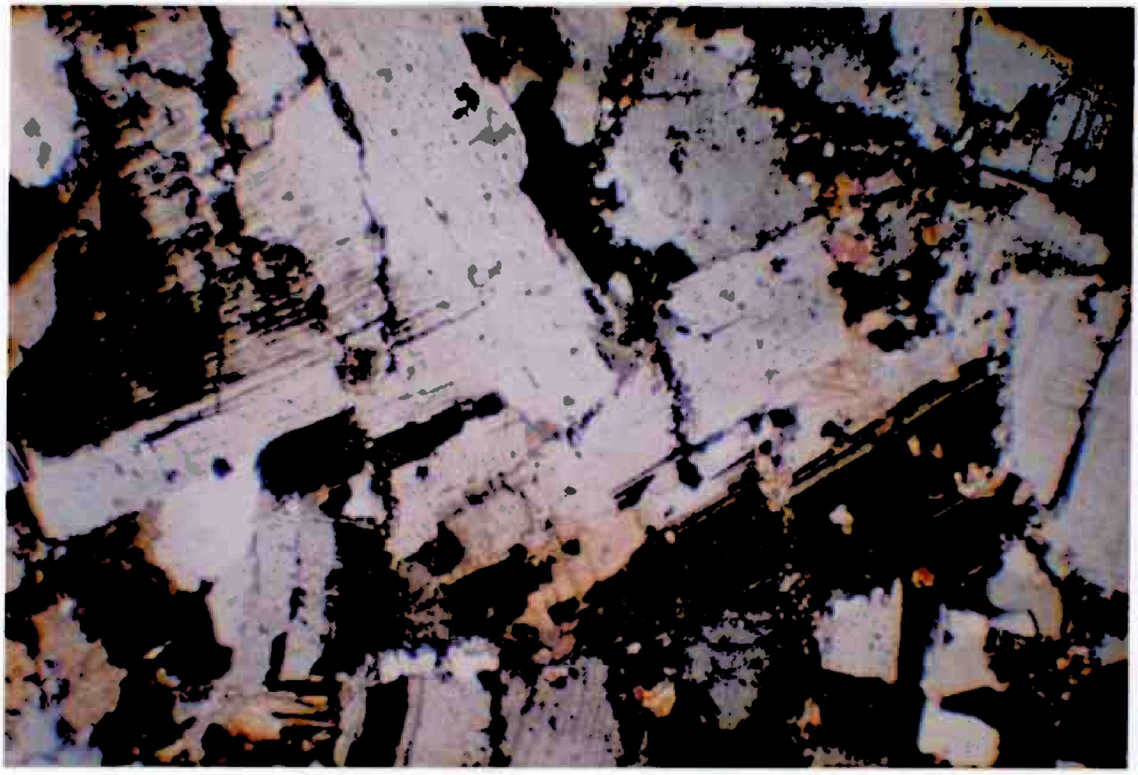


Fig. 3.24 A comparison in textures among the keratophyric pyroclastic rocks (a), fine-grained porphyritic (b) and (c) coarse-grained trondhjemites " + " 2.5 x 3.2 x 1.25

(a) porphyritic texture in the felsic meta-extrusive rocks; (b) porphyritic texture in the fine-grained porphyritic trondhjemite; (c) holocrystalline-granular texture in the coarse-grained trondhjemite

The trondhjemites consist predominantly of plagioclase of dominating albite or oligoclase, quartz with small amounts of chloride, epidote, muscovite, sericite and carbonate plus very few potassic feldspar, and pyrite is are main accessory minerals. The mafic minerals are very low in content, ranging usually from 2 to 3 percent and occasionally up to 10 % (chlorite after epidote, chloritized biotite), but the albite is high, generally about 60 per cent, and very few potassium feldspar. The albite is often associated with obvious twinning but without zoning. The fine-grained porphyritic trondhjemite consists of phenocrystals ranging usually from 1 to 2 mm in size setting in the matrix composed mainly of albite, quartz, chlorite, carbonate, muscovite and sericite, generally less 0.1 mm in size. The phenocrystals rang usually from 20 to 30 percent in content and comprise predominantly anhedron to euhedron, tabular albite with obvious twinning and a few amount of subrounded quartz. Phenocrystals of the albite occur as either individual or aggregate of the crystals, and some of them are altered by muscovite and sericite. The coarse-grained trondhjemite is similar in main mineral assemblages to the fine-grained porphyritic trondhjemite, but not associated with the porphyritic textures. It is of typical holocrystalline with approximately equigranular granitic texture, although recrystallization of quartz is common, resulting in the development of a mosaic texture. The albite is about 60 percent in content, and mainly euhedron and tabular grains with obvious twinning, about 1 - 3 mm in size. The albite is locally clotted with secondary sericite and muscovite. The quartz is anhedron grains, varying from 0.2 to 2 mm in size, and about 35 percent in content. The mafic minerals are low, generally less 5 percent in content, and consist mainly of chlorite with small amounts of epidote and chloritized biotite.

The gabbro is composed of chlorite, clinozoisite, chloritized biotite and amphibolite with small amounts of secondary quartz and carbonate. The clinozoisite often keep in pseudomorphs of the plagioclase and is about 40 - 50 percent in content. The biotite is anhedron, scaly, with perfect cleavage, but frequently chloritized. The amphibolite have two good cleavages.

3.3.4 Chemistry of the rocks

(1) Bimodal feature

The meta-intrusives in the Gjersvik Formation are also characterized by an obvious bimodal chemical composition that are comparable with the meta-extrusives with which they are associated in the Gjersvik volcanic arc (Fig. 3.13). Spectrum of the meta-intrusive rocks in chemical compositions is obviously bimodal in SiO2 contents, that is, SiO2 contents vary mainly between 45 - 53 in the gabbro and between 70 - 78 percent in the trondhjemites, but are obviously lack of intermediate composition (Table 3.4). No typical diorite has so far been found within the Gjersvik Formation.

(2) Chemical series of the intrusive rocks

Chemical series of different types of the intrusive rocks and their relationships to tectonic environments were discussed by several authors. The trondhjemite has been considered as a low-K\Na-ratio type of calc-alkaline rock (Barker and Arth, 1976) or as a low-(FeO* + MgO) type (Barker, 1979). They are different from the calc-alkaline quartz diorite-tonalite-granodiorite-granite suites that form the bulk of the Mesozoic circum-Pacific batholiths. As the recent knowledge state, magma of the normal calc-alkaline series are totally restricted in their occurrence to subduction-related tectonic settings (Wilson, 1989). However, the trondhjemite and cogenetic, less siliceous and more mafic rocks are now known to be a major component of Archean greiss terranes, which occur in the volcanic and plutonic parts of Late Archean granite-greenstone terranes, to form widely scattered extrusive and intrusive bodies in plate-tectonic environments of convergent oceanic-continental and oceanic-oceanic types, and to be a prominent if volumetrically minor component of many ophiolites (Barker, 1979).

Plots of the trondhjemites occurring within the Gjersvik volcanic arc on the K-Na-Ca ternary diagram define a compositional variation trend towards the Na-apex that is similar to that of the trondhjemite suite from S.W.Finland (Barker and Arth, 1976), but is distinct to the calc-alkaline suite (Fig. 3.25). A corresponding trend of the trondhjemites is also displayed in a normal Q-Ab-Or diagram (Fig. 3.26). This strong trondhjemitic trend is rather different from the normal calc-alkaline suites in chemical series.

(3) Major elements

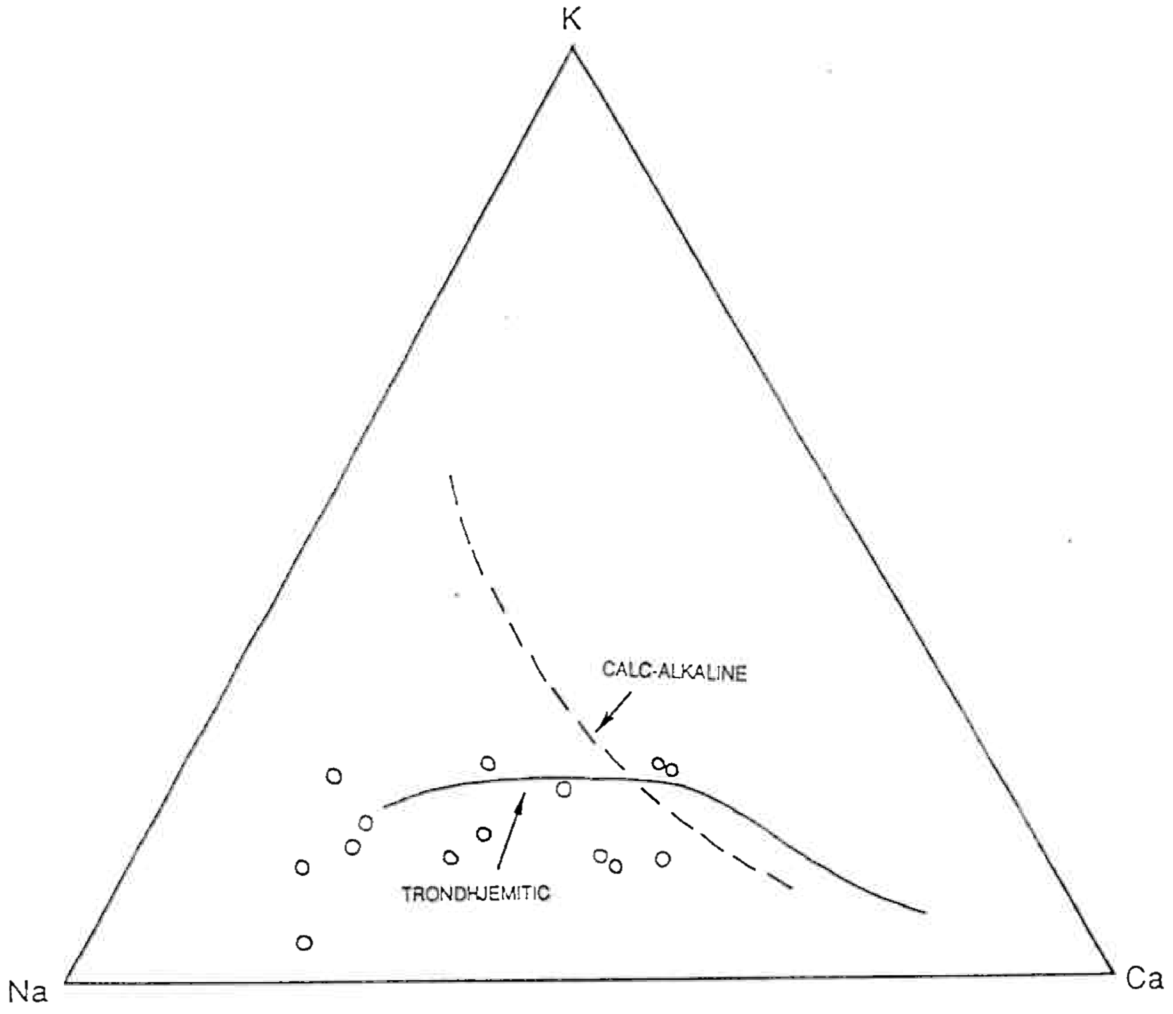


Fig. 3.25 Trondhjemites associated with the Gjersvik volcanic arc plotted on a Na-K-Ca diagram, showing trends of the typical trondhjemitic and calc-alkaline suites

Trondhjemitic trend, southwest Finland (Barker and Arth, 1976); "normal" calc-alkaline trend, southern California batholith (data from Larsen, 1948)

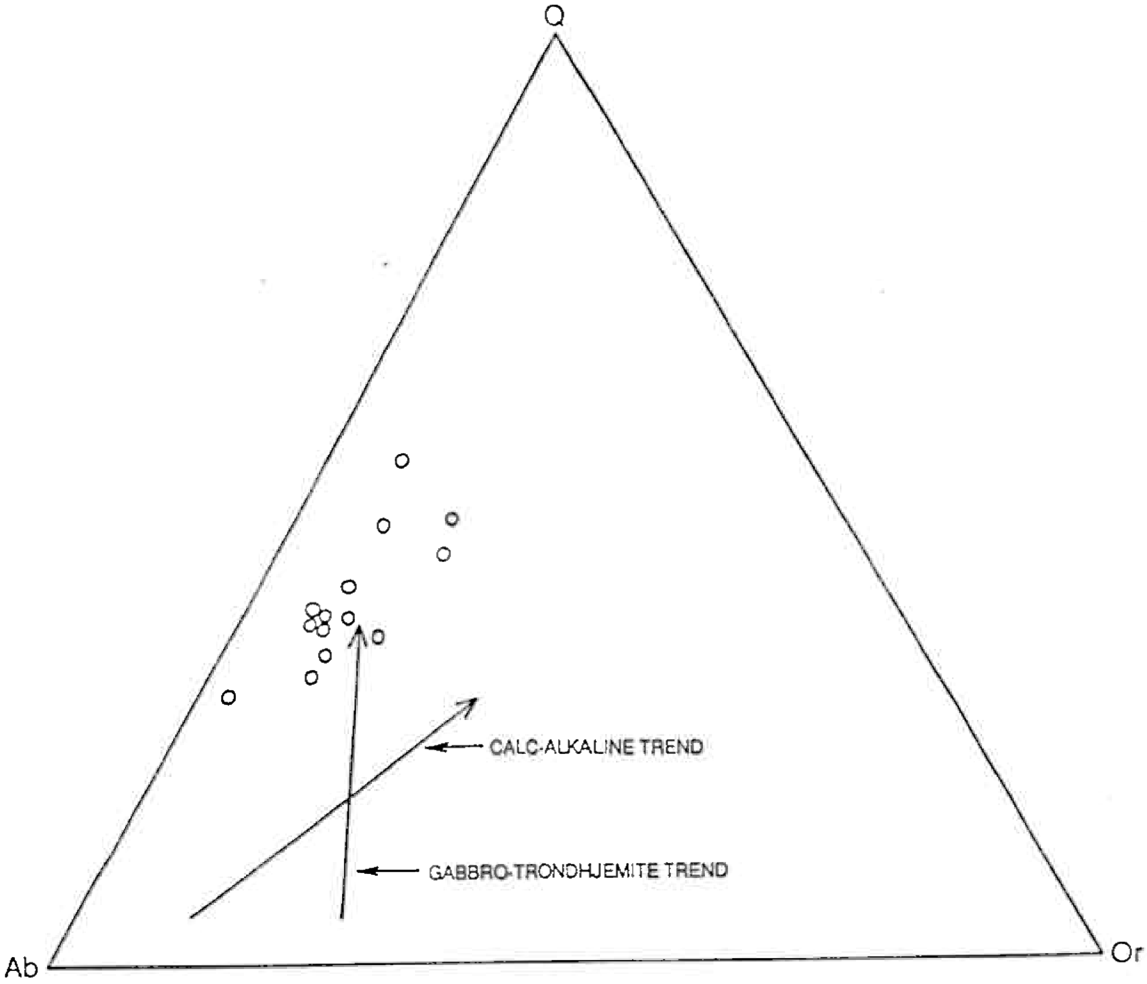


Fig. 3.26 Plots of the trondhjemites in the triangular normative Q-Ab-Or diagram, which indicates a gabbro-trondhjemite trend. The calc-alkaline and gabbro-trondhjemite trends are from Barker and Arth (1976)

The bulk chemical composition of the trondhjemite is different from that of normal granite in continental environment in sodium and potassium contents. The trondhjemites are characterized by unique low-K2O and high-Na2O contents comparative of granites. For example, the trondhjemites in the Gjersvik Formation generally contain K2O less 2 percent varying from 0.32 to 2.22 percent in content and Na2O more than 4, ranges from 4.49 to 6.88 percent (Table 3.4), whereas granite usually contains about 4 percent or more K2O and less 4 percent Na2O in contents (Middlemost, 1985) when the trondhjemites are compared with granites containing SiO2 content over 70 percent.

The trondhjemites have been subdivided into two suites: low-Al2O3 and high-Al2O3 types at 15 percent Al2O3 and 70 percent SiO2 (Barker, 1979). These two kinds of trondhjemites tend to occur in different environments: continental trondhjemites generally contain more than 14.5 to 15 percent Al2O3, whereas oceanic trondhjemites contain less than 14.5 to 15 percent (Arth J.G. 1979). The trondhjemites in the Gjersvik volcanic arc generally contain less than 14 percent Al2O3, ranging from 12.8 to 14.8 (Table 3.4), which appears to indicate that they originated from the ocean environment.

The trondhjemite has further been divided into coarse-grained and fine-grained porphyritic subtypes. And, they have been proposed to represent the deep-seated and shallow-seated phases of a co-magmatic processes, respectively, based on the transitional contact relationship and parallel mineral assemblages and chemical compositions between the two. Due to the fact that the extrusive keratophyric pyroclastic rock is completely comparative in major mineralogy and chemical compositions and only different in rock textures to the intrusive trondhjemites, the keratophyric pyroclastic rock can possibly be interpreted as an extrusive equivalent of the felsic pluton. This point is further supported by Na2O, K2O and CaO systematic exchanges in these three kinds of the felsic rocks. K2O and CaO contents are higher, but Na2O is much low in the coarse-grained trondhjemite, K2O and CaO contents become very low, but Na2O is very high in the keratophyric pyroclastic rock, while KeO, Na2O and CaO contents in the fine-grained porphyritic trondhjemite lie between the two. More importantly, the changes of K2O, CaO and Na2O contents in these three types of the felsic rocks are systematic and gradually transitional to each other. For example, the K2O and CaO gradually decrease with Na2O increase from the coarse-grained, via fine-grained porphyritic trondhjemites to the keratophyric pyroclastic

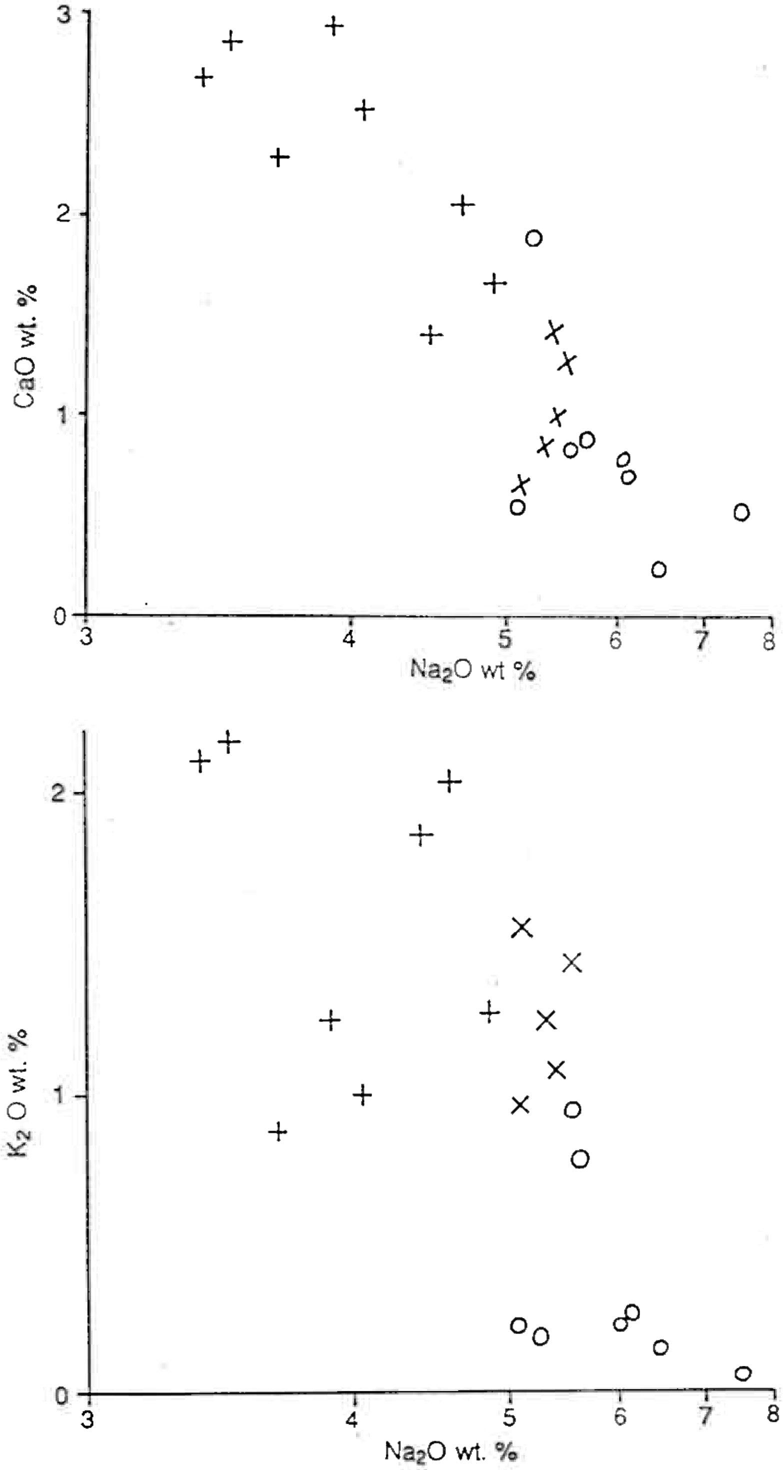


Fig. 3.27 Diagrams of Na2O against K2O, and Na2O against CaO, showing their relations and trends in the deep- and shallow-seated felsic plutons as well as extrusives

+ coarse-grained trondhjemite; x fine-grained porphyritic trondhjemite;
o keratophyric pyroclastic rocks

Table 3.6

Major (wt.%) and Trace (ppm) Element Chemistry of the Intrusive Rocks

	1	2	3	4	5	6	7	8	9
	M15-14-1	M15-14-2	M18-16	913403	913206	M6-5	911711	911712	911713
SiO_2	74.10	74.14	74.28	75.20	73.62	73.25	75.00	78.15	76.77
TiO_2	0.23	0.22	0.36	0.48	0.36	0.41	0.31	0.19	0.25
Al_2O_3	13.18	13.05	13.65	13.77	14.67	13.72	13.28	12.92	13.65
*FeO	3.52	3.61	2.66	3.31	3.10	3.05	3.04	1.73	2.16
MgO	0.31	0.27	0.32	0.58	0.29	0.46	0.56	0.15	0.43
CaO	0.88	1.00	0.67	1.47	1.30	1.02	2.95	2.28	2.52
Na_2O	5.36	5.43	5.14	5.41	5.56	6.88	3.90	3.63	4.06
K_2O	1.24	1.06	1.55	0.97	1.48	0.32	1.24	0.88	1.00
MnO	0.04	0.05	0.17	0.11	0.09	0.10	0.05	0.04	0.04
P_2O_5	0.04	0.05	0.07	0.09	0.05	0.08	0.06	0.02	0.04
Loss	1.05	1.09	1.40	0.76	1.20	1.00	0.93	0.64	0.68
SUM	99.95	99.97	100.27	101.39	100.62	100.29	100.49	99.99	100.92
Sr	94	112	101	129	86	136	196	250	144
Rb	28	21	33	22	32	<1	29	24	27
Nb	9	10	15	12	15	10	9	9	10
Y	42	43	58	41	46	47	17	20	18
Zr	120	115	157	127	167	115	123	123	131
Ba	96	91	257	188	231	<10	484	269	585
V	23	21	10	16	26	29	36	20	31
Ni	6	7	43	5	6	3	10	6	7
Co	3	3	3	3	4	3	4	2	3
Cr	92	118	63	74	61	50	137	113	94
Pb	3	7	9	4	10	15	6	14	6
Cu	15	13	28	7	43	15	14	17	1
Zn	23	28	51	74	37	66	21	11	10

Table 3.6, continue

	10	11	12	13	14	15	16	17	18	19
	912323	912502	M6-9	M7-20	M7-4	M6-41	M6-42	M6-49	913110	913101
SiO_2	72.11	74.31	74.99	70.32	74.92	47.54	44.65	50.13	52.27	53.29
TiO_2	0.31	0.28	0.22	0.17	0.19	0.80	1.55	0.63	1.04	1.12
Al_2O_3	14.45	14.03	12.80	14.80	14.19	15.36	17.44	11.97	15.83	14.50
*FeO	3.32	2.70	2.23	2.10	1.60	13.21	15.18	10.33	11.05	12.10
MgO	0.76	0.50	0.30	0.34	0.28	5.64	4.77	11.93	6.31	6.37
CaO	2.86	2.68	1.67	2.05	1.41	8.87	10.42	11.39	10.41	9.22
Na_2O	3.45	3.36	4.90	4.63	4.49	2.21	2.14	1.53	3.16	3.82
K_2O	2.19	2.14	1.24	2.01	1.85	0.04	0.03	0.05	0.04	0.03
MnO	0.10	0.08	0.06	0.08	0.04	0.20	0.19	0.19	0.17	0.21
P_2O_5	0.08	0.05	0.05	0.05	0.04	0.08	0.10	0.09	0.09	0.10
Loss	1.97	2.49	1.96	2.73	1.22	6.57	2.55	1.87	1.61	1.99
SUM	100.11	100.13	100.42	99.28	100.23	100.52	99.02	100.11	100.37	100.73
Sr	242	202	191	264	203	160	210	137	212	125
Rb	67	58	25	56	47	<1	<1	<1	5	7
Nb	11	11	13	16	12	16	17	22	11	11
Y	18	20	30	11	22	16	16	17	21	21
Zr	108	113	126	121	114	44	43	42	36	33
Ba	709	665	493	745	860	<10	<10	<20	<10	<10
V	57	46	38	31	33	392	362	214	244	291
Ni	6	6	3	4	4	28	22	181	44	79
Co	5	4	4	3	4	63	62	62	49	56
Cr	100	120	85	92	80	38	17	361	60	142
Pb	12	9	14	9	12	<1	<1	<1	<1	<1
Cu	8	13	6	7	7	68	51	51	49	36
Zn	36	30	31	22	13	92	89	86	86	98

1 - 5 fine-grained porphyritic trondhjemite; 6 fine-grained trondhjemite (a marginal phase of the coarse-grained trondhjemite); 7 - 14 coarse-grained trondhjemite; 15 - 19 gabbro

All elements were analysized by I. Romme and I. Vokes with PHILIPS PW1480 X-Ray Spectrometer in Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology, 1991 rock, which show a linear and negative correlation (Fig. 3.27). This phenomena can be explained by evolution of the magma system and reaction between magma and sea water during magma ascent processes. The magma composition would be gradually exchanged with magma ascent from deep-seated, via shallow-seated intrusion to extrusion due to magma evolution by itself and the reaction of the oceanic water to magma system, which the latter is getting stronger and stronger from deep, via shallow to ocean floor environments. In this case sodium in the ocean water constantly attach into the magma system or replace plagioclase, while the potassium (perhaps including Ca) in the magma system is gradually removed by oceanic water system. Good linear correlations in K2O, CaO and Na2O among coarse-grained, fine-grained porphyritic trondhjemites and keratophyric pyroclastic rocks (see Fig. 3.27) can be interpreted as a considerate evidence in connection to this kind of geological processes, which should further be confirmed by systematic variations of the trace elements.

(4) Trace elements

Due to similarity in mineralogy and chemical compositions between the trondhjemites and the keratophyric pyroclastic complexes, they will be discussed in trace element behaviors together. Study of trace element behavior during magmatic processes indicates that Ba and Rb are major substitutes for K in K-feldspar, hornblende and biotite, while Sr often substitutes readily for Ca in plagioclase and for K in K-feldspar. Thus, change in Ba or K/Ba ratio and Rb and K/Rb ratio may indicate the role of one of these phases in petrogenesis, whereas Sr or Ca/Sr ration is a useful indicator of plagioclase involvement at shallow levels (Wilson, 1989). These element content changes are gradual and systematic in the felsic intrusives and extrusives. Rb, Sr, and Ba concentrations gradually decrease from the coarse-grained (av. 41.63 ppm Rb, 211.5 ppm Sr, and 601.25 ppm Ba), via the fine-grained porphyritic trondhjemites (av. 27.2 ppm Rb, 104.4 ppm Sr, and 172.6 ppm Ba) to the keratophyric pyroclastic rock (av. 3 ppm Rb, 90 ppm Sr, and 63 ppm Ba) (see Table 3.3, 3.6), while their substitutes K and Ca display parallel geochemical behaviors. For example, diagrams of K2O versus Ba and Rb show that these element changes in the coarse-grained, the fine-grained porphyritic trondhjemites and the keratophyric pyroclastic rock are characterized by very well positive correlations, that is, the Ba and Rb systematically increase from the coarse-grained, the fine-grained porphyritic trondhjemites and the keratophyric pyroclastic rock with K2O increase (Fig. 3.28

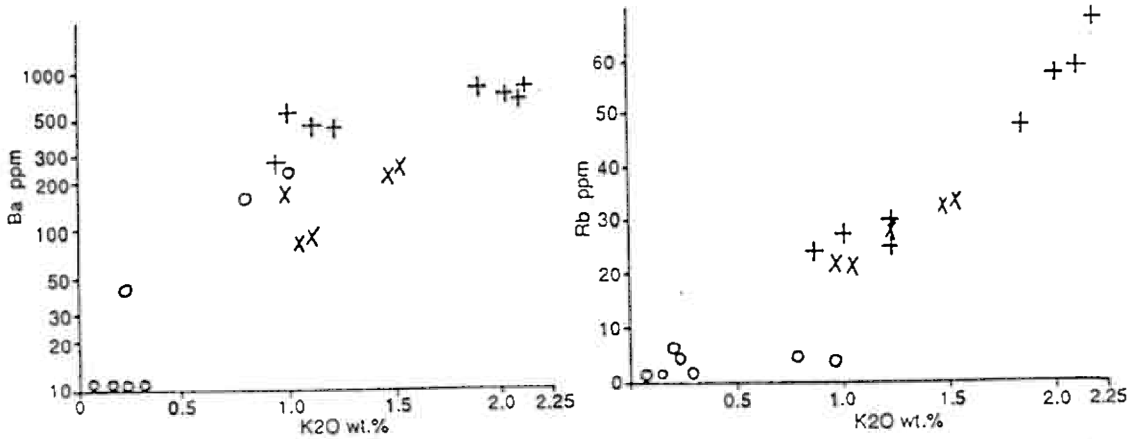
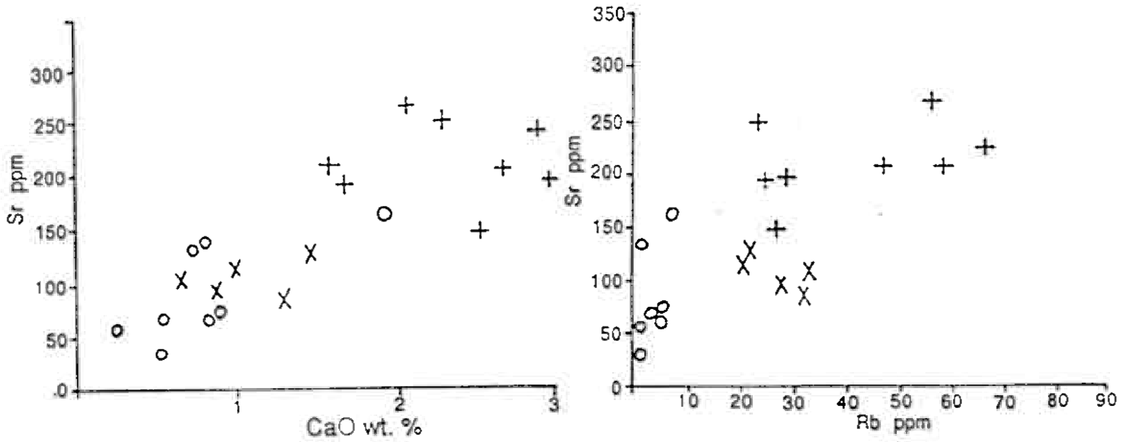


Fig. 3.28 Diagrams of K2O against Ba and Rb, showing their relations and trends in the deep- and shallow-seated felsic plutons as well as extrusives

+ coarse-grained trondhjemite; x fine-grained porphyritic trondhjemite;
o keratophyric pyroclastic rocks



ig. 3.29 Diagrams of CaO against Sr and trace elements Sr against Rb showing their relations and trends in the deep- and shallow-seated felsic plutons as well as extrusives

+ coarse-grained trondhjemite; x fine-grained porphyritic trondhjemite;
o keratophyric pyroclastic rocks

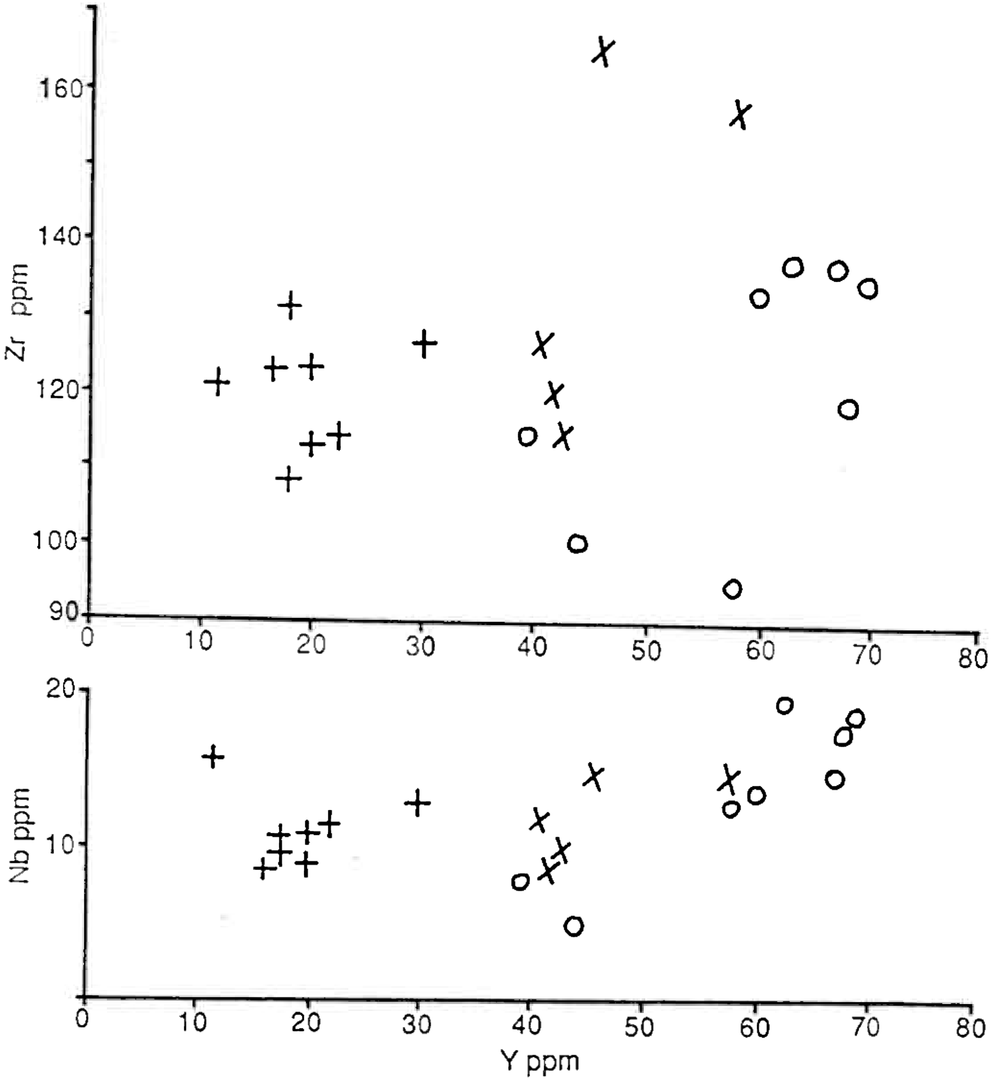


Fig. 3.30 Diagrams of incompatible trace elements Y against Zr and Nb, showing their relations and trends in the deep- and shallow-seated felsic plutons as well as extrusives

+ coarse-grained trondhjemite; x fine-grained porphyritic trondhjemite;
o keratophyric pyroclastic rocks

). Parallel situation is shown in diagrams of CaO versus Sr and Rb versus Sr that display good positive, linear correlative trends between both of Rb and Sr as well as CaO and Sr (Fig. 3.29). This property of the element correlations and their behaviors indicates an evolution of the trondhjemitic magma from relative deep, via shallow levels to extrusive phase and the co-magmatic affinity of the trondhjemites and keratophyric pyroclastic complexes.

This conclusion is further confirmed by the incompatible element behaviors. For example, the incompatible elements, Zr, Y, and Nb tend to be gradually concentrated in residual phase during magma evolution, which is revealed by their concentrated tendency of step-by-step supplements from the coarse-grained trondhjemite (av. 116.5 ppm Zr, 17.5 ppm Y, and 11.25 ppm Nb), via the fine-grained porphyritic trondhjemite (av. 147.6 ppm Zr, 40.4 ppm Y, and 27.8 ppm Nb) to the keratophyric pyroclastic rock (157 ppm Zr, 47.75 ppm Y, and 47.4 ppm Nb) (see Table 3.3, 3.6). In addition, these incompatible elements such as Y - Nb and Y - Zr also exhibit trends of positive, linear correlation from the coarse-grained, via the fine-grained porphyritic trondhjemites to the keratophyric pyroclastic rock (Fig. 3.30).

3.4 Relationships among different types of the rocks

3.4.1 Relationship between dark and pale greenstones

The pale and dark greenstones are the most dominant types of the rocks constituting the Gjersvik volcanic arc. They are very characteristic of and distinct in geological contact relationship and geochemistry to each other. The pale greenstone has evidently proposed to be stratigraphically younger than the dark greenstone and contact is sharp but original because the exhalative sedimentary layers often occur conformably just in junction between the two. And, the pale greenstone are characterized by much high Cr, Ni, and relative high Mg, but low Fe and Ti relative to the dark greenstone. Cr content in the pale greenstone is generally higher than 130 ppm, Ni higher than 65 ppm, and MgO higher than 6 wt.%, but FeO less than 12 wt.%, and TiO2 less than 1.2 wt.%, while Cr and Ni in the dark greenstone are usually less than 50 ppm, MgO less than 6 wt.%, but FeO higher than 13 wt.%, and TiO2 higher than 1.2 wt.% (Fig. 3.31). Especially, average Cr and Ni contents in the pale greenstone are roughly eight times as much as those in the dark greenstone, respectively (Table 3.4). Representative contact and

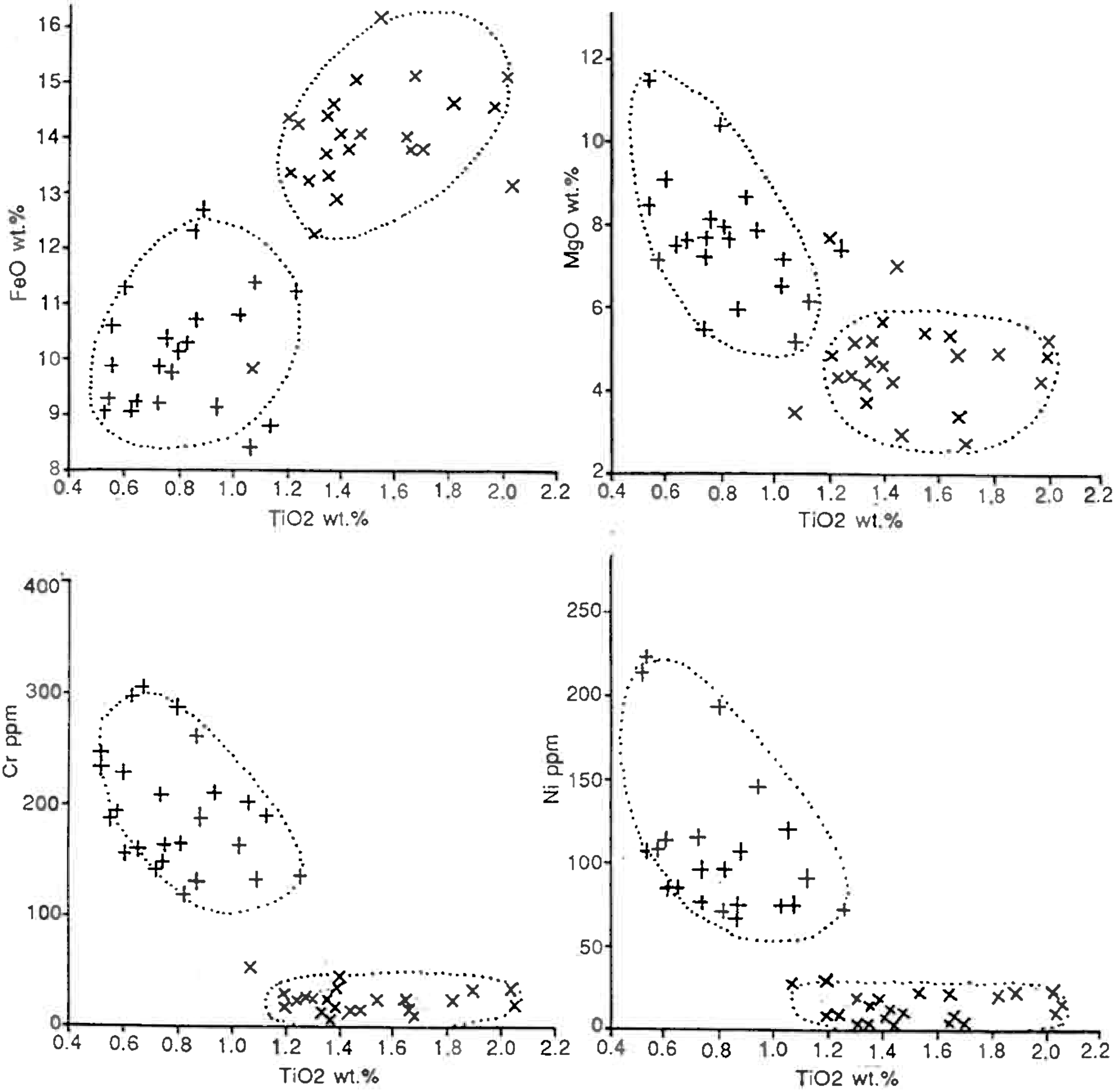


Fig. 3.31 Comparative diagrams in TiO2, FeO, MgO, Cr, and Ni contents and behaviors between the dark and pale greenstones

\+ pale greenstone; x dark greenstones

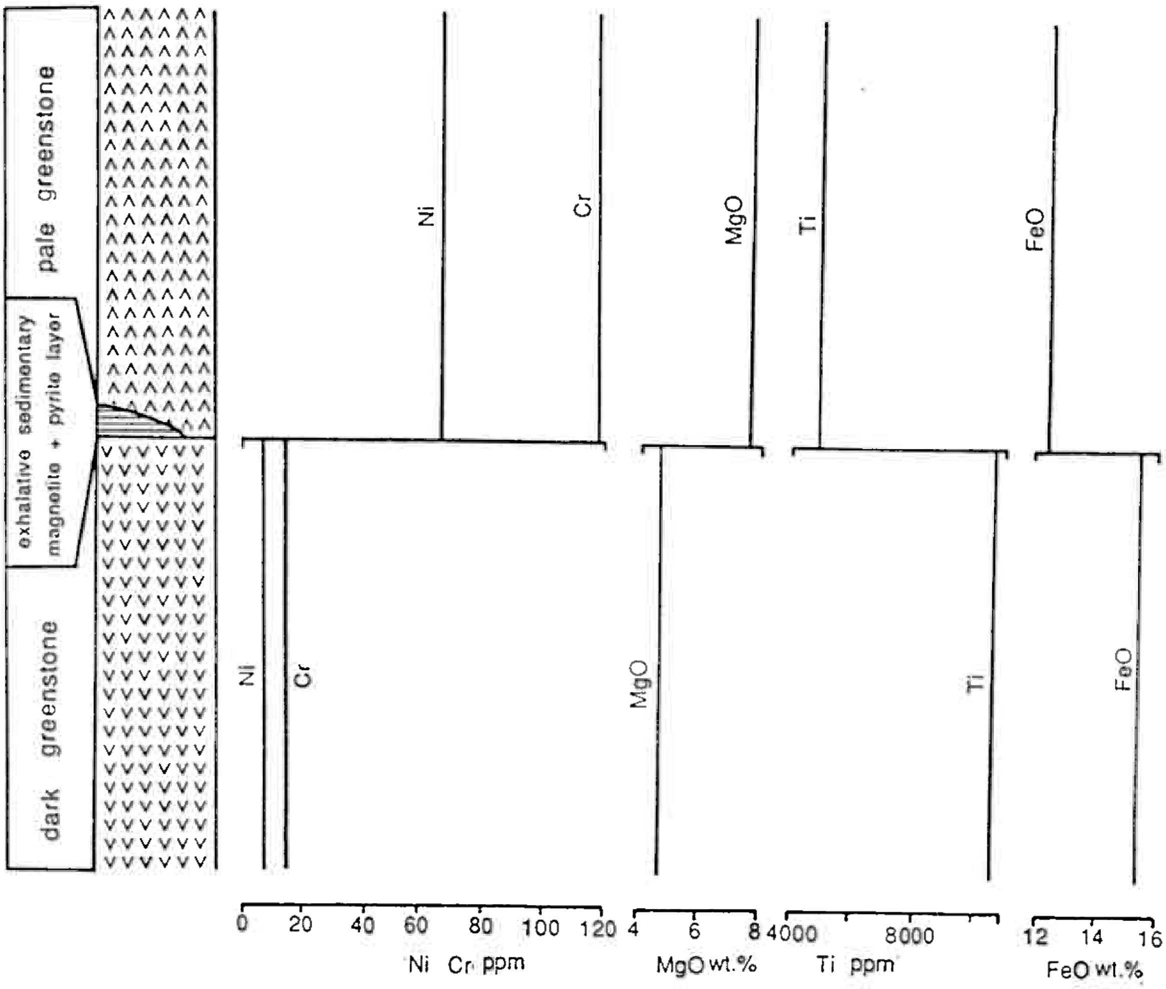


Fig. 3.32 Diagram showing geological contact relation and distictively systamatic differneces in geochemical behaviors between pale and dark greenstones on an exposure (see Fig. 2.11) in the northeast of Bjørvatnet Lake about 2000 m

distinctive geochemical behaviors between pale and dark greenstones have well been revealed in some exposures. For example, the exposure on the surface in the northeast of Bjorkvatnet Lake about 2000 m shows that contact between pale and dark greenstone is sharp and they are separated by distal exhalative sedimentary magnetite + pyrite layer (Fig. 2.12), and that they are very different and distinct in geochemical behaviors such as elements Ni, Cr, Ti, MgO and Fe (Fig. 3.32). These distinct and systematic differences in abundance of chemical elements most probably imply a difference of magma sources generating the dark and pale greenstones of tholeiitic composition, respectively. At same time, correlations of MgO against Ni and Cr point out that the pale greenstone was generated by more evolved tholeiitic magma, while the dark greenstone was produced from undifferentiated tholeiitic magma.

3.4.2 Relationship between greenstones and keratophyric pyroclastic rocks

Keratophyric pyroclastic complexes are evidently interpreted to be formed as an episode of felsic magma processes between tholeiites, representative of their metamorphosed equivalents of dark and pale greenstones. Major massive sulphide mineralization occurring within the Gjersvik volcanic arc are predominantly associated with the keratophyric pyroclastic complexes.

3.4.3 Relationship between felsic intrusive and extrusive rocks

The felsic plutons are mainly coarse-grained and fine-grained porphyritic trondhjemites. The geological evidence from detailing surface mapping shows that the coarse-grained trondhjemite is transitional and continue in contact with the fine-grained porphyritic trondhjemite, which has been considered as a considerable evidence that they are co-magmatic and that the fine-grained porphyritic trondhjemite most probably represent a shallow-seated phase in connection with relative deep-seated coarse-grained trondhjemite. This conclusion is further confirmed by major and trace element compositions.

Furthermore, what is relationship between the intrusive trondhjemites and the extrusive keratophyric pyroclastic complexes is asked because they are completely comparable in mineralogy and chemical compositions, but only distinct in textures. The problem of keratophyre and its possible relationship to trondhjemite have been addressed by several authors. For example, one interpretion of keratophyre is that its high-Na, low-K character is the result of low-temperature hydrothermal alteration of intermediate to siliceous lava, involving interaction with seawater (Amstutz, 1974). However, there is textural and field evidence to suggest that the "keratophyre" are indeed magmatic, not metasomatic products, and may be thought of as the volcanic equivalents of plagiogranite (Coleman R.G. and Dinato M.M. 1979). No matter how to interpret relationship between felsic plutons and extrusives associated with the Gjersvik volcanic arc, two aspects must be considered: the extrusive keratophyric pyroclastic rocks and the plutonic trondhjemites, on the one hand, are completely comparative in mineralogy and chemical compositions and only different in rock textures to each other; on the other hand, correlations between some major elements such as Na2O, K2O and CaO and trace elements, including Rb, Sr, Ba, Nb, and Y as well as between trace elements exhibit strongly systematic and linear variations from deep-seated coarse-grained trondhjemite, via shallowed-seated fine-grained porphyritic trondhjemite to extrusive keratophyric pyroclastic complexes. These properties have been interpreted as a result both of felsic magma evolution in the crust higher level and of reactions of ocean water to felsic magma system during magma ascent processes from relative deep portion towards the surface. Thus, the felsic intrusive and extrusive populations are proposed to be co-magmatic and the keratophyric pyroclastic rocks can be interpreted as an extrusive equivalent of the intrusive trondhjemites. Property of rich sodium and poor potassium of the keratophyric pyroclastic complexes are considered to be related mainly to magma evolution, reaction of ocean water to magma system as well as low-temperature hydrothermal alterations on the ocean floor.

The felsic plutons and their eruptive equivalent are mainly related to an epidose of felsic magma activity between two tholeiitic magma processes. It must be emphasized, however, that some felsic plutons associated with the pale greenstone such as those in the northern part of the Gjersvik-Royrvik road have two possibilities. First, they were formed earlier than the pale greenstone and are as same as their eruptive equivalents in chronology, but the later tectonic movements, especially penetrated structures, made them to be associated with the pale greenstone, which is illustrated by obviously tectonic contact between the trondhjemites and the pale greenstone. Second, they probably represent a latest episode of felsic magma activities which was later than the tholeiitic magma processes producing the pale greenstone. Otherwise, felsic magmatic activity is most probably multystages, which has been proved in terms of absolute dating for the felsic plutons associated with the Gjersvik volcanic arc on the regional scape. For example, the Moklevatnet granodiorite as an most extensive and yougest plutonic body in the souther part of the Gjersvik Napper has yielded a U-Pb zircon age of 456 +\- 2 Ma (Roberts & Tucker, 1991), while the trondhjemitic body that occurs in the lower level of the Gjersvik metavolcanic succession in the northern part of the Gjersvik Group is associated with a U-Pb zircon age of 483 +\- 4 Ma (Kullerud, et. al., 1988). This means that the felsic magmatic activities were multistages and covered a time span of, at least, 25 to 30 Ma during construction of the Gjersvik volcanic arc.

3.5 Petrogenetic and paleotectonic model

3.5.1 Principal philosophy

We must be cautious in assuming that the present is the key to the past. Plate tectonics, as it operates in the modern earth, represents in a fundamental sense a mechanism by which excess thermal energy from the mantle is dissipated (Sclater et al., 1980). This may be essentially correct for the Phanerozoic (<600 Ma), even though Precambrian magma generation processes may have been significantly different from those of today (Wilson, 1989). Thus, the proposed petrogenetic and paleotectonic model is mainly based on a comparison of the volcanic-plutonic complexes constituting the Gjersvik volcanic arc to those in recent distinct and typical tectonic environments.

3.5.2 Fundamental considerations in interpreting origin of the Gjersvik volcanic arc

dark and pale greenstones

The dark and pale greenstones are the most dominant rock types and hence their origins are of importance in petrogenetic interpretion of the Gjersvik volcanic arc. Due to the fact that the geochemical characteristics of the primary magmas depend mainly upon parameters such as the source composition and mineralogy and the depth and degree of partial melting as well as magmatic crystalization and fractional processes, some aspects described below have a considerable significance in petrogenetic interpretions of the dark and pale greenstones.

(1) The dark and pale greenstones represent the metamorphosed equivalents of ocean-floor basaltic lavas of tholeiitic composition. Distinct and systematic differences in chemical compositions and geological characteristics between the two show that they were formed respectively in different stages of tholeiitic magma processes during accumulation of the Gjersvik volcanic arc, the dark greenstone was formed earlier than the pale greenstone.

(2) Distinguished and systematic difference in chemical compositions, i.e., the pale greenstone is characterized mainly by higher Mg, Cr, and Ni but lower Ti and Fe relative to the dark greenstone, most probably reveal distinction of the magma sources where they were generated. The reason is that it has been known that the upper mantle to depths of about 200 km are not homogeneous and consist predominantly of the two principal rock types: peridotite (olivine, orthopyroxene, diopside, +\- garnet) and eclogite (garnet, pyroxene). The peridotites are characterized in chemical compositions by higher MgO, NiO, and Cr2O3 but the lower CaO, Ti02, and Al2O3 contents relative to the eclogite. In addition, xenoliths derived from the mantle have been revealed that they can be classified as two groups: Group I inclusions are mainly olivine-rich rocks (lherzolite, harzburgite), and Group II pyroxene-rich xenoliths (orthopyroxenens, clinopyroxenes, websterites). Geochemically, Group I xenoliths are more rich Mg, Cr, Ni relative to Group II, while Group II xenoliths typically are more Fe-rich, contain more TiO2, Al2O3, and less Cr2O3 and NiO2 than Group I (Hess, 1989).

(3) Correlative analysis in immobile trace elements and their ratios such as Zr, Ti, Y, Ni, Co, Cr, Cr/Ni, Ni/Co, Zr/Y and Ti/Zr points out that the pale greenstone is largely correlative to E-type MORB and, in certain extends, to N-type MORB, but has few relations to back-arc and island-arc tholeiitic basalts, while the dark greenstone is broadly related to island-arc and back-arc tholeiitic basalts but has few correlations to the E-type and N-type MORB (see Table 3.5). Study of the recent igneous petrogenesis points out that the mid-ocean ridge basalts have been classified as normal (N-type or depleted-type) and plume (P-type or E-type, enriched-type) (Bryan et al. 1976; Sun et al. 1979; Schilling et al. 1983). N-type basalts are recovered mostly from the Pacific and from the Atlantic south of 30 N, whereas N-type basalts

come mostly from the Atlantic north of 30 N and from the Galapagos spreading center. These two types of the MORB have significant variations in the trace element concentrations, but major elements compositions remain remarkably uniform. N-type MORB are derived mainly by partial melting of the isotopically fairly homogeneous, well mixed, depleted upper-mantle reservoir, whereas N-type MORB are derived from sources containing variable amounts of a "blob" component from the underlying isotopically heterogeneous reservoir, which is also the source of oceanic-island basalts (Wilson, 1989). Thus, the immobile element behaviors further confirm the difference of magma sources between the pale and dark greenstones and the pale greenstone was originated from more deep-crust magma source than the dark greenstone.

(4) The different geochemical behaviors of the Cr, Ni and Mg in the dark and pale greenstones display the different evolved trends of magmatic processes. Correlative relationship between MgO and Ni as well as MgO and Cr are apparently positive and linear, i.e., the Ni and Cr systematically, obviously increase with the increase MgO in the pale greenstone, but the Ni and Cr are not obviously variable with increase MgO in the dark greenstones. It has been revealed that NiO in peridotite strongly prefers olivine, and Cr2O3 prefers spinel, clinopyroxene, and garnet. High values (e.g. Ni = 250-300 ppm, Cr = 500-600 ppm) for these elements are good indicators of derivation of parental magmas from a peridotite mantle source because these trace elements are compatible in peridotite that are concentrated in minerals rather than the melt phase. Thus, Ni abundances in MORB strongly controlled by olivine fractionation. Its content ranges from > 300 ppm in primary glass basalts to 25 ppm in highly evolved basalts, and correlate well with MgO content. Cr contents similarly show a marked reduction from 700 to 100 ppm with progressive fractionation (Wilson, 1989). Good correlations between MgO and Ni as well as MgO and Cr in the pale greenstone indicate the importance of olivine fractionation or accumulation. Same good correlations between MgO and Ni as well as Cr are frequently displayed in oceanic-island basalts (Le Roex, 1985). Thus, different correlative trends between MgO and Ni as well as Cr point out that the pale and dark greenstones were originated from the more differentiated and undifferentiated tholeiitic basaltic magmas and further confirm that they most probably originated from different magma sources, respectively.

Felsic plutonic and extrusive complexes

The Gjersvik volcanic arc is characterized by volcanic-plutonic association. The felsic plutonic and extrusive complexes have geochemically been demonstrated to be co-magmatic, and their low-Al properties, generally $Al_2O_3 < 14.5$ percent, seem to point out an oceanic environment because it has been proved that Low-Al_2O_3-, high-Yb-type trondhjemites generally originate in oceanic environments whereas the high-Al_2O_3-, low-Yb-type generally originates at continental margins or interiors (Arth J.G. 1979)

It is now generally accepted that the generation of trondhjemites is related to a basaltic or gabbro source. Generation of low-Al_2O_3-type trondhjemites is thought to occur by fractional crystallization or partial melting of basalt at shallow depths where residual phases would include plagioclase. Generation of high-Al_2O_3-type trondhjemites is thought to occur by fractional crystallization of basalt at intermediate depths where residual phases include hornblende and plagioclase or by partial melting of metabasalt at intermediate depths leaving a hornblende-rich residue; or by partial melting at mantle depths leaving an eclogitic residue (Barker, 1979; Arth, 1979). It is advantageous to support this opinion of trondhjemite origin that the trondhjemites and their eruptive equivalent are closely associated with the greenstones of tholeiitic composition and gabbro within the Gjersvik volcanic arc.

It is perhaps important to mention that geological evidences reveal that the felsic volcanic rocks and their plutonic equivalents, i.e., trondhjemites, are mainly related to an episode of the felsic magma processes between two tholeiitic magma processes.

3.5.3 Major evidences reconstructing paleotectonic environment of the Gjersvik volcanic arc

The Gjersvik Group has been proposed to form in an island arc environment (Gale & Roberts, 1974; Halls et al., 1977; Lutro, 1979; Reinsbakken, 1980, 1981; Gale & Peace, 1982). On the basis of the recent study, it may be necessary and fundamental to pay more considerable attentions in major geological and geochemistrical characteristics described below when paleotectonic environment of the Gjersvik volcanic arc would be reconstructed.

(1) Stratigraphic successions

The Gjersvik Nappe (Halls et al., 1977) consists of a sequence of polymict conglomerates and flysch-like sediments (Limingen Group) in the east of the area generally overlain by metavolcanic and meta-intrusive rocks (Gjersvik Group) to the west. And, the Limingen Group is evidently interpreted as being stratigraphically younger than the Gjersvik Group (Halls et al., 1977; Kollung, 1979; and Lutro, 1979).

The Gjersvik Group is subdivided into two Formations, i.e., Boyrvatnet and Gjersvik Formations. The former consisting of massive amphibolite and actinolite-bearing schist with a MORB affinity is proposed to be stratigraphically older than the latter, and represents a remnant of the ancient ocean crust on which the Gjersvik volcanic arc was built.

The Gjersvik Formation dominates the Gjersvik Group and constitutes the Gjersvik volcanic arc. It consists of a thick bimodal volcanic suite with associated bimodal intrusive complexes. The metavolcanic succession comprises the greenstones of tholeiitic composition and the keratophyric pyroclastic complexes of rhyolitic composition, while the plutons are composed of the trondhjemites and gabbro. On basis of the isostatic principle, Sawkins (1984) pointed out that thicknesses of sedimentary and/or volcanic rocks in excess of the felsic volcanic rocks with their plutonic equivalent few thousand meters and associated massive sulphide deposits related to them cannot accumulate and be preserved in intracontinental areas unless extensional attenuation of the between the episodes of magmatic process of tholeiitic basalts crust takes place.

The metavolcanic succession constituting the Gjersvik volcanic arc has been subdivided into three stratigraphic units, i.e., felsic volcanic complexes, dark and pale greenstones. The dark greenstone is evidently proposed to be stratigraphically older than the pale greenstone, whereas the keratophyric pyroclastic complexes represent an episode of felsic volcanic activity between tholeiitic basalts, their present metamorphosed equivalents of the dark and pale greenstones, respectively. It is very significant and important in reconstructing primary magma processes that the Gjersvik volcanic arc was built by multicycle magma processes that can roughly be divided into three stages, i.e., early undifferentiated tholeiitic, via felsic
to late differentiated magma processes.

(2) Rock types and magma series

The Gjersvik volcanic arc consists of ocean-floor volcanic-plutonic complexes with extensively associated the distal exhalative chemical sedimentary horizon related to the felsic volcanic processes. It is significant, however, that no any sorts of normal sedimentary rocks have so far been found within the Gjersvik volcanic arc. This means the Gjersvik volcanic arc was undoubtedly formed in an ocean-floor environment in where there are no a voluminous sediment supply, perhaps, far away from the continental crust, which differs from the convergent margins near continents or in areas with extensive sediment supply.

The metavolcanic rocks are predominantly composed of the greenstones of tholeiitic composition plus only small keratophyre pyroclastic complexes of rhyolitic composition, the latter being about 20 % in volume. That means the Gjersvik volcanic arc was built mainly by basalts of the tholeiitic series. It has been recognized that the typical volcanic-plutonic series of more mature island arcs and active continental margin is generally "andesitic" and "calc-alkalic", but basaltic rocks of the tholeiitic series may actually be the fundamental magma type in young or immature arcs in intro-oceanic settings (Coats, 1962, 1968; Ewart et al., 1973; Shiraki and Kuroda, 1977; Wilson, 1989).

(3) Bimodal compositions both in the metavolcanic and meta-intrusive rocks

Bimodal compositions both in the metavolcanic and meta-intrusive rocks are one of the most characteristic features of the Gjersvik volcanic arc, that is, the volcanic rocks are mainly tholeiitic and rhoylitic in compositions, but lack of andesitic rocks, and the associated plutons consist of trondhjemite-gabbro complexes short of diorite. Martin and Piwinskii (1972) pointed out that igneous rocks generated at convergent plate boundaries tend to be characterized by unimodal petrochemistry, whereas those generated in rift zones are characterized by bimodal petrochemistry, especially in silica content of volcanics.

(4) Meta-intrusive association

The co-existence of basaltic and silicic rocks is typical of the convergent margin setting where these lava occur (Smith et al, 1990). The plutons associated extensively with the Gjersvik volcanic arc comprise the trondhjemite-gabbro complexes dominated by the trondhjemites. The trondhjemite has so far been known to occur mainly in three tectonic settings: Archean gneiss terrances and Late Archean greenstone-granite terrances; Phaneaozoic and some Proterozoic extrusive and intrusive bodies in plate-tectonic environments of convergent oceanic-continental and oceanic-oceanic types; and as volumetrically minor component of many ophiolites (Barker, 1979).

(5) Geochemistry of the metavolcanites

The dark and pale greenstones can be well distinct in geochemistry to each other. The pale greenstone has strong enrichment in Cr, Ni, and Mg, but depletion in Ti and Fe relative to the dark greenstone. Greatly systematic differences in chemical, especially trace elements, compositions between the dark and pale greenstones demonstrate their different primary magma sources. Correlations of Mg against Cr and Ni point out that the pale greenstone was formed by differentiated tholeiitic magma, while the dark greenstone was originated from undifferentiated tholeiitic magma. Immobile trace element behaviors in the pale greenstone are largely comparative to these in E-type MORB, whereas in the dark greenstone are relative mainly to the island arc tholeiites.

On the basis of discussions above, it is perhaps essential for reconstruction of the paleotectonic environment to consider some fundamental and characteristic features in advance. (1) the Gjersvik volcanic arc was formed in an intro-ocean floor environment in where there are no a voluminous sediment supply, perhaps, far away from the continents; (2) the fundamental tectonic environments during accumulation of the Gjersvik volcanic arc is extensive or rifting rather than compressive; (3) the magma processes leading formation of the Gjersvik volcanic arc must be multi-stages or polycyclic, but they can be roughly confined in three major stages: early undifferentiated tholeiitic, middle felsic, and late differentiated tholeiitic magma processes. And, each stage of major magma activities may corresponds to a limited paleo-tectonic environment; (4) the Gjersvik volcanic arc consists of bimodal volcanic-plutonic complexes, which are definitely different from those in mature island arc or continental margin related to convergent plate, and are also distinct from those in typical mid-ocean ridge and within ocean plate island arc environments related to divergent plate; (5) structure of the Gjersvik Nappe reveals that the metasedimentary succession of the Limingen Group is stratigraphically younger than the metavolcanic succession of the Gjersvik Group, and hence this makes it very difficult to assume that the Gjersvik volcanic arc was present in an back-arc environment; (6) the Gjersvik volcanic arc was most probably formed in an intro-ocean, immature, rifting volcanic arc. And, the rifting development corresponds to the magma processes during accumulation of the Gjersvik volcanic arc.

3.5.4 A simplified petrogenic and paleotectonic model

A model for petrogenic and tectonic evolution of the Gjersvik volcanic arc is proposed to has focused on the development of intro-ocean crustal extension in where there is no an extensive supply of sediment but it is in some ways related to the plate convergence processes. Figure 3.33 shows a series of schematic cross sections depicting the petrogenetic and tectonic evolution of the Gjersvik intro-ocean rifting volcanic arc.

Section (a) shows that the first step in development of an intra-ocean rifting system at a convergent plate margin may involve the imbrication of lithosphere plates of, perhaps, different net density and thickness. The fault zones may be important in determining the locus and the beginning of a subduction cycle.

Section (b) represents that subduction sets up mantle counterflow which causes thermal upwelling of overriding plate and crustal rupture, and hence the initial rifting begins over the subduction zone. Accompanying this processes, a volcanic arc begins to form in a deep intro-ocean floor. The volcanic arc is immature and consists predominantly of the undifferentiated tholeiites. At this stage, hydrous fluids derived from the subducting oceanic lithosphere metasomatize a MORB-like mantle source, i.e., depleted mantle source, which then partially melts to produce the rifting arc tholeiites. The newly erupted undifferentiated tholeiites are characterized by relative high Ti and Fe but low Cr, Ni and Mg, and are associated mainly with of island-arc but mixing back-arc tholeiite and MORB affinity. Therefore, mixture of preexisting abyssal tholeiites may be important during accumulation of the rifting arc tholeiites.

Section (c) represents a more advanced stage of the rifting development. The tholeiitic magma processes appear to cease around time when the subduction becomes failure, but the rifting is not cessation. At this stage, the rifting is further developed, perhaps, as a consequence of high thermal anomaly derived from deep mantle initial upwelling. Continue extension of the developed rifting causes partial melt of the arc undifferentiated tholeiites and gabbro within lower crust to produce the trondhjemitic magma. An episode of the felsic volcanic activity and felsic plutons begin to emerge in following the undifferentiated tholeiitic magma processes within the rifting volcanic arc.

Section (d) points out the deeper rifting development and formation of a new oceanic crust, generated as a consequence of the diapiric upwelling of deep, enriched mantle source. The deep mantle diapiric upwelling partially melt to produce E-type MORB-like rifting tholeiites, which display good affinity mainly similar with E-type MORB but plus E-type MORB, island-arc and back-arc tholeiites. This indicates that the new tholeiites derived from relative deeper mantle are in some ways related to enriched mantle source. The new tholeiites are characteristic of high Cr, Ni, and Mg as well as lower Ti and Fe and exhibit a well considerably differentiated property. At this stage, the subduction system may be not important, but fractional melting of the rising deep mantle diapir and interference of preexisting arc tholeiites play probably an essential role during deep rifting development, accumulation of new tholeiitic volcanic arc and formation of new ocean crust.

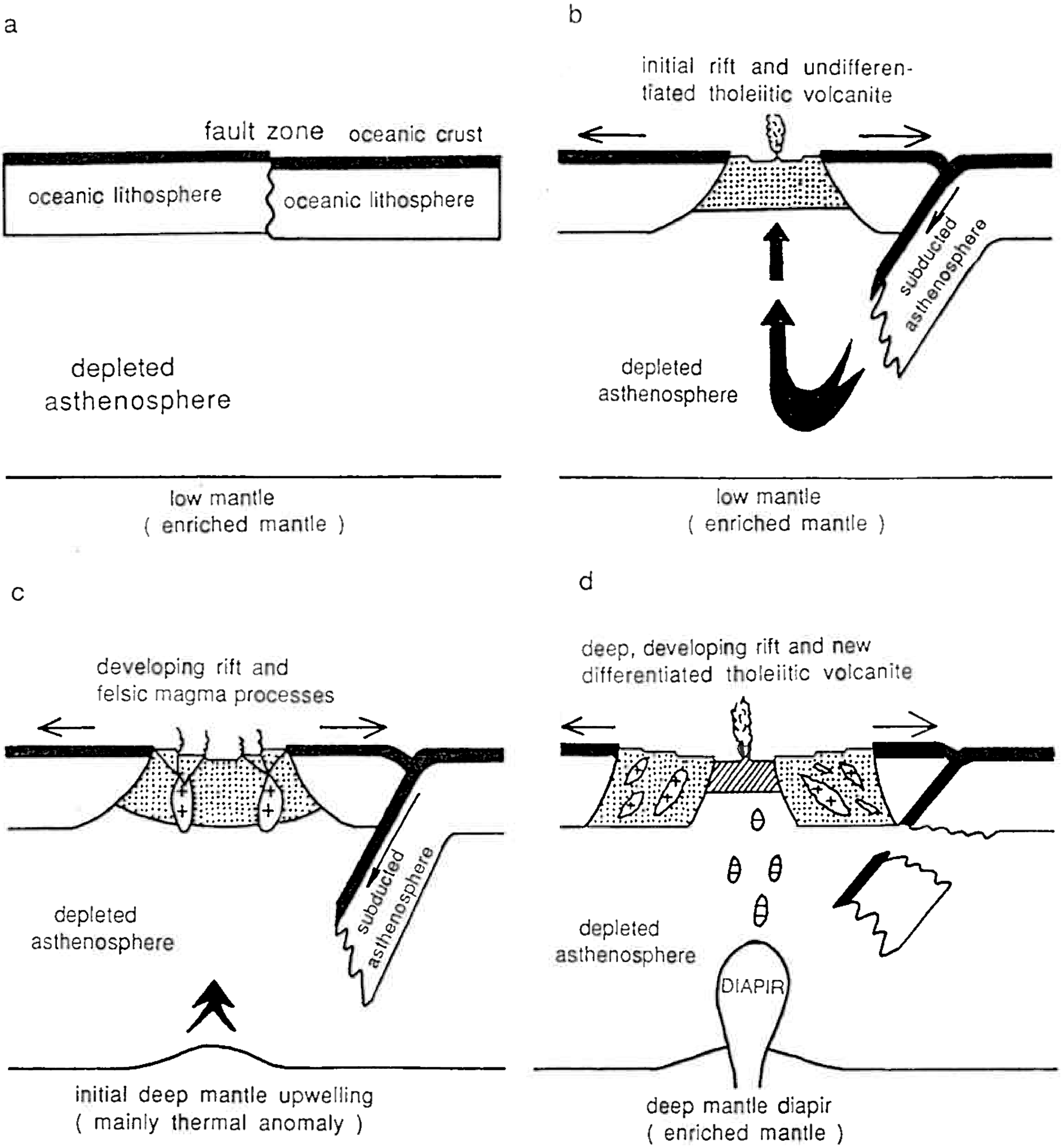


Fig. 3.33 A simplified petrogenetic and tectonic model of the Gjersvik intro-ocean rifting volcanic arc

(a) first step in development of an intro-ocean rifting system at a convergent plate margin, and emphasizing an important role of the fault zone in determining the locus and the beginning of a subduction cycle; (b) processes of the initial rifting over a subduction zone accompanying eruption of the undifferentiated tholeiitic basalts derived from the depleted mantle source and formation of new oceanic crust; (c) an advanced stage of the rifting system development around which the tholeiitic magma processes appear to cease due to failure of the subduction, but emergency of the felsic magma activity which is generated by partial melt of the preexisting tholeiitic basalts caused by the deeper heat anomaly related to the rifting system development; (d) step of the deeper rifting development associated with activities of the differentiated tholeiitic basalt magma derived from the more deeper enriched mantle source and with formation of the new ocean crust

Section 4: Massive sulphide mineralization

4.1 Introduction

4.1.1 Distribution of massive sulphide mineralization

The massive Cu-Zn sulphide deposits have so far been found to occur extensively within the bimodal metavolcanic sequence of the Gjersvik volcanic arc. They are present as a part of the volcanic sequence and are predominantly closely associated with the keratophyric pyroclastic complexes of rhyolitic composition. Of them the Gjersvik and the Skorovass deposits are most important both in sizes and in economic value. The Gjersvik ore deposit as second big one following the Skorovas orebody in size is associated with c. 1.6 m.t. of ores (massive and disseminated) with an average of 31 % S, 1.6 % Cu and 0.9 % Zn with few amounts of Pb and precious metals (Oftedahl, 1958). Unfortunately, the deposit has never been set into production although it was discovered early in this century and was already planned for production as early as 1920s. The Skorovas orebody, located in about 40 km to the south of the Gjersvik deposit, with c.10 m.t. of ores massive and disseminated predominantly pyritic ore with an average grade of 1.3 % Zn and 1.0 % Cu, together with trace amounts of Pb, As and Ag (Halls et. al. 1977) used to be in production, but was closed in 1986. The Skorovas deposit was proposed to be comparative with and very similar to the Gjersvik ore body in tectonic setting, stratigraphic horizon, geological and lithological environments, as well as geology of ore bodies by Reinsbakken (1980, 1981). Some considerable differences, however, do exist between the two deposits. On the one hand, for example, the Skorovas massive sulphide ore body is associated with relative more Zn and Pb metals and is lack of pyrrhotite, while the Gjersvik ore body is dominated by Cu plus minor Zn but without Pb metals and the pyrrhotite is one of the most important components of ore mineral assemblages; on the other hand, a lot of jasper has been distinguished to occur as distal exhalative sediments in the mineralization horizon in the Skorovas area (Reinsbakken, 1980), whereas magnetite-rich cherts constitute the most important distal exhalative sediments extending in the mineralization horizon, but very few jasper have so far been found in the Gjersvik area. These sorts of differences appear to point out that the Gjersvik deposit was probably formed in a relative more reduced, higher temperature, more restricting basin on ocean floor environment in comparison with the Skorovas orebody. In addition, the other smaller deposits such as Annlifjellet, Tjiermajaevrieh, Gjersvikklumpen and those in the southern and northern shore of the Bjorkvatnet Lake, have been found to have less importantly economic value. These deposits are also associated with the keratophyric pyroclastic complexes and are comparative and similar to the Gjersvik deposit.

The thin, iron- and silica-rich, base-metal-depleted, pyrite-rich, exhalative sedimentary mineralization occur extensively within the extrusive sequence. They are generally present within the greenstones but not associated with the felsic volcanic rocks. This kind of mineralization has been interpreted as exhalative chemical sediments related mainly to a volcanic episode of the keratophyric pyroclastic complexes. The veining mineralization characterized by veining and veinlet sulphide mineralization associated with apparent hydrothermal alterations are also extensively present in the underlying dark greenstone, but very few within the overlying pale greenstone. Th is kind of mineralization has been well revealed by drilling core such as Drilling core Nr.4, and the detailing surface mapping (Fig. 4.1). It should, however, mention that no any economic value has so far been found from the later two kinds of mineralization.

4.1.2 Types of mineralization and their structural styles

The sulphide mineralization can be subdivided into three types, i.e., massive sulphide, exhalative, and veining mineralization. They can be clearly separated in host rock associations, relationship of mineralization to their wall rocks, mode of ore bodies in occurrence, ore mineral assemblages and hydrothermal alterations. The detailing descriptions are given in follow.

(1) Massive sulphide mineralization

This kind of mineralization refers to those that the ore horizon, situated generally at an interface between metavolcanic stratigraphic units of the greenstone and of the keratophyric pyroclastic rock, consists of massive sulphide ores (sulphides generally over 60 vol.%) associated initially with a stringer (so-called feeder zone) characterized both by intensive wall-rock hydrothermal alterations and by extensively interconnected and disseminated

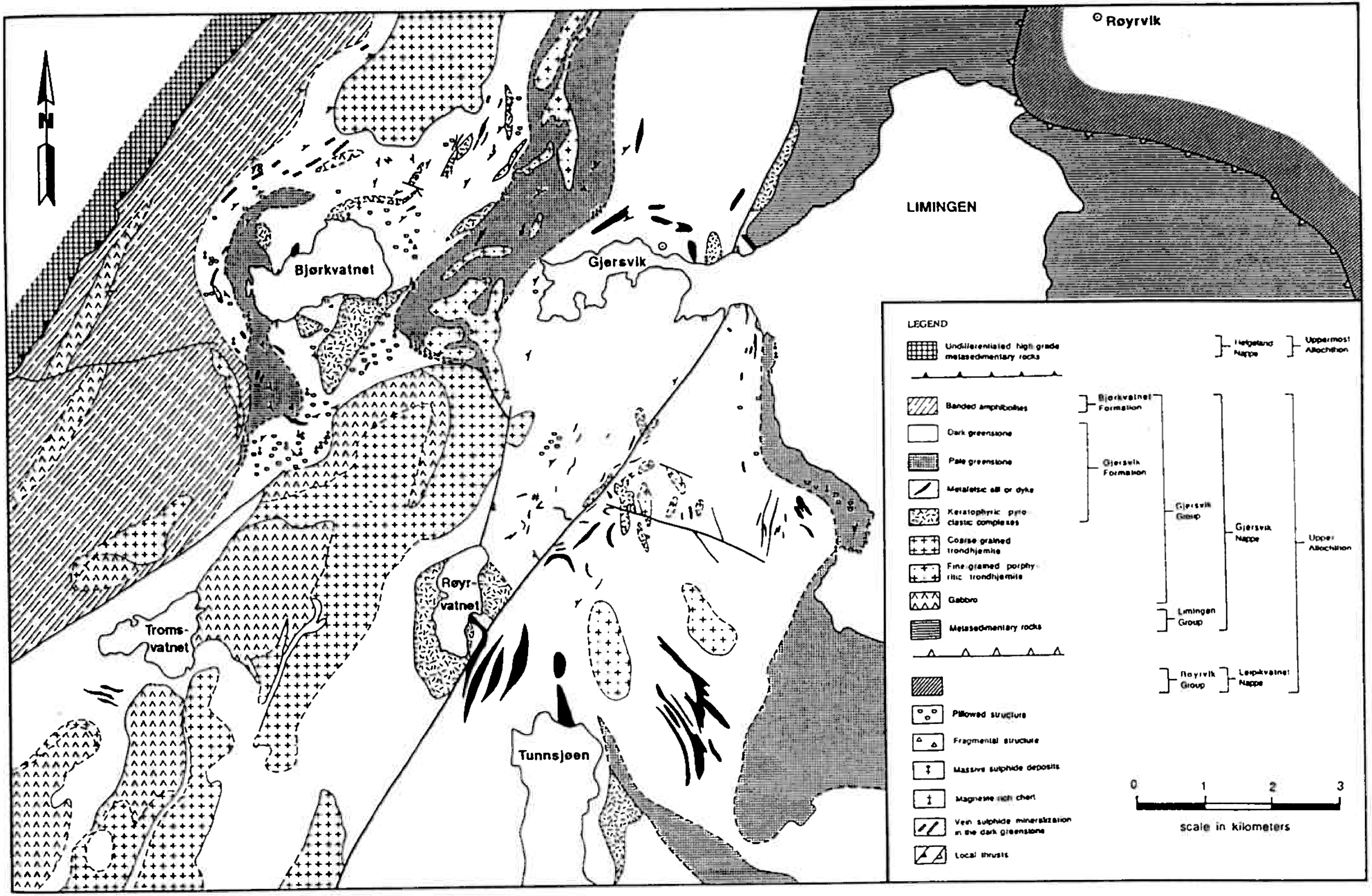


Fig. 4.1 Sketch geological map of the Gjersvik area

sulphide mineralization which occur within and cut through the keratophyric pyroclastic complexes directly below the massive orebody. The association relationship between massive sulphide ores and altered stringer is intimated and the feeder zone has been interpreted as a path leading the mineralized solution flow towards the surface on the ocean floor in where accumulate the massive sulphides. This type of mineralization is only and most important in economic value known so far in the Gjersvik area, such as the Gjersvik and Skorovas ore bodies all belonging to this group.

The keratophyric pyroclastic complexes associated with massive sulphide mineralization consist predominantly of the metavolcanic clastic and tuffaceous rocks. For example, the keratophyric pyroclastic complex hosting the Gjersvik ore body is exposed on the surface as an approximately ellipsoid shape with axis length 350 meters in N-S direction and 200 meters wide and composed of pale-moderate, massive, keratophyric pyroclastic rocks plus welded lapilli tuff. The felsic pyroclastic rocks comprise flattened, angular, pale keratophyric fragments setting in a white-moderate greenish, quartz-sericite-chlorite-calcite matrix containing much pyrite disseminatation. The angular and lensoid fragments vary in size from 1-5 cm (maximum dimension) and consist of a very fine-grained, porphyritic, homocrystalline quartz, albite and sericite with subordinate chlorite and small epidote. Pyrite and magnetite, up to 2%, are nearly always present in fragments along with accessary apatite and sphene. Immediately adjacent to the massive sulphide ores, there often occur a paler, more massive and dense, highly siliceous, sericite- and carbonate-rich metarhyolite, which is commonly characterized by associated interconnected network of thin pyrite vein and veinlet mineralization. The quartz-sericite-carbonate rocks which result from intensive silicification, sericitization and carbonatization frequently occur in the most intensively pyrite-veined and disseminated portions. These altered felsic rocks associated with interconnected vein and veinlet sulphide mineralization have been interpreted as the feeder zone connecting directly to the massive ores. The parallel situations also well repeat in the other places where occur the massive sulphide mineralization associated with the keratophyric pyroclastic complexes. For example, the Tjiermajaevrieh massive sulphide body is directly overlain by a small felsic pyroclastic complex consisting of felsic volcanic fragments, about 10 - 20 cm in size, cemented by fine-grained, pyrite-rich, altered felsic tuff (Fig. 4.2). And, the biggest keratophyric pyroclastic body in the Gjersvik area, located at the south of the Bjorkvatnet Lake, is also

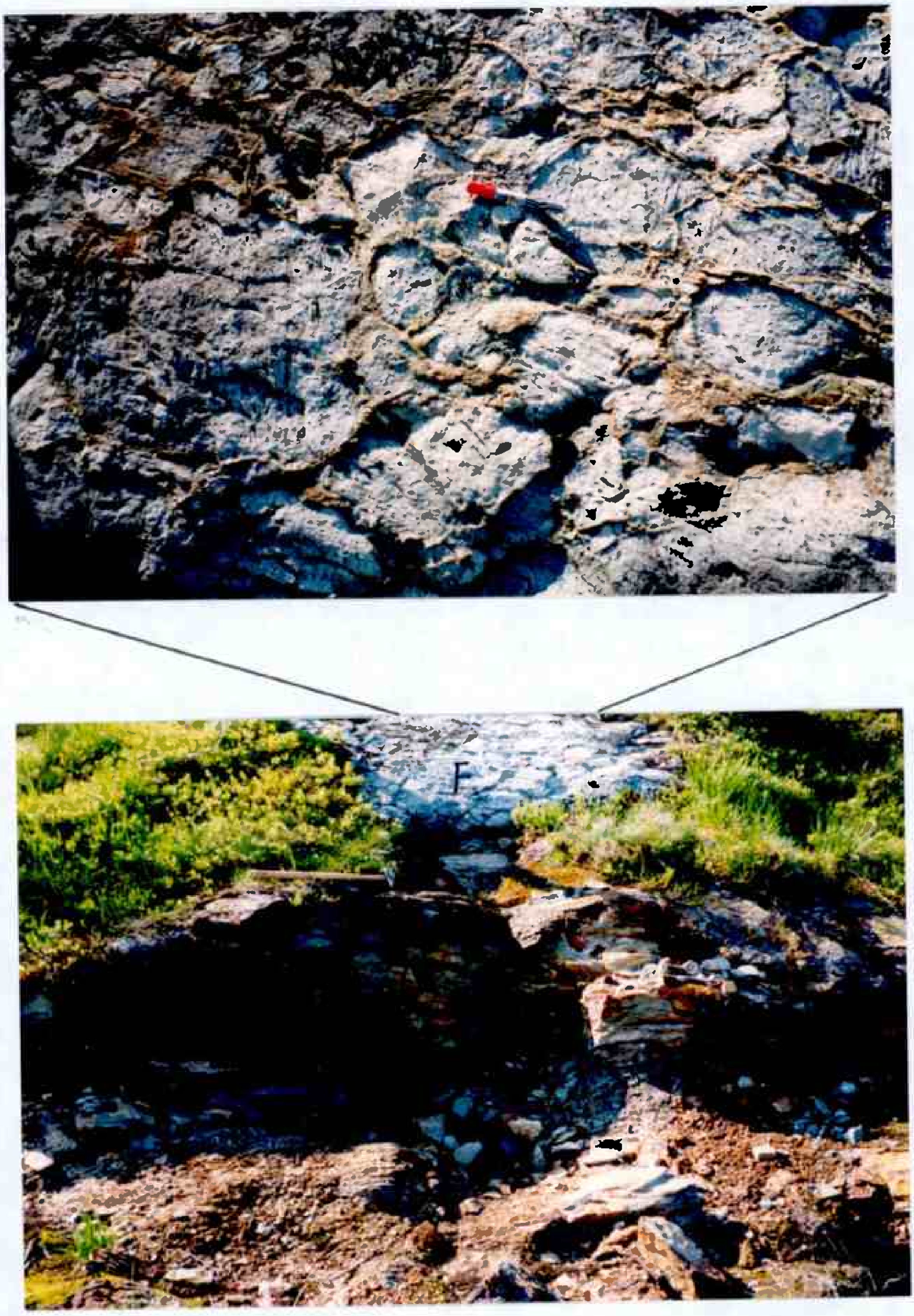


Fig. 4.2 Relationship between massive sulphide mineralization (M) and the keratophyric pyroclastic complex containing altered, interconnected pyritic mineralization (F) at the southwest of Tjierme-jaevrie Lake about 300 m in Tjiermejaenrieh area

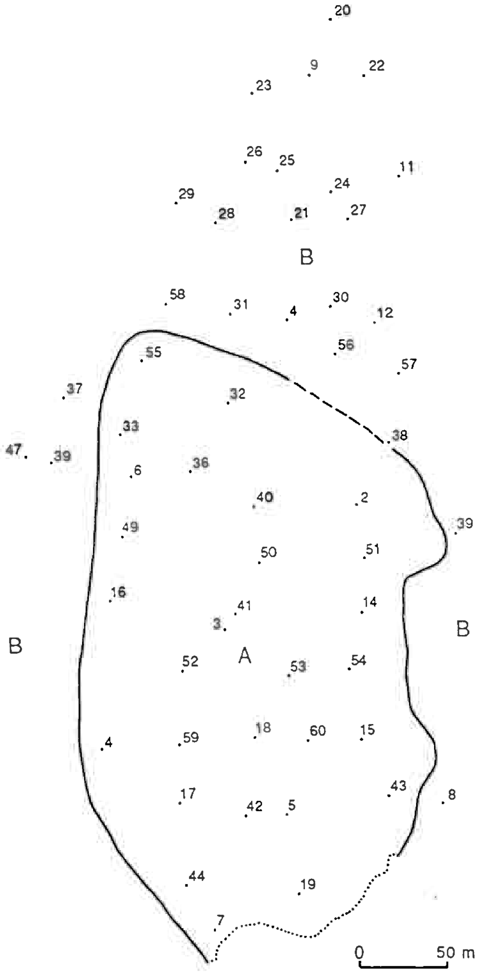
associated with the massive sulphide mineralization (Fig. 4.1). Apart from the keratophyric pyroclastic complex at the level where the ore horizon is located, the sequence becomes the unaltered, dark greenstone of tholeiitic basaltic composition. The massive sulphide horizon is, however, underlain by the unaltered greenstone but overlain by the altered, interconnected pyritic felsic complex in Gjersvik deposit. In this case, relationship between massive sulphide bodies and their wall rocks has been interpreted to indicate an inverted stratigraphic succession. The same stratigraphic succession and relationship between ore bodies and wall rocks were reported from the Skorovas ore deposit (Reinsbakken 1980).

The massive sulphide ore bodies are generally stratiform, lensoid, and plate-like, varying from tens cm to several meters in thickness and from tens to several hundred meters in length and are conformable with their wall rock, while the feeder zone underlying directly below massive orebody is usually pipe-like or irregular, and is discordant with the host keratophyric pyroclastic complex. For example, the drilled exploration for the ore bodies was revealed that the present geometry of the Gjersvik orebody consists of an asymmetrical, spoon-shaped, synformal structure which plunges southerly with the eastern limb more steeply dipping than the western. The horizon of massive ores itself is an irregular 1 - 5 m thick and occurs just in junction between felsic pyroclastic complex and the greenstone, extending into within the greenstone (Fig. 4.3). The road sections (both old and new roads) cutting through both limbs of this structure exhibit clearly outcrops of the massive orebody which is directly overlain by the interconnected network of sulphide veining and sulphide disseminated mineralization associated with intensive hydrothermal wall-rock alterations cutting and occurring within the felsic pyroclastic complex. The present sequence that the massive sulphide horizon is overlain by the altered, pyritic felsic complex but underlain by unaltered dark greenstone most probably indicates an inverted stratigraphic position.

(2) Exhalative sedimentary mineralization

A thin, iron- and silica-rich, base-metal-depleted facies occurs extensively but generally not associated with the felsic volcanic rocks in the metabasaltic succession of the Gjersvik Formation. The exhalative sedimentary horizon is comfortable with their wall rocks and occurs mainly either in or near junction between the dark and pale greenstones or within the dark

(a)


20
9
22
23
26
25
11
24
29
28
21
27
B
58
31
4
30
12
56
55
57
37
32
33
38
47
39
36
6
40
2
49
39
50
51
16
41
14
3
B
B
A
52
53
54
4
59
18
60
15
43
8
17
42
5
44
19
7
0
50 m

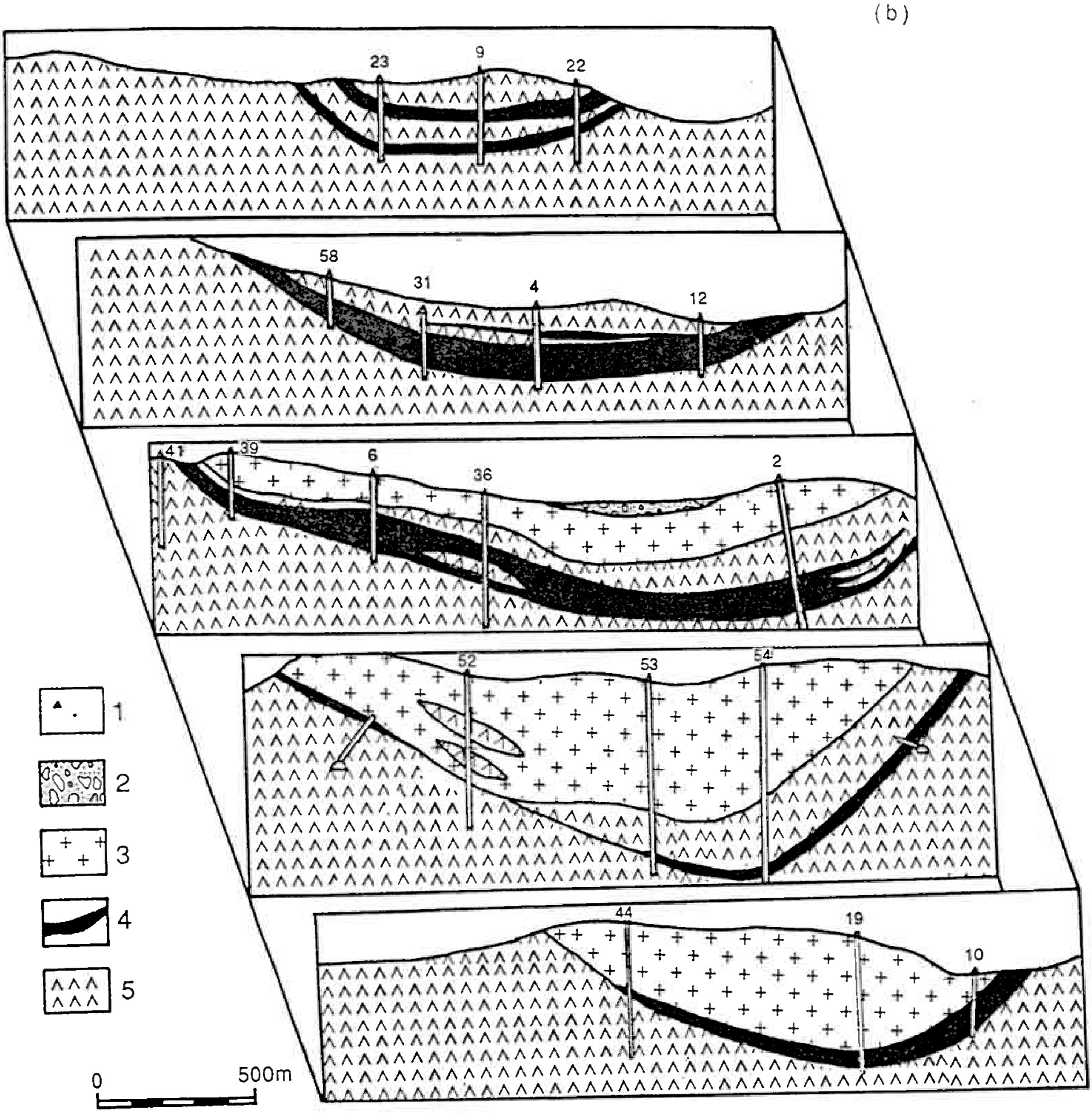


Fig. 4.3 Simplified geological map (a) and a series of geological sections of the Gjersvik deposit (b) (Modified from Gjersvik Malmfelt report by Øystein Pettersen, 1973)

1 - positions and number of the drilling core; 2 - slope wash; 3 and A - keratophyric pyroclastic rocks; 4 - massive sulphide horizon; 5 and B - dark greenstone;

pillowed greenstone. They are usually characterized by obvious sedimentary structures and not associated with hydrothermal alterations. This kind of mineralized horizon is interpreted as an exhalative sediment of setting of colloidal iron and silica hydrosol following explosive dispersal into the submarine environment related either to a volcanic episode of the keratophyrical pyroclastic rocks or to the pillowed tholeiitic basalts during construction of the Gjersvik volcanic arc. The exhalative sediments occur mainly as thin, sheet- or plate-like layers or lenses, generally several tens cm to meters in thickness and several to tens meters in length or width. They are very regular in occurrence and concordant with the metavolcanic host succession, but some of them are obviously synchronously folded together with their wall rocks. These thin, exhalative sedimentary layers can in places be traced about several hundreds to thousand meters along an identical stratigraphic horizon either between the dark and pale greenstones or within the dark pillowed greenstone, which have frequently been used as an useful key horizon that separates the metamorphosed volcanic-stratigraphic units formed in different episodes of tholeiitic basaltic magma activities.

(3) Veining mineralization

This kind of mineralization refers to those that occur mainly as thin vein, stockwork and disseminated sulphide mineralization associated with intensive hydrothermal alterations within the underlying dark greenstone but that are not associated with the felsic volcanic complexes. They were well revealed by the surface detailing mapping and the drilling core. It is, perhaps, significant to discuss them as an independent mineralization type in interpreting origin of the ore deposits although there are no any valuable value with them known so far. The vein sulphide mineralization associated with the dark greenstone extensively occur in the western part of the Gjersvik Formation and are characteristic of yellow-brown color on exposures on the surface. They occur mainly as long belts, generally several to tens meters wide and tens to hundreds meters long, which cut through the dark greenstone and are sharp in contact with their wall rocks (Fig. 4.1). This kind of relationship in contact and in occurrence shows that they are apparently controlled by fault or fissure structures. The same type of the mineralization was revealed by the drilling core Bh.4 in the northeastern part of the Royrvatnet lake, within which the vein sulphide mineralization occur non-homogeneously but intensively in different levels of the drilling core such as in 317 - 325 m, and 369 - 360 m within the dark greenstone.

4.2 Ore mineralogy, types, textures and zoning

Mineralogy of the Gjersvik deposits is comparatively simple, dominated by pyrite, pyrrhotite, chalcopyrite, sphalerite and magnetite in decreasing order of abundance. The principal gangue minerals include quartz, carbonate (calcite) together with minor chlorite and sericite. Three different types of mineralization above described, i.e. massive sulphide, exhalative sedimentary and veining mineralization are generally different each other in host rock, ore types, ore and gangue mineral assemblages as well as their zoning.

4.2.1 Massive sulphides

This kind of mineralization consists of massive sulphides associated with a stringer zone (feeder zone) characterized by interconnected pyritic mineralization plus intense hydrothermal alterations. The massive sulphide body generally occurs between stratigraphic units of metavolcanic greenstone and felsic volcanic complex, whereas a stringer mineralization is present within the felsic complex directly below the massive body.

The terms of `massive sulphides' are here defined as > 50 vol.%, and `disseminated' as < 50 vol.% sulphides.

Massive sulphide phase

The massive sulphide phase consists largely of massive sulphide ores containing sulphides generally over 90 vol.% with less importantly banded sulphide ores containing sulphides about 50 - 70 vol.%. The ores comprise predominantly pyrite, pyrrhotite, chalcopyrite, and sphalerite with a considerable amount of magnetite. Non-metal minerals include quartz (about 60 - 90 %), chlorite (about 10 - 30 %) as well as minor carbonate and sericite (generally less 10 %). Quartz is generally less 0.05 mm, but some up to 0.1 - 0.3 mm in size. Chlorite often occur as aggregate or recrystalline big crystal. Sericite is mainly associated with chlorite.

Textures of the ores indicate an extensive and intense affection of metamorphism and deformation on the deposits. For example, typical foam textures of the massive pyrite indicate an affection of slow heating during metamorphism to the ores, which made pyrite recrystalization to minimize the areas of grain surface and interfacial tension through the development of roughly equal grains with 120 degree interfacial angles (Fig. 4.4). The sphalerite also recrystallized along fissures of or between pyrite grains during metamorphism (Fig. 4.5). Deformation of the ores is strongly evidenced by cataclastic texture of the pyrite (Fig. 4.6) and compressive strain texture in the massive pyrite ores (Fig. 4.7). It must be emphasized, however, that some primary textures can still be reserved in the ores even though metamorphic and deformed textures are most dominant within the ores. For example, small pyrrhotite crystal occur as discontinue circling drops within big pyrite crystal (Fig. 4.8). This kind of texture most probably reflects a primary paragenetic relationship between pyrite and pyrrhotite during the pyrite crystallization from mineralized fluid, and also indicates a relative high temperature condition because phase relation in the Fe-S system demonstrates that temperature of pyrite + pyrrhotite paragenesis is about 350 - 600 C (Vaughan & Craig, 1978).

On the basis of major metal mineral assemblages, mineral content, their spatial relationship to each other and to the adjacent host rocks, the ore horizon of the Gjersvik massive orebody can be subdivided into five major ore facies or ore types (Fig. 4.9). Distribution and zonation of these different ore types constitute a part of volcanic stratigraphic succession and display a feature of the sedimentary succession. Their orders are described from the felsic complex to the greenstone as follows:

unaltered greenstone (in top)

Type V: fine-grained, massive, banded pyrite-magnetite facies
Type IV: fine-grained, compact, massive pyrite-sphalerite (with magnetite) facies
Type III: fine-grained, massive to banded pyrite facies
Type II: fine- and coarse grained, compact, massive pyrrhotite-pyrite-chalcopyrite facies
Type I: fine-grained, compact, massive Cu-rich pyrite facies

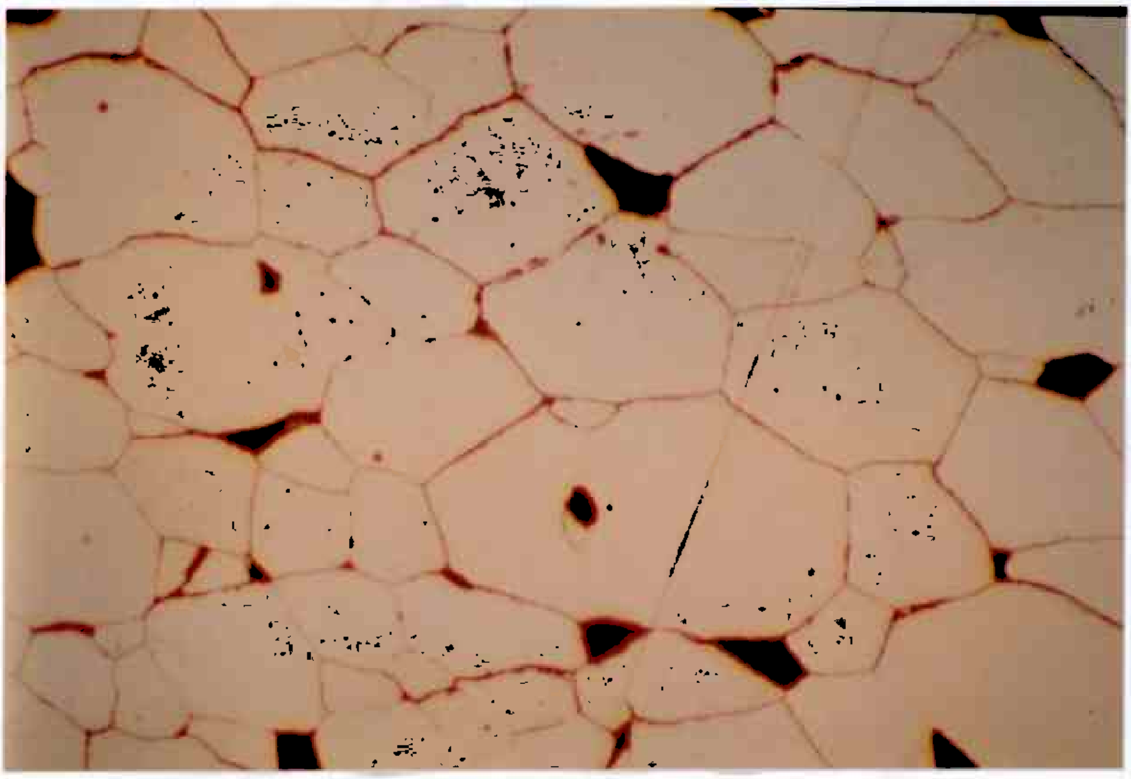


Fig. 4.4 Typical foam texture in the massive pyrite ores 16 x 3.2 x 1.25

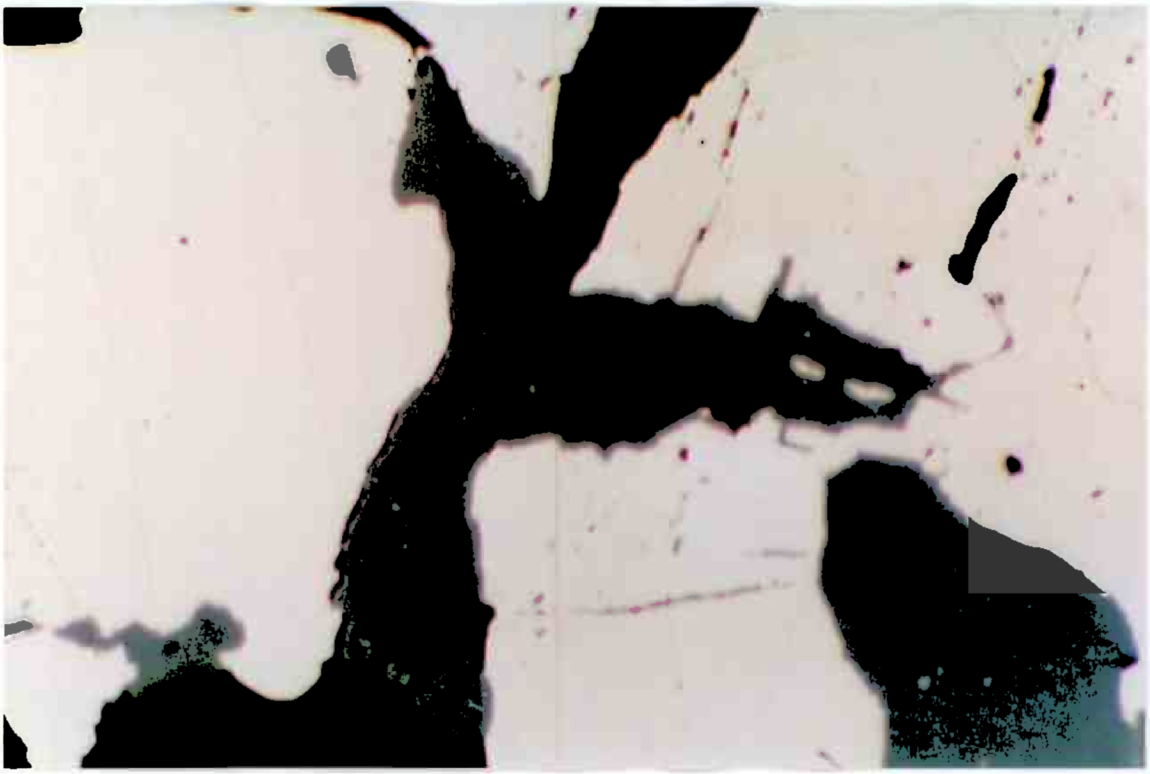


Fig. 4.5 Recrystallization of sphalerite (grey) along fractures of or between pyrite (white) grains 16 x 3.2 x 1.25

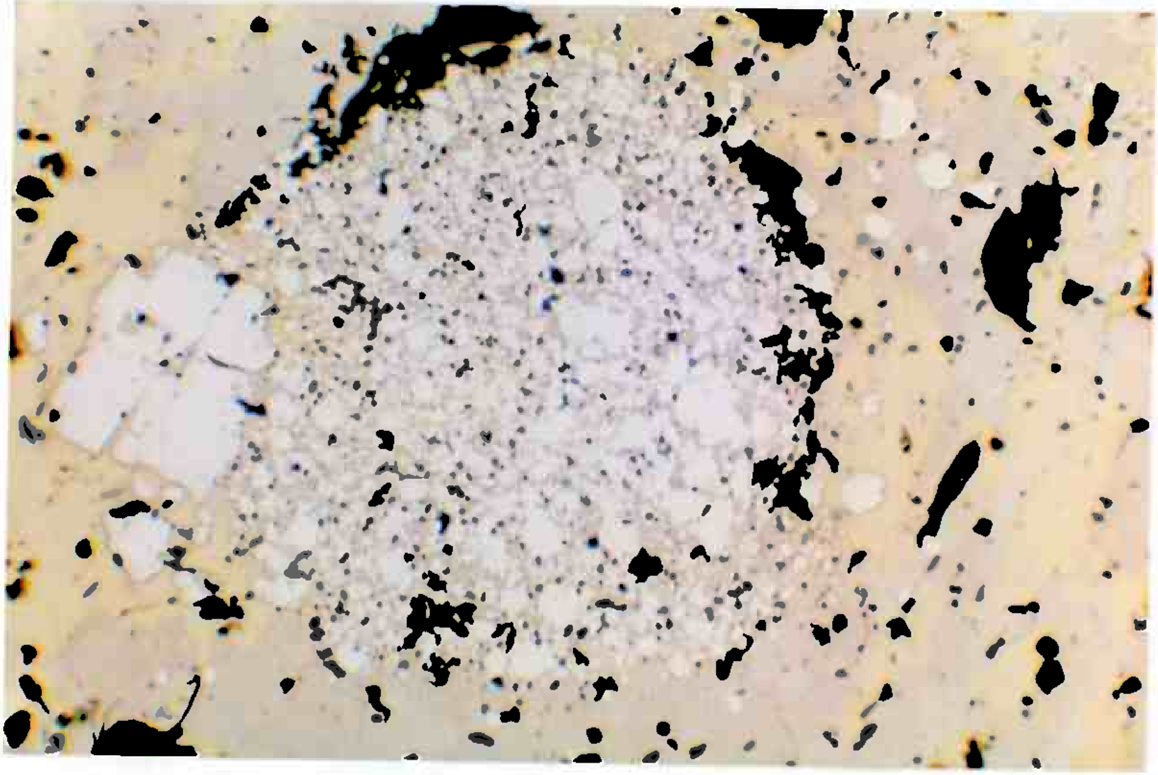


Fig. 4.6 Cataclastic texture of the pyrite in massive pyrite - chalcopyrite - pyrrhotite ores 4 x 3.2 x 1.25

Fig. 4.7 Compressive strain texture consisting of fine-grained pyrite belt setting in the relative coarse-grained massive pyrite ores 2.5 x 3.2 x 1.25

? pressure-solution ?

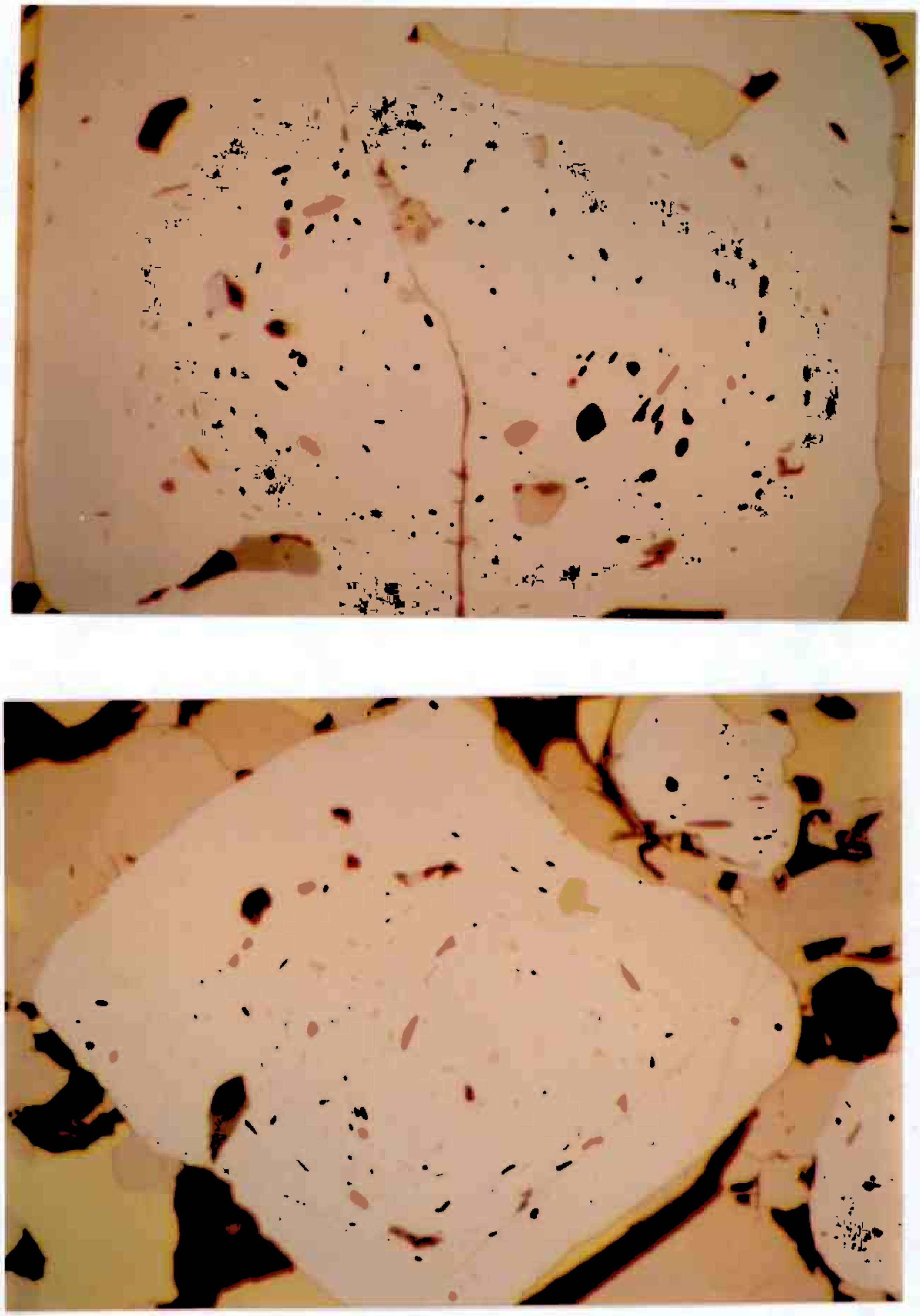


Fig. 4.8 Paragenetic texture of pyrite (big crystal) and pyrrhotite (small crystal with the pyrite) 2 x 3.2 x 16

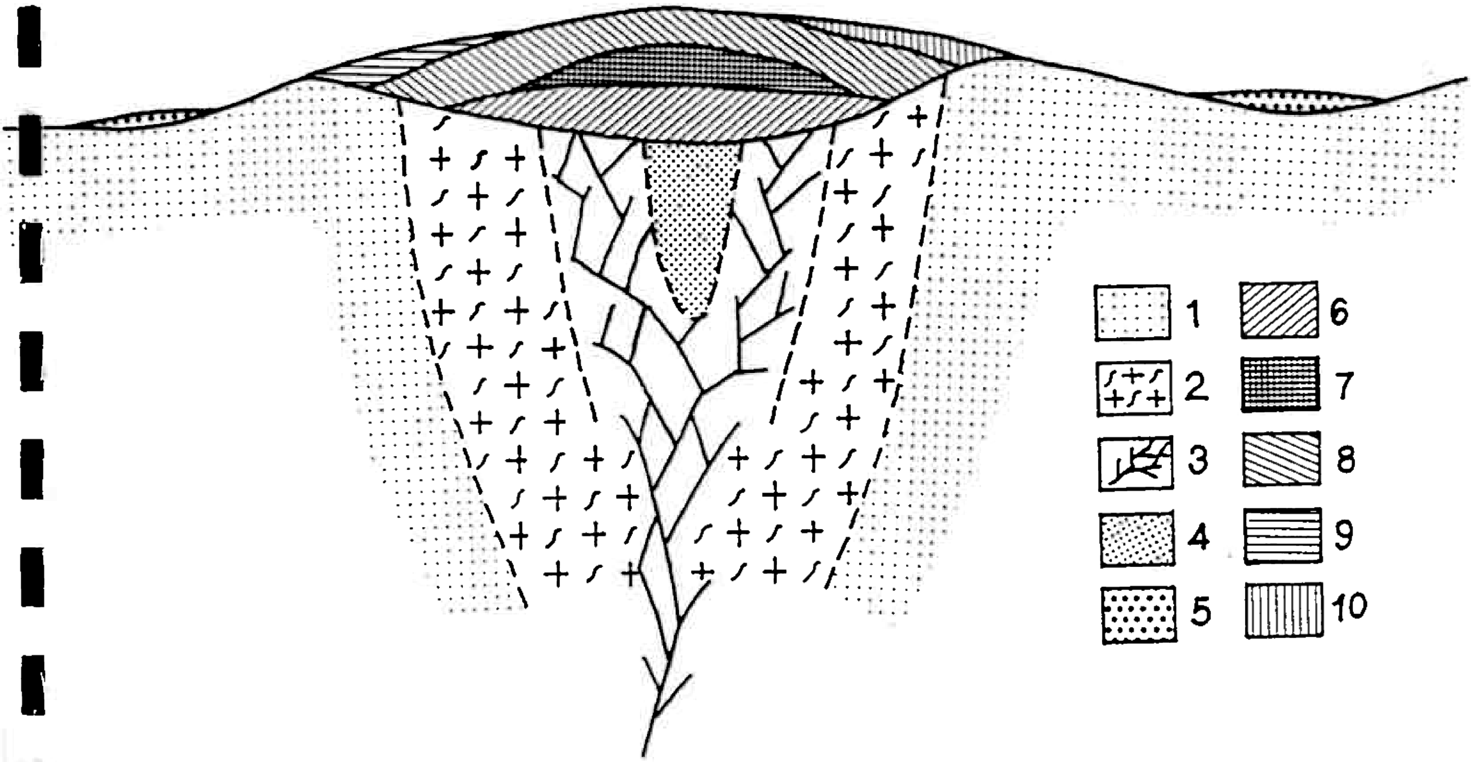


Fig. 4.9 Ideal section and original zoning of the massive sulphide horizon, and of the hydrothermal alteration and mineralization in the feeder zone

1 - dark greenstone of tholeiitic composition; 2 - weak alteration zone (silicification) associated with slight pyrite mineralization within the keratophyric pyroclastic complex; 3 - moderate alteration zone (silicification, sericitization and carbonitization) with obvious veining, veinlet and stockwork pyrite, sphalerite, and chalcopyrite mineralization within the keratophyric pyroclastic complex; 4 - intense alteration zone (silicification, sericitization) with strong or slight disseminated Cu-rich pyrite mineralization within the keratophyric pyroclastic complex; 5 - magnetite-rich chert; 6 - massive, compact pyrite + chalcopyrite ores; 7 - massive, compact pyrite + chalcopyrite + pyrrhotite ores; 8 - massive to banded pyrite ores; 9 - massive pyrite + sphalerite (with magnetite) ores; 10 - massive to banded pyrite + magnetite ores

keratophyric pyroclastic complex associated with the feeder zone (in bottom)

Type I: fine-grained, compact, massive Cu-rich pyrite-chalcopyrite facies

Representative polished sections are GS1-25, GS2-8 (?).

This type of ores is characteristic of pyrite + chalcopyrite + magnetite assemblages, so-called Cu-rich pyrite facies, and tends to occur in side of the massive orebody immediately overlying or adjacent to the altered pyritic feeder zone occurring within keratophyric pyroclastic complex. The Cu-rich pyritic ores are yellow-colored, fine-grained, harder, massive, very homogeneous and compact, being seldom of primary layering. Sulphides in the ores are over 95 vol.%, consisting mainly of pyrite (60 - 70 vol.%) with varying chalcopyrite (10 - 20 vol.%) and magnetite plus small sphalerite and pyrrhotite. Pyrite are generally anhedron, very fine-grained about 50 um, but some of recrystalline pyrite become euhedron, relative coarse-grained, ranging from 0.2 - 0.4 mm in size. Chalcopyrite and magnetite are very irregular, generally less 0.1 mm but some up to 0.2 - 0.3 mm in size. Chalcopyrite and pyrrhotite often replace the pyrite and occur mainly along edges and fractures of or as intergranular minerals within pyrite grains, as well as between boundaries of pyrite grains (Fig. 4.10).

Type 2: fine- and coarse-grained, compact, massive Cu-rich pyrrhotite-chalcopyrite-pyrite facies

Representative polished sections are GS1-23, GS1-24, GJK90.7, GJK90.8, and J30.

This type of the ores occurs within inside of the massive sulphide body and grades into massive Cu-rich pyrite and compact pyritic facies. It is characterized by rich pyrrhotite and contains sulphides over 95 vol.% consisting of pyrrhotite (about 50 vol.%), chalcopyrite (varying between 10 - 40 vol.%), and pyrite (ranging from 10 to 35 vol.%) with minor amounts of sphalerite and magnetite. In general, pyrrhotite, sphalerite and magnetite have a few variation in volume, but chalcopyrite and pyrite vary from sample to sample. For instance, samples GS1-23, GS1-24 comprise pyrrhotite (50 vol.%), pyrite (25 - 35 vol.%),

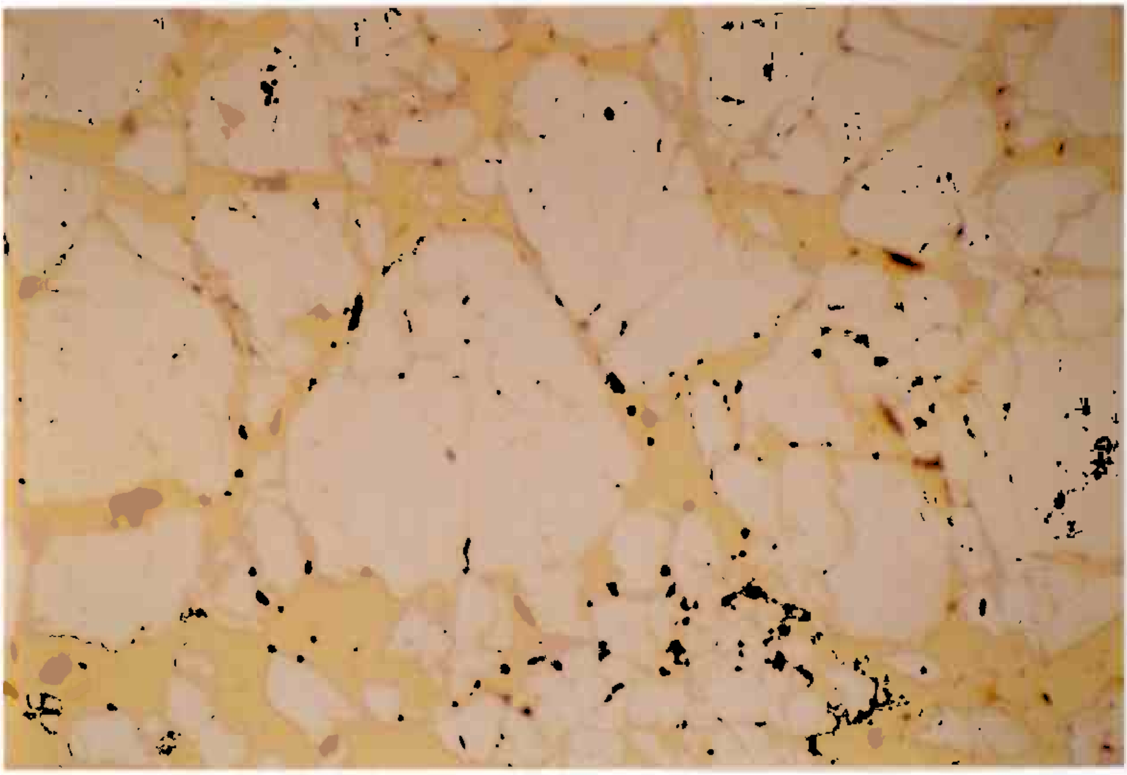


Fig. 4.10 Replacement of chalcopyrite and pyrrhotite along fractures of and boundaries between pyrite grains 6.3 x 3.2 x 1.25

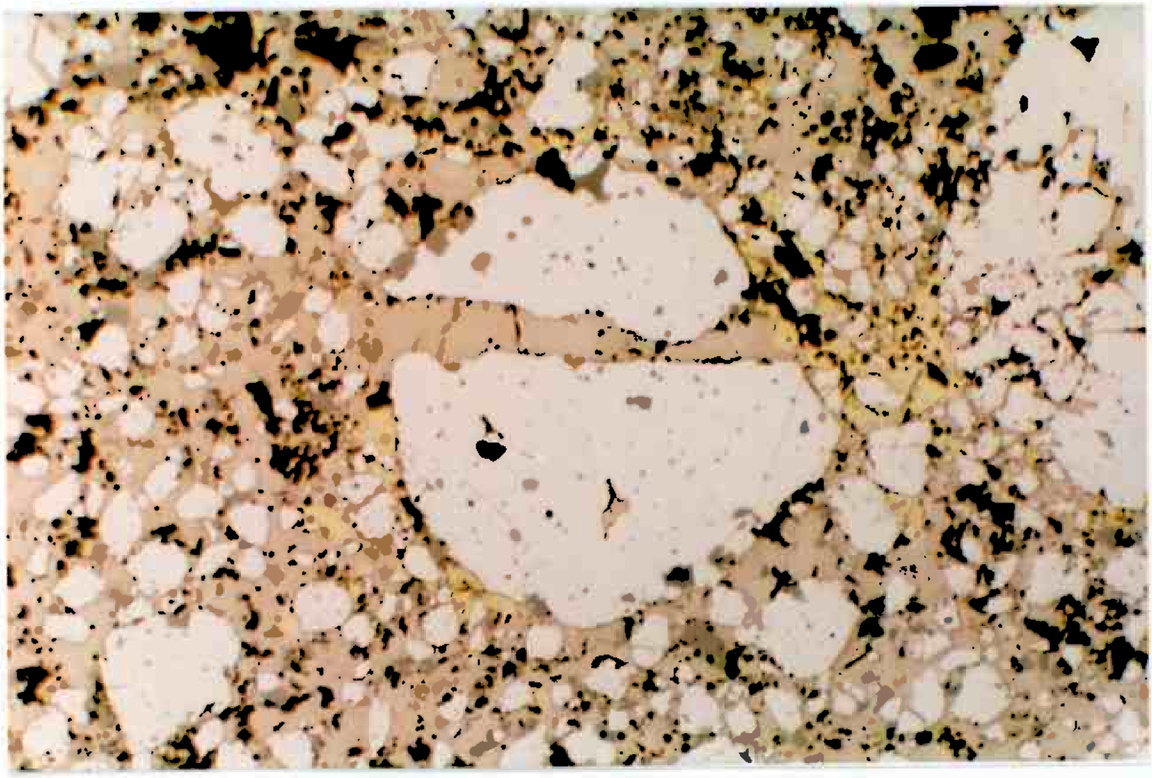


Fig. 4.11 Typical pyrrhotite + pyrite + chalcopyrite ores with more pyrite 4 x 3.2 x 1.25

chalcopyrite (5 - 15 vol.%) with small sphalerite and magnetite (Fig. 4.11), whereas samples GJK90.7 pyrrhotite (50 %), chalcopyrite (about 40 %) and pyrite (about 10 %) (see Fig. 4.12). Because of the larger amounts of pyrrhotite and chalcopyrite in these ores, this type of the ores is typically more yellow to brownish-yellow in color. Pyrite are euhedron to subhedron or rounded, very fine to fine-grained, varying generally between 0.01 to 0.6 mm in size. A good cataclastic texture is, sometimes, associated with pyrite. They generally set in a matrix consisting of irregular, anhedron monoclinic pyrrhotite and chalcopyrite (Fig. 4.11, 4.12). Magnetite are often associated with sphalerite as individual, anhedron crystal or occur as very thin layers dominated by magnetite (less 0.1 mm wide) intercalated with sulphides (Fig. 4.13).

According to sulphide grain size, this type of ores can be separated into two phases, i.e., fine-grained phase (sulphides generally 0.01 mm - 0.1 mm) and coarse-grained phase (sulphides usually 0.1 - 0.6 mm) in size. According to microscope study of limited ore specimen, it may be significant to mention that the coarse-grained phase generally contains more chalcopyrite than the fine-grained phase. It appears that the coarser the sulphides are in size, the higher the chalcopyrite is in content.

Type 3: fine-grained, massive and banded pyrite facies

Representative polished sections include GS1-22, RS2-4, GS2-9-2, GS2-9-3, GS2-9-4, J3Q, and J3N.

This ore type constitutes the most simplest ore facies consisting almost totally of monominerallic pyrite setting in a matrix of quartz, carbonate with a minor chlorite. It immediately lies outside and drapes the massive pyrrhotite-pyrite-chalcopyrite and Cu-rich pyritic ores. It goes towards outside, in places, to be direct contact with greenstone. The pyritic facies are mainly composed of massive, very dense, harder, and compact pyritic ores that grade, in places, into banded pyrite in peripheral parts of the orebody adjacent to the dark greenstone. The massive ores contain sulphides generally over 90 vol.%, whereas the banded ores from 50 - 70 vol.%. The ores are characteristic of yellow color. Metal minerals include pyrite (over 90 percent) with small amount of chalcopyrite, sphalerite, and magnetite. Massive, compact

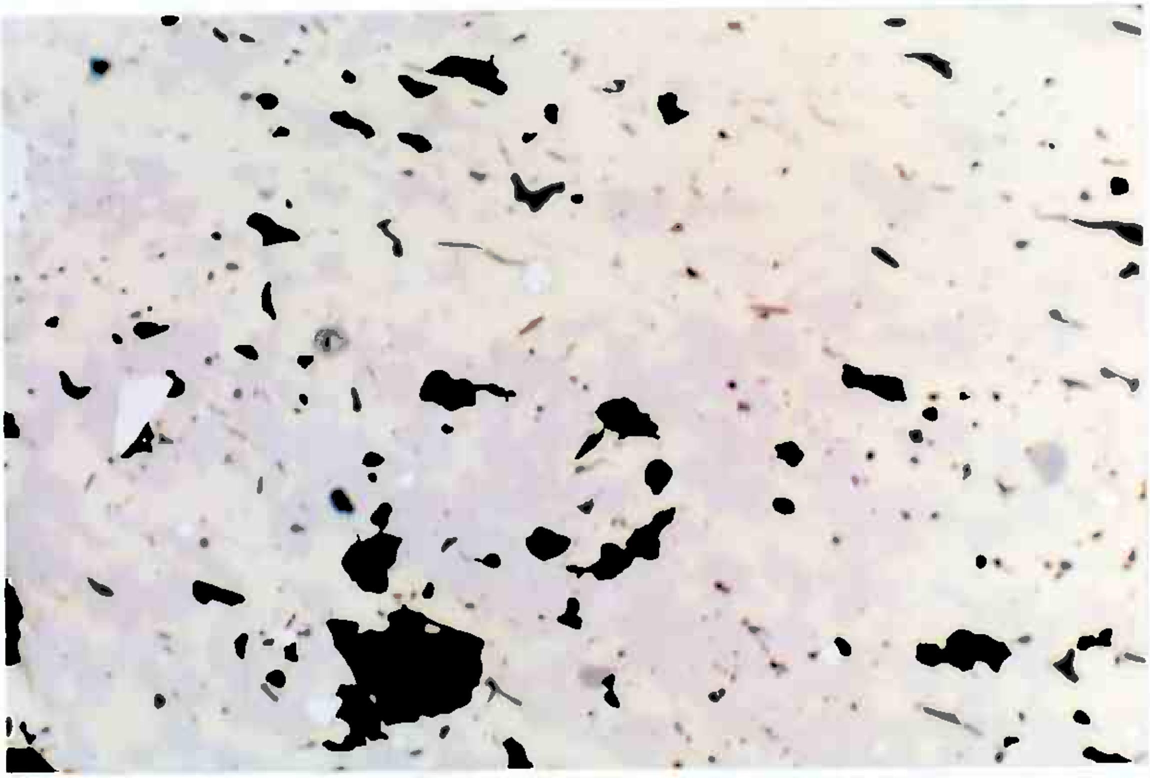


Fig. 4.12 Typical pyrrhotite + pyrite + chalcopyrite ores with a few pyrite 2.5 x 3.2 x 1.25

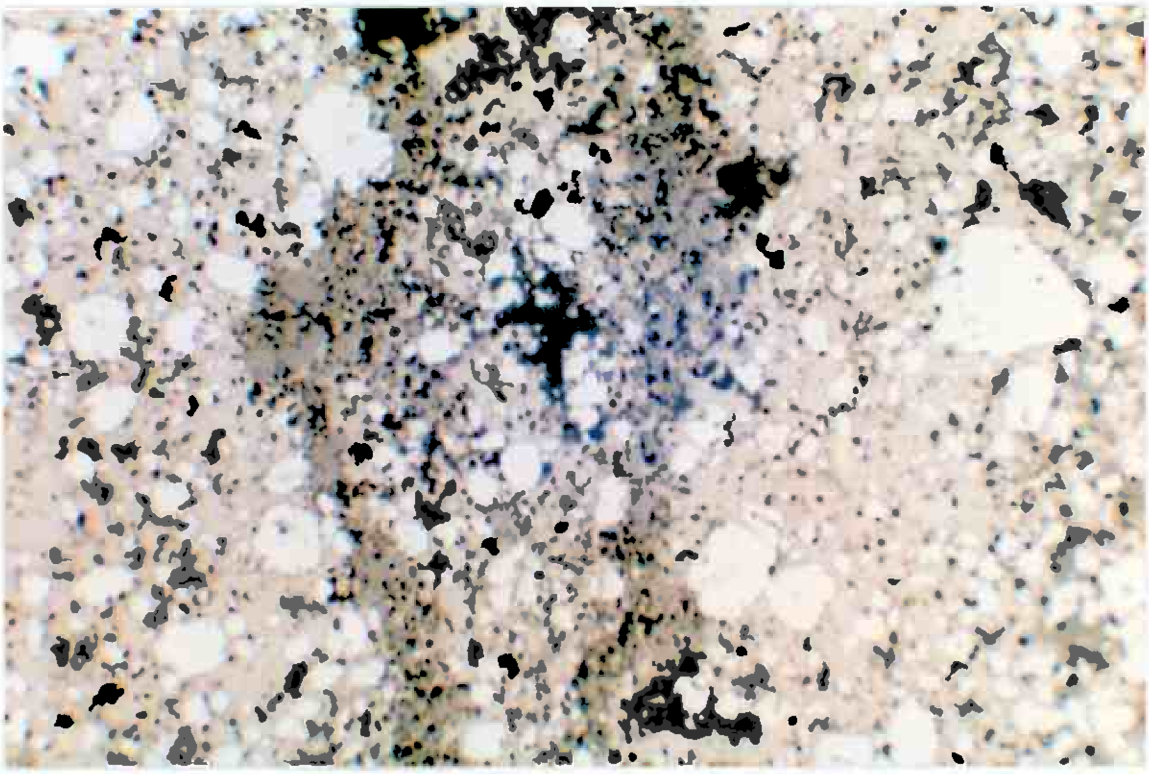


Fig. 4.13 Irregular, thin magnetite band associated with pyrite + chalcopyrite + pyrrhotite ores 2.5 x 3.2 x 1.25

pyrite shows anhedron to subhedron, extremely fine grains. In general, it is not ease to distinguish boundary between pyrite grains under microscope. However, outline of the pyrite grain becomes very clear when dropped HNO3 liquid on surface of the polished section, which shows that pyrite ranges from 0.04 to 0.4 mm in size (Fig. 4.14). Some pyrite are characterized by recrystallization, especially in banded ores, which show euhedron to subhedron, relative coarse grains about 0.1 - 1 mm, even up to 2.5 mm in size. Chalcopyrite and sphalerite are irregular, and often occur or replace along edges and fractures of or as intergranular minerals within pyrite grain.

Type 4: fine-grained, compact, massive pyrite-sphalerite (with magnetite) facies

Representative polished sections are GS1-32, GS1-33, and J3D.2, and polished thin section J3D1.

This facies is characterized by comparative rich sphalerite. Metal minerals are generally over 80 vol.% consisting of pyrite about 70 percent, sphalerite ranging 15 - 25 percent, and magnetite ranging 5 - 15 percent with a trace amount of chalcopyrite (Fig. 4.15). It is only present in local places in where they occur as part of marginal zone or of lateral extent of the massive orebody transitional from the fine-grained massive pyrite to wall-rock greenstone. The sphalerite-rich layers are directly in contact with and underlain by the greenstone. Pyrite is anhedron to subhedron, generally varying from 0.04 to 0.4 mm in size. Sphalerite is very irregular and often associated with pyrite, but it often occurs along edges and fractures of or between pyrite grains. Magnetite is very irregular, fine-grained, generally less 0.1 mm in size. It occurs mainly as thin banded or very small lenses intercalated with sulphides, which sometimes constitutes a good banded structure. Magnetite bands or lenses are generally associated without or with few pyrite. Sometimes, magnetite bands are synchronously folded with host sulphides, which indicates an original structure feature. Gangue minerals consist of quartz and calcite. They are approximately equal in content. Quartz and calcite are all anhedron, generally 0.2 - 0.5 mm in size. They often intergrowth each other and constitute a paragenetic texture. In the banded locality, gangue minerals often occur as thin bands alternated with thin sulphide bands.

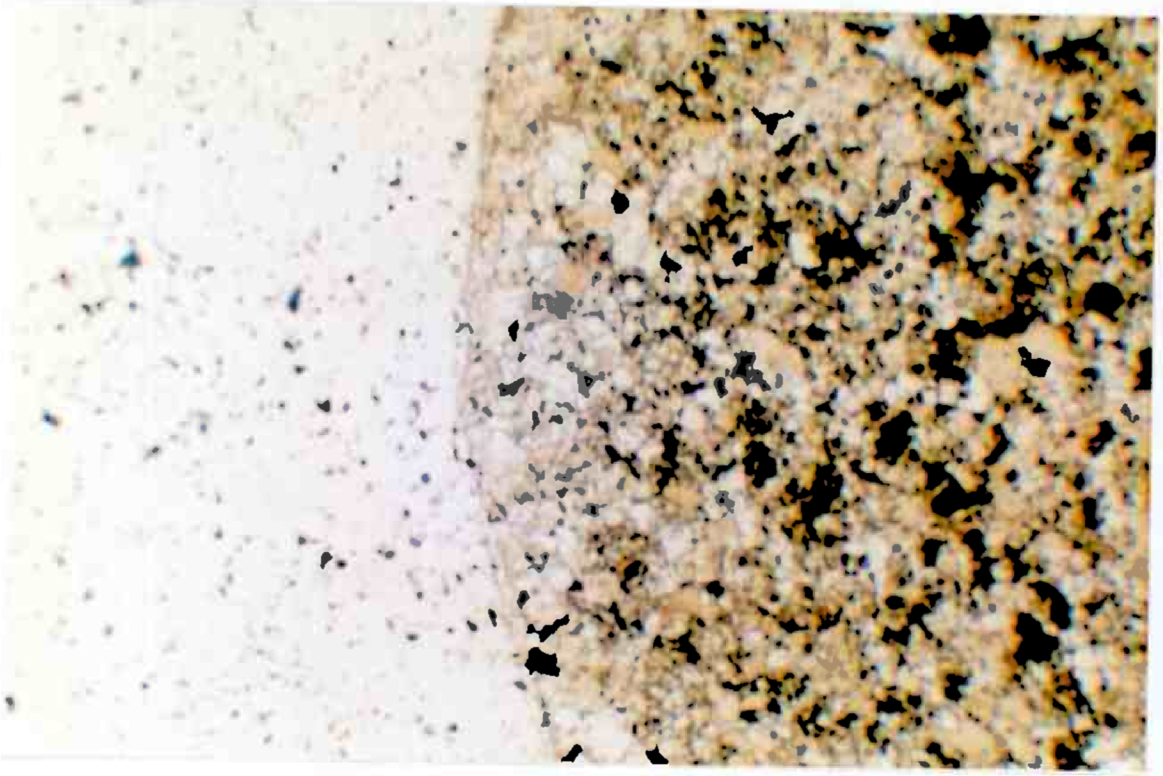


Fig. 4.14 Massive, compact, very fine-grained pyrite ores, a comparison in texture before (white) and after (dark yellow) a HNO_3 drop on it 1.25 x 3.2 x 4

Fig. 4.15 Typical pyrite (white) + sphalerite (grey) ores 6.3 x 3.2 x 1.6

Type 5: fine-grained, massive, banded pyrite-magnetite facies

Representative polished section is RS2-3, and polished thin sections are J3R and GJK90.11.

This facies is also present in local places in where they occur mainly as part of marginal zone or lateral extend of the massive orebody transitional from massive, compact pyritic phase to wall rock greenstone. The ores are characterized by relative rich magnetite. Metal minerals generally range from 50 to 60 percent consisting of pyrite (about 60 - 80 percent) and magnetite (ranging from 20 to 40 percent) with trace amounts of chalcopyrite and sphalerite. Pyrite and magnetite often occur respectively as very thin alternating bands, which are intercalated each other to constitute a banded structure. Pyrite is mainly anhedron, generally 0.1 - 0.7 mm in size, but often characterized by good cataclastic texture. Magnetite is euhedron to anhedron, usually less 0.1 mm in size, sometimes up to 0.5 mm.

Sulphide stringer phase or feeder zone

A stockwork mineralized system consisting of interconnected pyritic quartz-calcite veining with associated extensive wall-rock hydrothermal alterations occurs within and cuts through the metafelsic volcanic complex directly beneath and adjacent to the massive, Cu-rich pyritic facies or fine-grained, compact pyritic ores, which have been interpreted as `feeder zone' or `root zone' of the ores. In the case of the Gjersvik ore body, the ` feeder zone ' within the keratophyric pyroclastic complex is overlain directly on the massive sulphide horizon, in which individual thin sulphide vein, generally several to tens mm wide, often coalesces upwards the massive sulphide horizon into larger mineralized zones about several meters in width, consisting of sulphide veins or channels associated with hydrothermal alterations.

It has been recognized that mineralization in the feeder zone is in some ways related to grade of the hydrothermal alterations. In the case of the Gjersvik deposit, for example, the intense alteration zone consisting mainly of silicification and sericitization is often associated with relative strong mineralization. In this zone, mineralization is largely disseminated, sulphides being in places up to approximate 40 percent. The sulphides are composed mainly of pyrite (

generally over 80 percent) with small amounts of chalcopyrite with trace sphalerite and pyrrhotite. Pyrite is mainly disseminated, anhedron to subhedron, ranging from 0.1 to 1 mm in size. The chalcopyrite and sphalerite occur mainly as replacements along edges of fracture of pyrite gains. Gangue minerals include quartz and sericite with small chlorite. The intermediate alteration zone characterized by silicification, carbonitization and sericitization is associated mainly with veining and veinlet sulphide mineralization. The sulphides range generally from several to about 20 percent and are composed either of dominant pyrite or of approximately equal pyrite and sphalerite. Pyrite is generally 0.1 - 0.4 mm in size and often associated with sphalerite together if the latter occurs. Non-metal minerals consist mainly of quartz, calcite, and albite with minor amount of sericite and chlorite. The weak silicification zone is mainly is only associated with weak pyrite mineralization, pyrite being is usually less 5 percent in content, and non-metal minerals are similar with those in unaltered metafelsic rocks.

4.2.2 Exhalative sediments

Exhalative sediments are simple in mineralogy and consist predominantly of magnetite, quartz and pyrite associated with or without subordinate sericite or muscovite and carbonate, which has been referred to as a special term ` vasskis ' in Norway. The exhalites are thin layered, plate-like and are conformable with their wall rocks. They are characterized by very well laminated structure, consisting predominantly of alternating laminae of pyrite, magnetite and chert, which are often superimposed by later fold structure (Fig. 4.16), and by very fine-grained texture, generally less 0.05 mm in size. The very fine-grained minerals in the exhalites are all anhedron, and often intergrowth each other to form a poikiloblastic texture. According to major mineral assemblages, they can be subdivided into three main subtypes, i.e., pyritic chert, magnetite-rich pyritic chert and chert. The former two types are distributed mainly in the west of the Gjersvik Formation and occur just in junction between dark and pale greenstones or within dark, pillowed greenstone, while the latter is largely associated with pale, pillowed greenstone in the eastern area. The pyritic chert is moderate-grayish and grey-yellowish in color, and consists mainly of quartz and pyrite with/without magnetite and sericite. The magnetite-rich chert are blackish to black grey in color which depends on magnetite and disseminated pyrite contents, and consist mainly of magnetite, quartz and pyrite. The pyrite and magnetite varies greatly in contents, ranging from several to over 40 per cent,

Fig. 4.16 Folded magnetite-rich cherts, collected from the northeast of the Bjørkvatnet about 2000 m (upper) and the western shore of the Limingen Lake (below)

respectively. The chert are generally pale-grayish and grey-pinkish in color, and comprise predominantly quartz plus small hematite, magnetite, pyrite and epidote. Some of them are associated with minor amounts of jaspers. This kind of exhalative horizon was found to be present mainly in the western shore of Limingen Lake and to occur in association with the pale greenstone, either within pale pillowed greenstone or in boundary between the pale, pillowed and schistose greenstones, which indicates an relative oxide ocean floor environment in where this kind of exhalative sediments were deposited.

The exhalative sediments have been interpreted as a setting of colloidal iron and silica hydrosol following explosive dispersal into the submarine environment related mainly either to a volcanic episode of the keratophyrical pyroclastic eruption occurring between basic magmatic activities of dark and pale greenstones or to pillowed tholeiitic basalts during construction of the Gjersvik volcanic arc. For example, the stockwork magnetite have in places been found to represent within the keratophyric pyroclastic complexes (Fig. 4.17), which are considered to be a root of the exhalative sedimentary magnetite. However, the exhalative sediments which are associated with the pale greenstone are probably related to the late magmatic activity of tholeiitic composition.

4.2.3 Vein mineralization in the underlying dark greenstone

The vein mineralization within the underlying dark greenstone are mainly veining, stockwork and linear-type disseminated in structures, and consist mainly of pyrite with varying amounts of chalcopyrite and sphalerite plus small magnetite. Sulphides within the mineralization zones generally varies from 20 to 30 percent in contents. According to main metal mineral assemblages, three types of mineralization can be separated: (1) pyrite, consisting of pyrite together with\without trace chalcopyrite and sphalerite; (2) pyrite-chalcopyrite, consisting mainly of pyrite (70 percent) and chalcopyrite (10 - 30 %) with small amounts of sphalerite; (3) pyrite-sphalerite, consisting largely of pyrite (80 - 60 %) and sphalerite (20 - 40 %) together with\without trace chalcopyrite. Pyrite is anhedron to euhedron, generally 0.1 - 0.5 mm, some recrystallized up to 1 - 1.5 mm in size. It appears that pyrite is often closely associated with altered chlorite. Chalcopyrite and sphalerite are irregular, and occur mainly along edge of pyrite or between pyrite grains. Magnetite is

Fig. 4.17 Stockwork magnetite within the keratophyric pyroclastic complex, in the southern shore of the Bjørkvatnet Lake

euhedron but extremely fine-grained, usually less 0.05 mm in size. It is often associated with greenstone adjacent to hydrothermal alteration zones. It is significant to mention that the metal mineral assemblages and hydrothermal alterations in the vein mineralization are very similar and comparative with those in the feeder zone.

4.3 Hydrothermal wall-rock alterations

4.3.1 Regional metamorphism and its relation to hydrothermal alterations

Mineralogical and textural evidence indicates that the rocks occurring the Gjersvik volcanic arc all have suffered regional low-grade metamorphism up to greenschist phase. Thus, it is necessary to justify relationship between regional metamorphism and hydrothermal wall-rock alterations. Due to the fact that the massive sulphide deposits are often associated with felsic volcanic complex containing a feeder zone characterized both by intense hydrothermal alterations and by veining, veinlet and disseminated sulphide mineralization, relationship between the hydrothermal alterations and the regional metamorphism can be evaluated through comparison of the altered, mineralized felsic pyroclastic complexes with regional unaltered felsic complexes away from the ore bodies.

The mineral assemblages of the regional low-grade metamorphic rocks in the Gjersvik volcanic arc contain mainly chlorite, epidote, plagioclase (albite and oligoclase), and less sericite, muscovite, biotite, and stilpnomelane. The contents and proportion of the metamorphic minerals depend on the types and the bulk compositions of the rocks. The regional unaltered felsic volcanic complexes consist mainly of albite or oligoclase, quartz with small amounts of sericite, muscovite, biotite, and chlorite, occasionally in places with few amounts of epidote and stilpnomelane. In contrast to this, the felsic complexes associated with alterations and mineralization contain much more hydrothermal altered minerals such as sericite, quartz, chlorite and carbonate, but less albite in content. Even more, the intense altered felsic complexes are almostly composed of sericite and quartz, while the weak altered felsic complexes mainly of quartz and subordernate albite with small amounts of sericite, muscovite, carbonate, chlorite, occasionally with few of epidote. Thus, sericite (muscovite) - quartz - chlorite assemblage become essential mineral assemblage in the altered felsic complexes although they

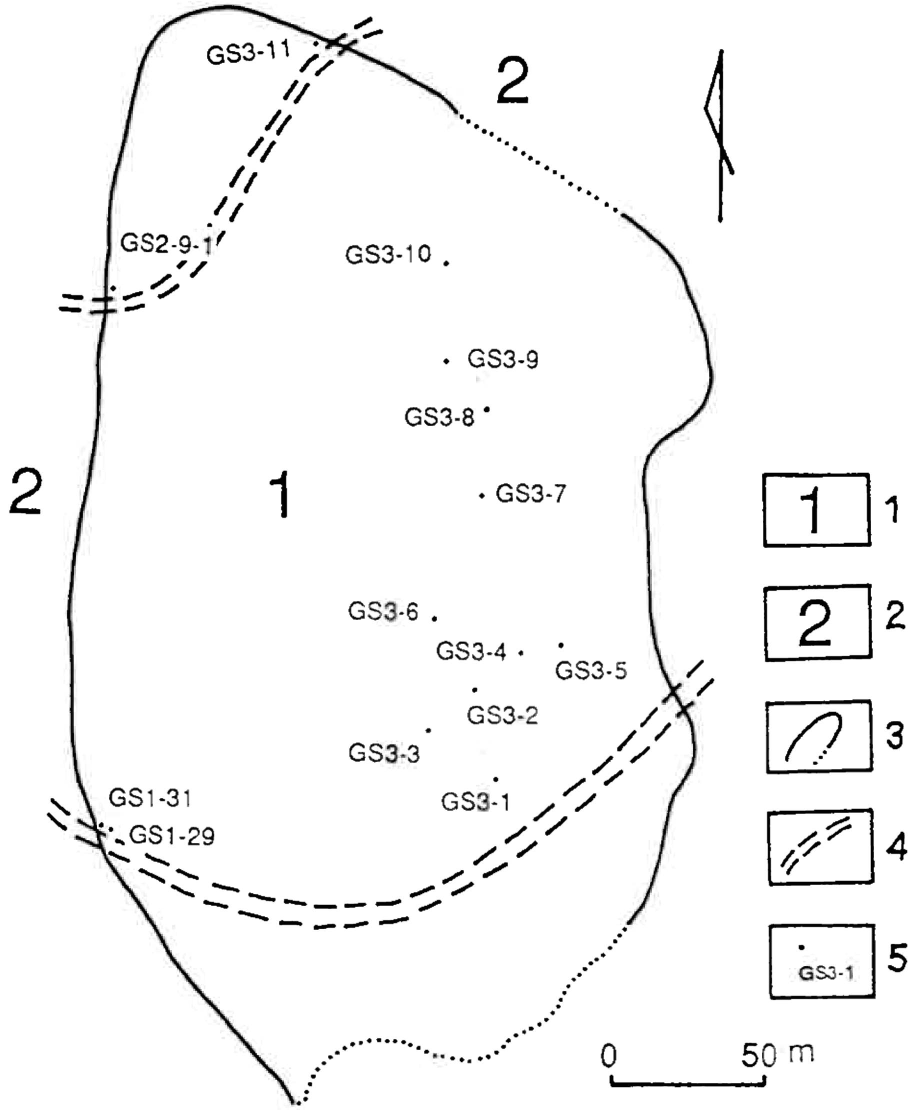


Fig. 4.18 Sketch geological map of the Gjersvik felsic body and positions of the collected alteration samples

1 - keratophyric pyroclastic complex; 2 - dark greenstone; 3 - massive sulphide horizon; 4 - roads; 5 - positions collected the samples and their numbering

do represent widespreadly in the unaltered felsic complexes as subordinate mineral components resulted from regional metamorphism.

Another important distinction between altered and unaltered felsic volcanic complexes is of difference in their textures. The unaltered felsic volcanic complexes often remain some typical volcanic textures such as obvious porphyritic and clastic textures, whereas the altered felsic volcanic complexes are characterized by obviously hydrothermal metasomatic textures, but associated poorly with (in the weak hydrothermal altered rocks) or without (in the intense hydrothermal altered rocks) typical volcanic textures. Thus, the hydrothermal alterations have been interpreted as a main result produced by hydrothermal replacement before the regional metamorphism. Due to the fact that the regional metamorphism is so low in grade that they have been considered as being isochemical, there are no enough evidences to demonstrate that the altered felsic pyroclastic complexes have been, to a great extent, affected by the regional metamorphism in their chemical compositions and mineral assemblages although they were indeed superimposed by the retrogressive regional low-grade metamorphism.

4.3.2 Sample collections

Owing to the fact that the Gjersvik ore body has so far been known to be still the biggest one in the Gjersvik area, the Gjersvik altered felsic pyroclastic complex has been selected as a typical example of systematic study in the hydrothermal alterations to be described below. This result is probably applied in comparison to other mineralization that are similar with the Gjersvik deposit.

A series of samples were systematically collected from surface exposures along section across the Gjersvik felsic pyroclastic complex from the south near shore of the Limingen Lake (at new road) to the north end both of the northern massive sulphide horizon and the northern boundary of the Gjersvik felsic complex (at old road), and from outcrops of the altered felsic rocks overlain directly on the western flank of the Gjersvik massive sulphide horizon along road sections (new road in the south and old road in the north), which the latter are characterized by obvious veining and stockwork sulphide mineralization (Fig. 4.18). All samples were examined and described under microscope. According to assemblages and contents of the altered minerals in the samples, they are classified into three groups, i.e., weal altered group representative of samples (GS3-1, GS3-2, GS3-3, GS3-4, GS3-5, and GS3-6),intermediate altered group of samples (GS1-29, GS1-31, and GS2-9-1), and intense altered group of samples (GS3-7, GS3-8, GS3-9, GS3-10, and GS3-11). The intense hydrothermal alteration samples have been subdivided into two group, i.e. slight (GS3-7, and GS3-8) and strong mineralization (GS3-9, GS3-10, and GS3-11). Some of them, for example, GS3-3 and GS3-6 as weak altered, GS1-29, GS1-31 and GS2-9-1 as intermediate altered, and GS3-7, GS3-9 and GS3-11 as intense altered representatives, were selected respectively to make chemical analysis.

All chemical compositions of the samples were analysized by I. Romme with PHILLIPS PW1480 X-Ray Spectrometer in Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology, Norway.

4.3.3 Alteration mineralogy and zoning

The Gjersvik orebody is directly associated with an altered felsic pyroclastic complex characterized by extensive hydrothermal alterations plus obvious stockwork and dense disseminated sulphide mineralization, which has been interpreted as the feeder zone, and is underlain by the dark, unaltered greenstone. Succession of the Gjersvik deposit, i.e., hanging wall altered felsic complex, via massive sulphide horizon to foot wall dark greenstone, has generally been interpreted to be reversed.

Several types of hydrothermal alterations can be distinguished within the felsic pyroclastic complex such as silicification, sericitization, carbonitization, in places, chloritization and albitization (?). Based on main altered mineral assemblages and their spatial distribution, three alteration zones can be subdivided: weak, intermediate and intense alteration zones. The weak alteration zone is generally away from the massive sulphide horizon, whereas intermediate and intense alteration zone occur usually in direct or near the massive sulphide body. Distribution of the hydrothermal alteration zones appears to indicate a trend that alteration grades gradually increase towards the massive sulphide horizon. The weak alteration zone directly grades into intermediate or into intense alteration zones. The weak alteration zone is characteristic of less differences from the unaltered metafelsic pyroclastic rocks in mineralogy, whereas the intense alteration zone almostly consists of altered minerals. The unaltered rocks as a comparable standard were taken from an average value of regional metafelsic volcanic complexes without associated massive sulphide bodies. It must be emphasized, however, that they may not be completely fresh, strictly speaking, since the most felsic complexes at the Gjersvik area contain more ore less stockwork or disseminated pyrite (generally less 2 %), which is undoubtedly of hydrothermal origin.

The weak alteration zone is generally associated with slight mineralization, the intermediated alteration zone often with obvious veining, veinlet and stockwork mineralization, whereas the intense alteration zone with either slight or strong disseminated mineralization. Different alteration zones are often distinct in altered and sulphide mineral assemblages (Table 4.1). More detailing descriptions will be given below.

weak alteration zone (or silicification zone):

The zone comprises the felsic pyroclastic complex with weak silicification and grades to intermediate or intense alteration zone, but generally doesn't contacts directly with the massive sulphide body. The altered rocks only have few differences in mineral assemblages and texture relative to regional metafelsic rocks that have been considered as the unaltered metafelsic rocks. They are composed predominantly of quartz and plagioclase (albite and oligoclase) with small amounts of chlorite, sericite, muscovite, epidote, calcite and pyrite, and are characterized by typical porphyritic texture consisting mainly of euhedron plagioclase with a few amounts of anhedron, rounded, and corroded quartz setting in the matrix. An only difference, however, is perhaps that the weak altered rocks contain more quartz but less albite than the unaltered felsic pyroclastic rocks. These quartz occur mainly as veinlet and fine-grained, allotriomorphic, and very irregular aggregates that are apparently of hydrothermal origin. The weak alteration zone is generally associated with slight mineralization consisting predominantly of disseminated pyrite about 3 - 5 percent in content.

intermediate alteration zone (or silicification-sericitization-carbonitization zone):

Table 4.1 A comparison in mineral assemblages of unaltered and altered metafelsic pyroclastic complexes

main altered and metal mineral assemblage	unaltered meta-felsic rocks	weak altered metafelsic rocks	intermediate altered meta-felsic rocks	intense altered metafelsic rocks	
				weal sulphide mineralization	strong sulphide mineralization
		GS3-1, GS3-3, GS3-4, GS3-5, GS3-6	GS1-29, GS1-34, GS2-9-1	GS3-7, GS3-8	GS3-9, GS3-10, GS3-11
quartz	++++++	++++++	++++++	++++++	++++++
albite or oligoclase	++++++	******	======	------	------
sericite	------	======	******	++++++	++++++
muscovite	------	------	------	------	------
chlorite	======	======	******	******	******
epidote			------		------
calcite	------	------	******	======	======
garnet				------	
pyrite	------	------	******	======	******
sphalerite			======		------
chalecopyrite			======	------	======

+++ major; *** subordernate major; === small; --- trace

This alteration zone associated with obvious veining, veinlet and stockwork sulphide mineralization is usually in contact directly with the massive sulphide body, which has been proposed as ` feeder zone ' (Fig. 4.18). The hydrothermal alteration minerals abruptly increase in this zone, sometimes, being up to 80 percent in their contents and no porphyritic texture occurs, that is, relics of plagioclase phenocrysts that are very typical and extensively present within the unaltered or weak altered felsic rocks are absent in this zone (Fig. 4.19). Furthermore, it is sole among these three alteration zones that this zone is associated with immense altered calcite. The zone consists mainly of quartz and subordinately of carbonate (calcite), sericite and albite with small amounts of muscovite, chlorite and epidote. The quartz is very fine-grained and anhedron, and occurs either as a gangue mineral of the vein and veinlet or as irregular aggregate. The calcite present mainly as gangue mineral in the mineralized vein and veinlet that is obviously of hydrothermal origin. The plagioclase (albite or oligoclase) is too small in size to be not recognized under microscope. It is very difficult to say that the albite is related to hydrothermal precesses or as a remnant of unaltered metafelsic rocks.

The veining, veinlet and stockwork sulphide mineralization in this zone are very thin, generally varying from less 1 mm to 5 mm, and consist predominantly of pyrite with minor amounts of chalcopyrite and sphalerite plus non-metal minerals such as quartz and calcite with a small amount of chlorite. The mineralized sulphides vary in this zone, ranging generally from 4 to 10 percent in contents.

Intense alteration zone (or silicification - sericitization zone):

In this zone, the rocks are almost entirely composed of altered minerals consisting of quartz and sericite together with small chlorite, carbonate and muscovite as well as varying sulphides. A few garnet occurs in places. The albite are completely destroyed in this zone. The hydrothermal quartz and sericite are generally over 80 percent and they are both approximately equal in contents (Fig. 4.20). The quartz and sericite are very fine-grained or scaly, very anhedron, and occur mainly as individual or irregular aggregates. The muscovite is only associated with sericite in occurrence, the carbonate occurs as individual and aggregate or in veining and veinlets. The chlorite is similar with those occurring within unaltered felsic

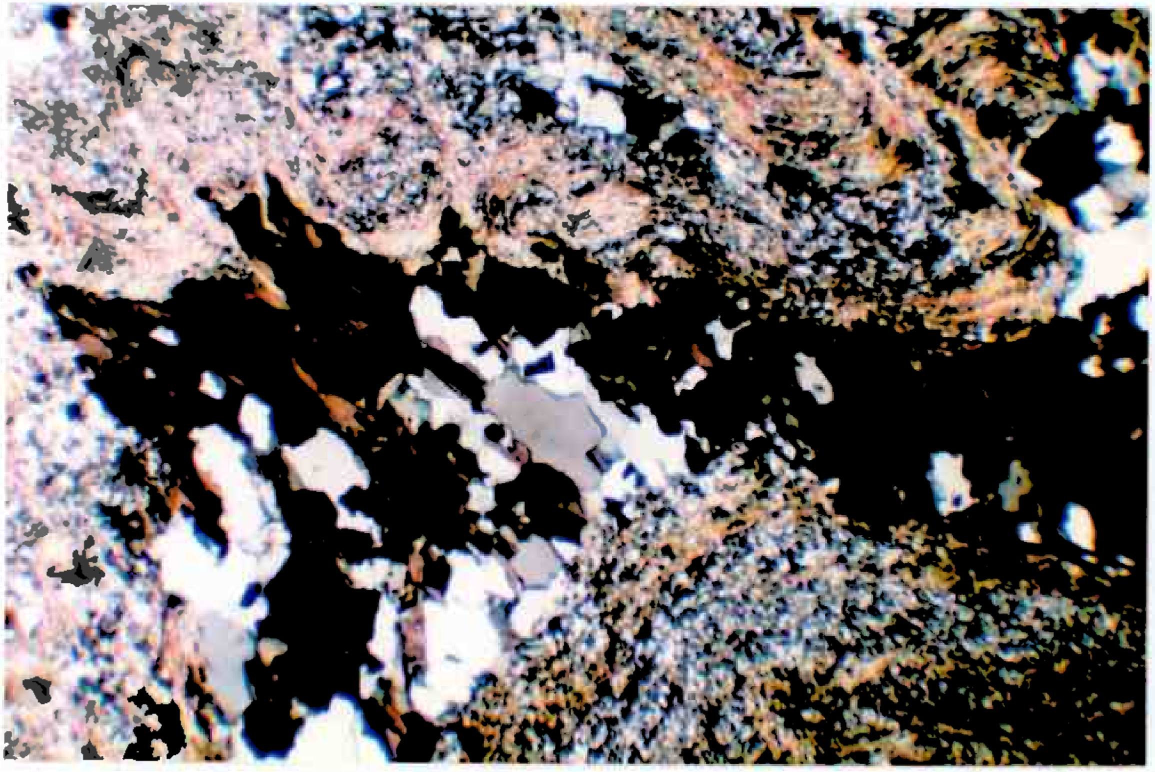


Fig. 4.19 Alterations (silicification, sericitization, carbonitization ?) and veining pyritic mineralization in the feeder zone from the Gjersvik deposit 2.5 x 3.2 x 1.25 " + "

Fig. 4.20 Intense alterations (sericitization and silicification) and pyritic mineralization 2.5 x 3.2 x 1.25 " + "

rocks, which appears to show a product of regional low-grade matemorphism.

This alteration zone is often associated with disseminated sulphide mineralization but the mineralization grade is various. Based on content of the sulphides, two subtypes can be comparatively subdivided: weak mineralization, which lies on the place transitional from the weak or the intermediate alteration zone towards to the strong mineralization, and intense mineralization zone. Mineralization in the weak mineralized zone consists mainly of disseminated pyrite about 4 - 6 percent in content, whereas in the intense mineralized zone are composed predominantly of disseminated or dense disseminated pyrite with a small amount of chalcopyrite, vatying between 20 - 50 percent.

In addition, some other samples of the altered felsic rocks were taken from other places on the exposures in where occur small massive sulphide bodies associated with felsic rocks, for instance, on surface exposures in the Gjersviklumpen area, and near the northern shore of the Bjorkvatnet along the Gjersvik-Royrvik road section. They are white to light grey in color, very hard, fine-grained, and are associated with disseminated pyrite on the outcrop. However, they appear to be similar with the rocks of the weak alteration zone, i.e. they are characteristic of weak silicification and still remain typical porphyritic texture, being consistent with unaltered metafelsic rocks. The mineralization associated with these weak altered felsic rocks is mainly disseminated pyrite, usually up to 5 percent in content.

4.3.4 Relative chemical variations of the alteration zones

Some typical samples selected from the different alteration zones were used to make chemical analysis of major and trace elements after they were first carefully examined under microscope. In comparison with unaltered metafelsic volcanic rocks, chemical data indicate that the major elements such as FeO, MgO, CaO, K2O, and Na2O were in great extent mobile to each other in different alteration zones if the constant volume is assumed. It is obvious that changes of bulk chemical composition of the altered rocks mainly result from hydrothermal alteration processes. Trends of major element behaviors and their contents in the different alteration zones are shown respectively in Fig. 4.21 and Table 4.2. In comparison with the unaltered felsic rocks, SiO2 increases in weak alteration zone and in intense alteration associated with slight

Table 4.2

Major (wt.%) and Trace (ppm) Element Chemistry of The Altered Felsic Volcanic Rocks

	1	2	3	4	5	6	7	8	9
	av.(8)	GS3-3	GS3-6	GS2-9-1	GS1-29	GS1-31	GS3-7	GS3-9	GS3-11
SiO_2	73.29	73.14	78.61	65.05	78.08	65.22	74.54	57.16	51.39
TiO_2	0.31	0.38	0.21	0.33	0.19	0.31	0.30	0.47	0.19
Al_2O_3	12.66	11.37	9.65	14.61	9.35	13.36	12.62	15.31	7.51
*FeO	5.03	6.89	5.05	6.31	3.40	10.52	3.44	15.23	24.61
MgO	0.71	2.31	1.34	1.63	0.03	2.78	2.90	0.11	0.44
CaO	0.78	0.06	0.70	2.09	2.68	0.95	0.12	0.02	0.02
Na_2O	5.90	3.80	3.48	6.31	5.09	4.88	2.11	1.22	0.41
K_2O	0.36	0.29	0.21	0.92	0.27	0.63	1.12	2.71	1.49
MnO	0.07	0.06	0.11	0.13	0.28	0.16	0.98	0.03	0.03
P_2O_5	0.04	0.04	0.03	0.05	0.04	0.05	0.05	0.03	0.02
Loss	0.81	2.10	1.11	1.96	0.81	3.02	2.81	8.69	12.84
SUM	99.96	100.44	100.50	99.39	100.22	101.88	100.99	100.98	98.95
Zr	121	109	98	110	77	96	122	121	61
Nb	14	10	16	17	17	22	23	24	21
Y	59	67	48	66	31	57	88	74	23
Sr	90	80	89	110	83	52	94	85	23
Rb	3	<1	<1	11	0	4	12	26	14
Ba	63	<10	<10	476	<10	31	605	657	334
V	33	51	38	18	17	107	7	31	18
Ni	7	5	11	2	6	4	3	3	1
Co	5	5	8	2	3	6	1	5	13
Cr	63	38	73	38	45	29	54	73	75
Pb	5	3	2	1464	72	27	12	48	<1
Zn	62	77	54	7154	189	502	113	1271	413
Cu	17	56	205	36	13	462	1	172	873

1 unaltered rocks (an average of 8 samples); 2 - 3 weak altered rocks; 4 6 intermediate altered rocks associated with obvious veining mineralization; 7 intense altered rock associated with weak mineralization; 8 - 9 intense altered rocks associated with intense dense disseminated mineralization

All elements analyzed by Ivar Romme with PHILIOPS PW1480 X-Ray Spectrometer, Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology, 1991 mineralization, but seems to decrease in intermediate alteration zone and in intense alteration zone with strong mineralization. Al2O3 trends to decrease obviously in weak alteration, but appears to be approximately consistent in intermediate and intense alteration zones. FeO has a roughly equal content in unaltered, weak and intermediate alteration zones, but decrease or increase very sharply within intense alteration zone. MgO increases in different extent in weak, intermediate and intense alteration zones, but decreases in the intense alteration zone associated with strong mineralization. CaO decreases gradually in weak and intense alterations but increases suddenly in intermediate alteration zone, which results from immense occurrence of the hydrothermal calcite in this alteration zone. Na2O decreases rapidly in weak and intense alteration zones but has less decrease in intermediate alteration zone. K2O decreases slightly in weak alteration zone, but increases distinctly from intermediate to intense alteration zones (Fig. 4.21).

The bulk chemical changes are parallel and comparative to those of mineralogy in different alteration zones (Table 4.1), strictly speaking, the chemical changes result from variation of mineral assemblages and their relative contents in the different alteration zones. According to knowledge of the mineral chemical compositions, Mg and Fe are major components of the chlorite, while Na and a small amount of Ca can be considered as main components of plagioclase. In addition, Fe is also major element of pyrite, whereas Ca constitutes an essential component of the calcite. Similarly, K and Al may be considered to be joined mainly in sericite, micas and feldspars. Si is always present in excess as quartz.

In weak alteration zone, silicification is a major type of hydrothermal alterations, and quartz content increases but albite content decreases in comparison with unaltered felsic rocks (Table 4.1). Chemically, this reflects in SiO2 increase, while Al2O3, Na2O and CaO decreases (Fig. 21). Similarly, MgO increase results from chlorite growth in this zone. In intermediate alteration zone, hydrothermal alterations are largely silicification, sericitization and carbonatization with scanty albitization, which consist of quartz, albite, sericite and calcite assemblages. This leads CaO abrupt increase relative of all other alteration zones and unaltered rocks, K2O greatly increases, Na2O increases, whereas Al2O3 and SiO2 slight decreases relative to unaltered rocks. The intense alteration zones consist predominantly of distinctive silicification and sericitization. Chemically, it apparently reflects in K2O immense increase but

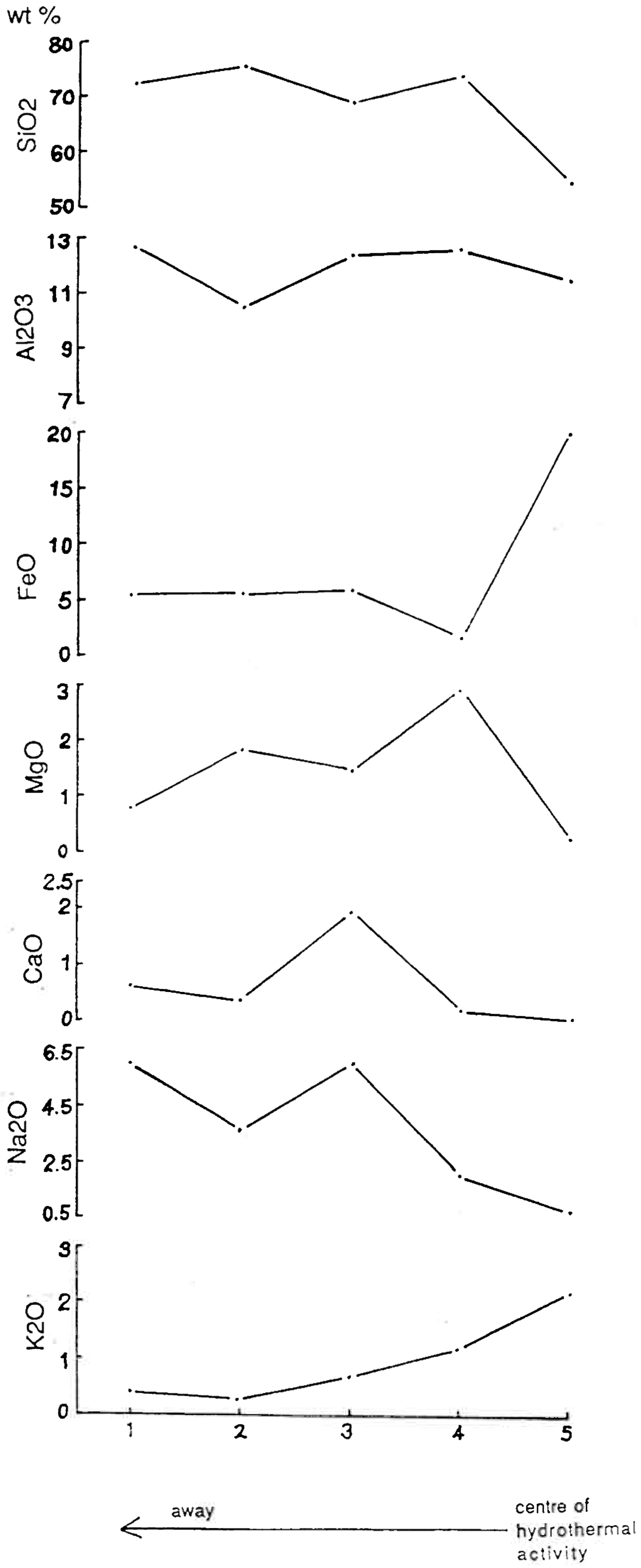


Fig. 4.21 Variation trends of major elements in different alteration zones within the Gjersvik keratophyric pyroclastic complex

1 - unaltered pyroclastic rocks;2 - weak altered zone; 3 - moderatealtered zone associated with obvious veining and veinlet mineralization; 4 - intense altered zone with weak mineralization; 5 - intense altered zone with strong mineralization

Na2O obvious decrease. When the strong mineralization is associated with this alteration zone, FeO abruptly increases, but in slight mineralization zone, FeO relatively decreases, which apparently reflects in variations of the pyrite contents.

Thus, it can probably conclude that K2O continuous, great increase is consistent with rapid sericite growth, while Na2O decrease is related to albite successive decomposition from weak, via intermediated to intense alteration zones. In general, CaO should gradually decreases with decomposition of the plagioclase from weak to intense alteration zones, but it abruptly increases in the intermediate alteration zone. This change is consistent with immense addition of the calcite in this zone comparative of other alteration zones and unaltered rocks. Similar, MgO trend in different alteration zones is approximately consistent with variation of the chlorite, whereas SiO2 and Al2O3 behaviors depend mainly on variations of quartz, albite and sericite each other in different alteration zones.

Trend of the gained or lost cations during the hydrothermal alteration process is shown based on isovolume change (Fig. 4.22). In comparison with unaltered rocks, Si and Al appear to be relatively immobile during hydrothermal alteration process although they are rather gained or lost, to a certain extent, in different alteration zones. Fe has no much change in each alteration zone but becomes very apparently additional component only in intense alteration zone associated with strong mineralization. However, K, Na, Ca, and Mg are very mobile during the hydrothermal alteration process, and trend seems to show that the stronger the hydrothermal alterations are, the more mobile they are. During the hydrothermal alteration processes, Na is a mostly principal lost component, which loses about 40 % in weak alteration zone, 10 % in intermediate alteration zone, and up to 65 - 85 % in intense alteration zones, whereas K is a mostly principal gained component that rapidly increases in intermediate alteration zone about 40 % and up to 170 % and 450 % in intense alteration zones associated with weak and strong mineralization, respectively, although it decreases about 40 % in weak alteration zone relative to unaltered rocks. Changes of Na, K compositions are consistent with bit-by-bit albite decomposition and step-by-step sericite addition from weak, via intermediate to intense alteration zones. Similarly, Ca displays an exceptional trend that it loses about 40 % and 83 - 97 % in weak and intense alteration zones, respectively, but extraordinarily increases up to 200 % in intermediate alteration zone, which was most probably caused by

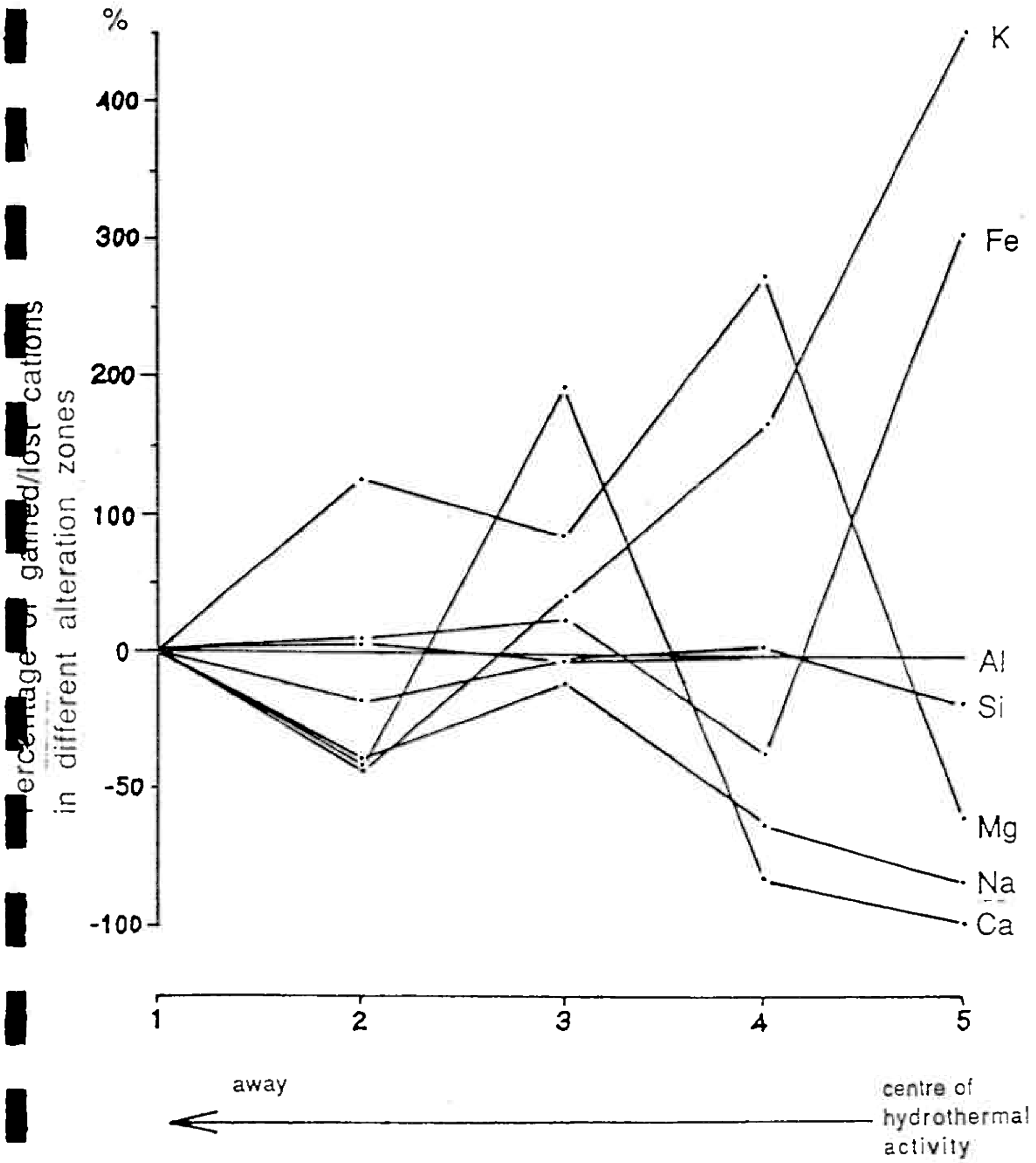


Fig. 4.22 Trends and percentages of gained\lost cations in different alteration zones within the Gjersvik keratophyric pyroclastic complex

1 - unaltered pyroclastic rocks; 2 weak altered zone; 3 - moderate altered zone associated with obvious veining and veinlet mineralization; 4 - intense altered zone with weak mineralization; 5 - intense altered zone with strong mineralization

calcite vast growth in intermediate alteration zone relative of other alteration zones and unaltered rocks. Mg is a largely grained component in weak and intermediate alteration zones, but is grained or lost in great extent in intense alteration zone, which mainly reflects chlorite variation in different alteration zones. Fe has less additions in weak and intermediate alteration zones, but abruptly increases in intense alteration zone associated with strong mineralization up to 300 % comparative of unaltered rocks, which is obviously caused by immense precipitation of pyrite in this zone. Al also displays a lost trend in weak and intermediate alteration zones, but has no much change in intense alteration zones relative of unaltered rocks. Si is only a slight gained or lost component in every alteration zone but seems to be lost greatly in intense alteration zone associated with strong mineralization. The reason causing Si relative decrease is due to Fe immense addition in this zone.

4.3.5 Alterations associated with the vein mineralization

The vein sulphide mineralization within the dark greenstone are usually associated with obvious hydrothermal alterations consisting mainly of silicification, chloritization plus varying, in places, carbonitization, sericitization and albitization. The altered minerals vary from 30 up to 90 percent in content. The hydrothermal alterations are generally non-homogenous and linear-type, and are controlled by fissures and fractures in occurrence. It is obvious that the vein mineralization and associating hydrothermal alterations represent a mark of mineralized solution flow through the tholeiitic basalt. The altered mineral assemblages are largely quartz - chlorite, quartz - calcite, chlorite - sericite, quartz - sericite - chlorite and quartz - calcite - chlorite. The altered quartz occur mainly as thin vein, very small lenses or irregular aggregate. It is mainly very anhedron, fine-grained generally less 0.05 mm in size, and often associated with other altered minerals such as chlorite, calcite and sericite. Sericite results mainly from rock-forming chlorite decomposition since it is often associated with the chlorite. Sericitization is generally not strong, and occurs mainly within the greenstone near quartz and carbonate veins. However, sericitization is, in places, so strong that the dark greenstone is almost replaced by sericite and quartz with minor amounts of chlorite such as at about 319.73 m level in the drilling core Bh4. Altered chlorite is mainly clinochlorite, and is different from rock-forming chlorite in crystalline behavior that it is generally twice to four times as big as rock-forming chlorite in crystal size. Calcite is non-homogenous, ranging from trace to about 40 percent in content of altered minerals, and often associated with quartz in occurrence.

More importantly, this kind of vein mineralization occurring within the dark greenstone is similar in alteration types and sulphide mineral assemblages with the feeder zone occurring in the felsic pyroclastic complexes directly below the massive sulphide mineralization. The only difference between them is that chloritization associated with the veining mineralization in the greenstone is obviously stronger more than that with the felsic complexes. This relationship points out that the hydrothermal convective system related to volcanogenic exhalative processes in ocean floor environment must be covered in a wide scope, but was not only limited within the felsic volcanic complexes.

4.3.6 Relationship of hydrothermal alteration in the Gjersvik deposits to those in other volcanogenic massive sulphide deposits

Two distinct groups of hydrothermal alterations associated with the two compositional groups of volcanogenic massive sulphide deposits have been summarized on the basis of the mineralogical characteristics and distribution of alterations by Franklin et. al., (1981): alterations associated with Cu-Zn deposits and with Zn-Pb-Cu deposits, respectively.

The alterations associated with Cu-Zn deposits occur often as the alteration pipes under Cu-Zn deposits, which is characterized by (1) well-defined, in some cases vertically extensive (1,000 m or more); by (2) an Mg-rich chlorite or talc-rich core surrounded by a sericite +/- quartz-rich halo; this zonation occurs on both the scale of an individual vein and through the entire pipe; and by (3) pervasive Na2O and CaO depletion, some K2O addition, and minor addition of SiO2; the central Mg-rich core is depleted in SiO2, whereas the outer sericite zone may be enriched in SiO2 such as the Millenbach Cu-Zn Mine, Noranda, Quebec, (Riverin and Hodgson, 1980). However, the alteration associated with the Zn-Pb-Cu deposits, as typified by the Kuroko and Tasmanian deposits, has a few different characteristics: (1) pipes are not as vertically extensive although they are mineralogically well defined, and (2) the zonation is essentially opposite to that in the Cu-Zn group, with a sericite-quartz core surrounded by an Mg-enriched chlorite halo.

The hydrothermal alteration in the Gjersvik deposit is in some extent closely similar with the second alteration group described above. From the view of ore composition, however, the Gjersvik deposit consists mainly of copper and zinc associated without\with only very few lead. Within the Gjersvik felsic complex, alterations are generally distributed in a central zone consisting most entirely of quartz and sericite, surrounded by a zone of sericite and quartz plus abundant carbonate, and finally enveloped in a weakly altered zone of dominantly silicification. Mg-enriched chlorite tends to increase within each alteration zone relative to unaltered felsic rocks, but is uneven in occurrence.

4.4 Zonation of the deposit and chemistry of the ores

4.4.1 Zonation of the deposit

Zonation of the ore facies and of the hydrothermal alterations does exist in the massive ore horizon and in the feeder zone, respectively. An ideal model of original zoning of the Gjersvik deposit has been proposed (Fig. 4.9). The model shows clearly that the massive sulphide horizon is directly overlain on a stringer zone characterized by intense hydrothermal alteration and mineralization, which constitutes a path leading mineralized fluid movement. These zonations are mostly probably present a primary variation determined by mineralized fluid compositions and physico-chemical conditions during ore-forming processes in ocean-floor basin environment.

Within the metafelsic complex, three hydrothermal alteration zones which each is associated with essential mineralization type have been separated described above. Weak alteration zone has no big difference in mineral assemblage and textures with regional metafelsic volcanic rocks besides more altered quartz, and is only associated with slight pyrite (usually less 5 percent) mineralization. However, great differences occur in intermediate and intense alteration zones comparative of regional felsic rocks. The intermediate alteration zone consists mainly of silicification, sericitization and carbonitization, and the altered mineral assemblages generally vary from 60 to 80 percent. And, distinct textures of the volcanic remnant such as porphyritic texture disappear in this alteration zone. This zone is often associated with distinctive veining and veinlet mineralization consisting either of pyrite-quartz-calcite or pyrite-sphalerite-quartz-calcite thin veins and stockwork. The intense alteration zone comprises almost totally altered minerals, quartz, sericite plus small chlorite characterized by silicification and sericitization. This altered zone is associated with slight or dense disseminated sulphides up to 40 percent, consisting mainly of pyrite with small chalcopyrite, sphalerite and pyrrhotite. The intermediate and intense alteration zones have hence been interpreted as the feeder zone or root zone of the massive ores, attesting to their submarine hydrothermal-exhalative origin.

Within the massive ore body, a distinct zonation consisting of five different ore facies has been separated. Massive, very compact, fine-grained Cu-rich pyrite facies occurs mainly in side contacting directly with and adjacent to the altered and mineralized feeder zone, which consists mainly of pyrite and chalcopyrite plus small pyrrhotite and magnetite. This zone grades outward into massive, compact, fine- or coarse-grained pyrrhotite-pyrite-chalcopyrite facies or into massive, compact pyrite facies. The pyrrhotite-pyrite-chalcopyrite facies occurs between Cu-rich pyrite and pyrite facies, and comprises mainly pyrrhotite, pyrite, chalcopyrite together with small sphalerite and magnetite. Pyrite and chalcopyrite seem to have a antipathetical variety each other in this facies, ranging from 20 to 50 percent in content, but pyrrhotite is relatively stable about 50 percent. The massive, compact pyrite facies constitutes mainly peripheral zone of the massive sulphide orebody and is composed almost of pyrite with a few chalcopyrite, pyrrhotite, sphalerite and magnetite. Some banded pyrite ores in this zone occur in places near the greenstone. The pyrite-sphalerite facies and pyrite-magnetite facies occur in places as parts of peripheral zone of massive ore body. The pyrite-sphalerite facies comprises largely pyrite and sphalerite together with a considerable content of magnetite, whereas the pyrite-magnetite facies is mainly composed of pyrite and magnetite. The gangue minerals in each ore facies are all quartz and calcite plus small chlorite. The chlorite increases in content in place near or adjacent to the greenstone.

The veining mineralization within the dark greenstone is similar with the feeder zone in mineralization, and alterations, metal and gangue mineral assemblages, but the feeder zone occurs within the felsic complex. This feature indicates that the path leading mineralized fluid movement is only not limited within the felsic complexes, and that it must be covered in a wide scope. This in certain extent means that the felsic complex is not sole and essential factor controlling formation of the massive sulphide deposits although they are both often spatially associated together.

4.4.2 Chemistry of the ores

The Gjersvik deposit comprises mainly Cu-Zn ore association with average grade of 1.55 % Cu and 0.84 % Zn, but no valuable Pb metal is associated with the ores, which was concluded from ore reserve estimation of the Gjersvik ore body by Oystein Pettersen (1973). However, it is also very interesting and important that distributions of the ore-forming metals are uneven and variable but zoning within the ore body, and their contents and variety depend on types, structure and texture of the ores.

Chemistry of the ores displays that the metal compositions of the ores are variable within the massive sulphide orebody, which depends mainly on the ore types. Cu is predominantly associated with in ore type I and II, i.e., in the pyrite + chalcopyrite and pyrite + pyrrhotite + chalcopyrite ores, within which Cu content is generally over 1 percent, while is low and variable in the ore type III, IV and V, i.e. in the pyrite, pyrite + sphalerite, and pyrite + magnetite ores, within which Cu is generally less 1 but over 0.1 percent but occationally less 0.1 percent in content such as in exposure of the massive pyrite mineralization in the northern shore of the Bjorkvatnet along Gjersvik-Royrvik road, in which ore minerals are almostly composed of pure pyrite and Cu content varies between 0.02 to 0.006 percent. Mineralogical study shows that the later three types of the ores consist predominantly of pyrite, pyrite and sphalerite as well as pyrite and magnetite, respectively, and hence Cu should occur mainly in pyrite lattice if they occur. Zn is the most dominant component in the ore type IV, i.e., pyrite + sphalerite ores, being up to 4 - 7 percent in content, and varies in the ore type I and II, ranging generally between 1 and 0.1 percent, while it is very low in the ore types III and V, usually less 0.01 percent in content.

Representative samples of the different ore types collected mainly from the Gjersvik ore body and lesserly from other massive sulphide exposure were analysized in their metal contents, which are shown in Table 4.3. Plots of the different ore types in triangular Cu-Zn-Pb

Table 4.3

Compositions of ore-forming elements in massive ores and in altered zones

massive ores

No	Sample No.	Ore Type	Major Metal Assemblages	Cu wt%	Zn wt%	Pb ppm	Fe wt%	Ag ppm
1	GS1-25	1	Py + Cpy	1.0600	0.2000	58	45.0	7
2	GS1-24	11	Py + Cpy + Po	1.1000	0.2900	147	44.5	7
3	GS1-23		"	0.7600	0.6300	64	45.5	6
4	GJK.90.7		"	4.4100	0.1600	43	41.4	12
5	GS1-22	111	Py	0.4000	0.0205	86	42.0	6
6	GS2-9-3		"	0.5000	0.0300	48	20.3	5
7	RS2-3		"	0.0210	0.0150	25	30.2	3
8	RS2-4		"	0.0068	0.0350	27	35.1	3
9	J314		"	0.1900	0.0990	83	40.6	5
10	GS1-32	1V	Py + Sph	0.3700	4.6400	180	27.6	7
11	GS1-33		"	0.8500	6.2900	62	32.3	8
12	J302		"	0.2200	4.7600	127	27.2	6
13	GJK.90.11	V	Py + Mt	0.0056	0.0094	15	21.4	1

1 - 6 and 9 - 13 samples collected from the Gjersvik massive sulphide ore body; 7 and 8 samples collected from exposure of the massive pyritic mineralization in the northern shore of the Bjørkvatnet Lake along the Gjersvik-Røyrvik road

Altered zones

No	Sample No	Altered Zones	Cu wt%	Zn wt%	Pb ppm	Fe wt%	Ag ppm
1	GS3-2	weak alteration zone	0.0032	0.0130	11	5.7	1
2	GS3-3	"	0.0062	0.0062	7	4.1	1
3	GS3-4	"	0.0140	0.0160	6	3.2	1
4	GS3-6	"	0.0230	0.0052	7	3.3	0
5	GS1-29	medium alteration zone (feeder zone)	0.0037	0.0240	44	2.1	1
6	GS1-31	"	0.0550	0.0370	38	6.5	2
7	GS2-9-1	"	0.0040	0.9900	1750	3.7	5
8	GS3-7	intense alteration zone with weak min.	0.0013	0.0088	10	1.9	1
9	GS3-8	"	0.0018	0.0180	63	3.9	1
10	GS3-9	intense alteration zone with strong min.	0.0260	0.1400	75	8.7	2
11	GS3-11	"	0.1300	0.0450	20	15.3	2

all altered samples collected from the Gjersvik keratophyric pyroclastic complex

All elements were analysized by Hans Øines, at laboratory of Grong Gruber A/S, 1991

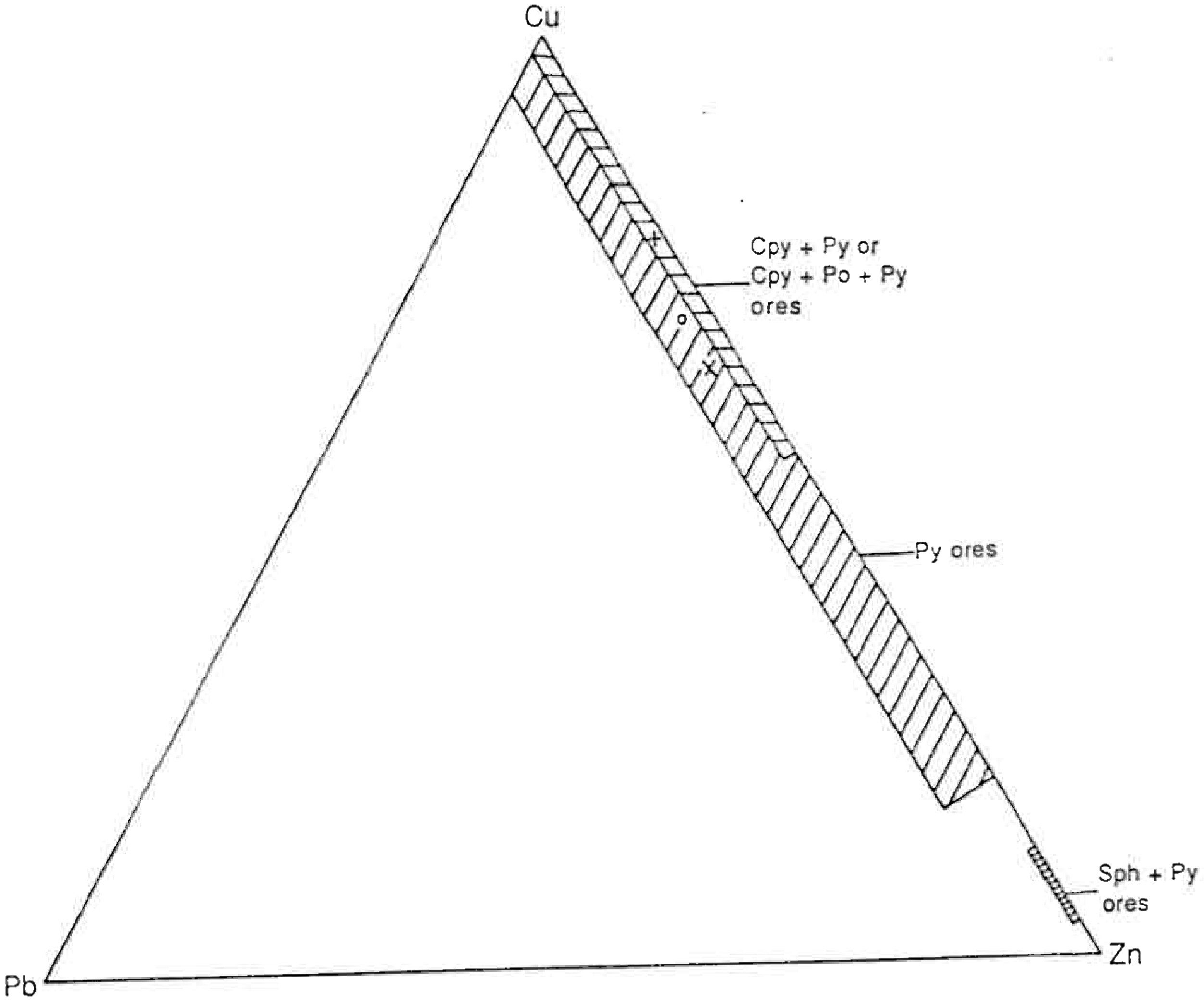


Fig. 4.23 Cu, Zn and Pb ratio of the different massive sulphide ore types in the Gjersvik deposits

\+ average value of the pyrite + chalcopyrite and pyrite + chalcopyrite + pyrrhotite ores;
x average value of the pyrite ores; o average value of the former two types of the ores

diagram show that Pb content is very low, generally less 5 percent, and hence the ores all belong to Cu-Zn association. However, ratio of Cu and Zn is different from type to type of the ores. The ores of pyrite + chalcopyrite and pyrite + chalcopyrite + pyrrhotite assemblages have highest ratio of Cu:Zn about 5.5, and hence they are dominated by Cu metal, while the ores of pyrite + sphalerite assemblages have lowest ratio of Cu:Zn about 0.09, and they are mainly associated with Zn metal. The pyrite ores have a variable scope in ratio of Cu: Zn, but their average value is about 5.5 (Fig. 4.23).

Due to the fact that metal contents and their varieties are related to the ore types which display an apparent zonation in the ore body, metals in the ores also exhibit zonation. For example, Cu tends to decrease and Fe gradually decreases in contents, while Zn tends to increase, and Pb seems to have a parallel behavior with Zn from the core ore zone grating towards outside zones, i.e., from pyrite + chalcopyrite, and pyrite + pyrrhotite + chalcopyrite, via pyrite, to most outside pyrite + sphalerite or pyrite + magnetite ore zones (Fig. 4.9, 4.24). This feature becomes much clear when Cu, Zn and Pb in different ore types are recalculated in percentage. Cu and Zn have an apparently and systematically antithetical behavior outward from the core ore zone, i.e., from ore type I to type V. Cu gradually decreases from the highest property in the ore type I (pyrite + chalcopyrite association), via ore type II and III (pyrite + pyrrhotite + chalcopyrite and pyrite associations) to ore type V (pyrite + magnetite association), and has the lowest property in ore type IV (pyrite + sphalerite association), while Zn tends to increase from the lowest property in the ore type I, via ore type II and III to ore type V, but has the highest property in ore type IV. Pb metal appears to have no obvious variety in different ore types although it also tends to be parallel with Zn in geochemical behavior (Fig. 4.24). Zonation of the ores and systematic variety of their chemical compositions in the different ore zones are most probably primary, which are related to chemico-physical conditions during precipitation of the ores.

Furthermore, a parallel trend in variations of the ore types and their metal compositions is further revealed through systematical study of the samples collected from the exposure of the eastern flank of the Gjersvik ore body along Gjersvik-Royrvik road section. The outcrop is about 10 m wide and consists of massive sulphides of the ore types I, II and III. Its section from the west to the east along the road section displays that the massive, fine-grained pyrite +

Ore Type	Ore Fabric	Major Metal mineral assemblages
I	massive, fine-grained	Py + Cpy
II	massive, fine- or coarse-grained	Py + Po + Cpy
III	massive and banded, fine-grained	Py
IV	massive and banded, fine-grained	Py + Sph
V	massive and banded, fine-grained	Py + Mt

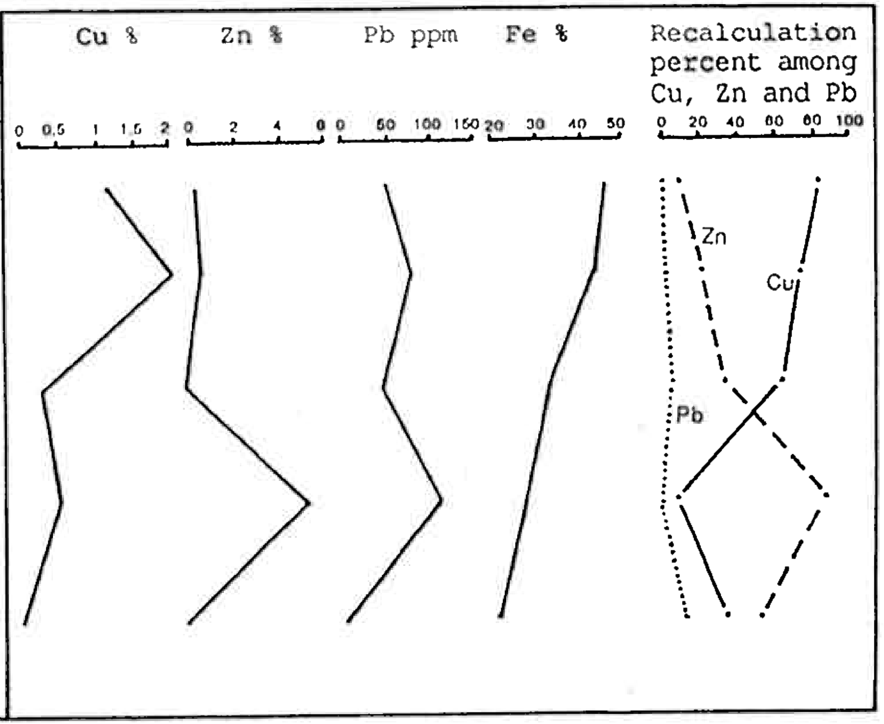


Fig. 4.24 Average contents and variations of metals Cu, Zn, Pb, and Fe, as well as percentages of Cu, Zn and Pb in the different ore types within the massive sulphide horizon

chalcopyrite assemblage (ore type I) is in direct contact with the altered, pyritic keratophyric pyroclastic rocks in the west, and grades to the east into the massive, coarse-grained and fine-grained pyrite + chalcopyrite + pyrrhotite assemblages (ore type II), which transfer to the massive, fine-grained pyrite ores (ore type III) further towards the east. The pyrite ores is in contact with the unaltered, dark greenstone in the east. Metal elements in the ores display that Cu and Fe tend to decrease from ore type I in the west, via ore type II to type III in the east, while Zn and Pb increase although Zn and Pb increase in ore type III and II zones, respectively (Fig. 4.25). More importantly, this section also reveals that variation of metal compositions in the ores not only depends on the ore types, but also is related to texture of the ores. For example, the coarse-grained pyrite + chalcopyrite + pyrrhotite ores contain higher Cu and lower Zn than their fine-grained ore equivalents (Fig. 4.25). Changes of the metal composition depond mainly on variation of ore mineral assemblages of the ores. On the basis of observation under microscope, for instance, the coarse-grained pyrite + chalcopyrite + pyrrhotite ores contain more chalcopyrite and lesser sphalerite than the fine-gained pyrite + chalcopyrite + pyrrhotite ores.

It is also interesting in ore-forming metal geochemical behaviors in different alteration zones associated with the feeder zone in the keratophyric pyroclastic complexes. In the Gjersvik felsic pyroclastic body, for example, Cu has the highest content in the strong alteration zone, but gradually decreases from strong, via intermediate to weak alteration zones. Zn and Pb display a similar geochemical behavior in different alteration zones, i.e., they are low in the weak and strong alteration zones in contents, but abruptly increase in intermediate alteration zone (Fig. 4.26). The reason is that the intermediate alteration zone is mainly associated with vein and veinlet mineralization, within which sphalerite and galena are relative higher in contents than in the weak and strong alteration zones.

4.5 Origin of the deposits

4.5.1 Geological environments

The Gjersvik deposits occur in a thick metavolcanic sequence within the Gjersvik Nappe. The metavolcanic sequence have been subdivided into the Bjorkvatnet and the Gjersvik Formations.

No.	Ore Type	No. of Samples	Ore Fabric	Major Metal mineral assemblages
1	1	GS1-25	massive, fine-graine	Py + Cpy
2	11	GS1-24	massive, coarse-grained	Py + Po + Cpy
3	11	GS1-23	massive, fine-grained	Py + Po + Cpy
4	111	GS1-22	massive, fine-graine	Py

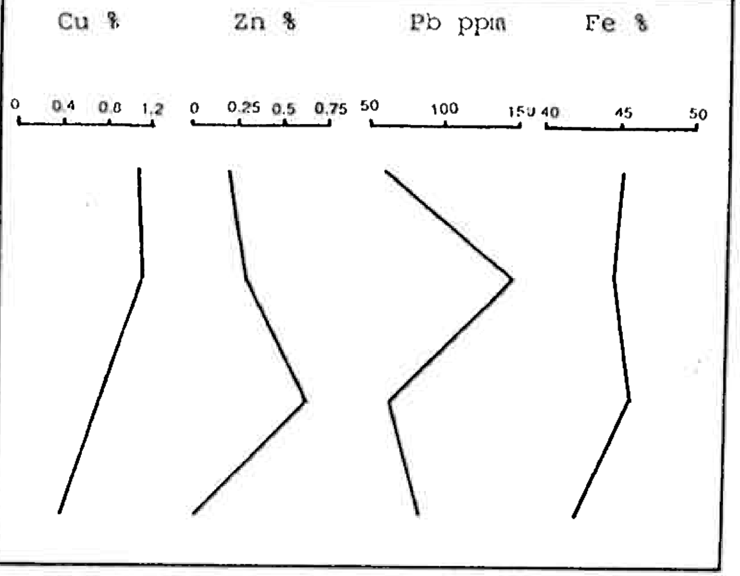


Fig. 4.25 Average contents and variations of metals Cu, Zn, Pb, and Fe in the different ore types within the massive sulphide horizon on exposure of the eastern flank of the Gjersvik ore body along the Gjersvik-Royrvik section

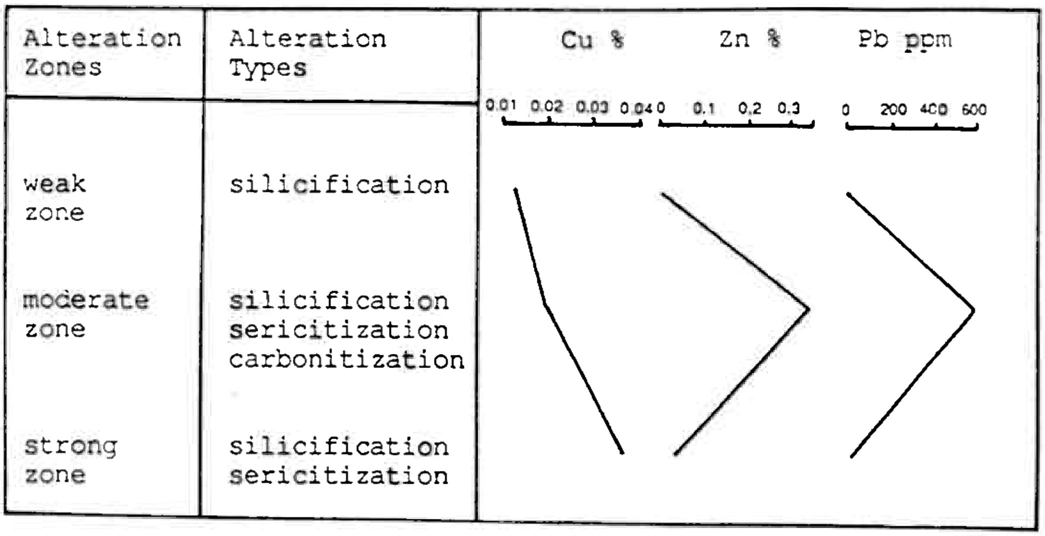


Fig. 4.26 Average contents and variations of metals Cu, Zn, and Pb in the different alteration zones within the Gjersvik keratophyric pyroclastic complex

The massive sulphide mineralization to have so far been found are all present in the Gjersvik Formation although few disseminated sulphide mineralization also occur within the Bjorkvatnet Formation. The Bjorkvatnet Formation is predominantly composed of relative high-grade metamorphosed amphibolite with MORB affinity on which was built the Gjersvik volcanic arc consisting of the magmatic complexes of the Gjersvik Formation. The Gjersvik volcanic arc is characterized by well-defined bimodal basalt-rhyolite volcanic assemblages that are essentially lack of andesite, and consists predominantly of the greenstones of tholeiitic composition plus small amounts of the keratophyric pyroclastic complexes of rhyolitic composition, which has been considered as a main evidence of the rift tectonic environment. The metavolcanites are tholeiitic in magma series, and are dominated by metamorphosed tholeiitic lava, massive flow and volcanic clastic rocks, within which the felsic pyroclastic volcanic rocks, about 20 % in volume of all volcanic rocks, are extensively scattered. The Gjersvik volcanic arc is also associated with the vast plutonic infrastructures consisting mainly of trondhjemites and gabbro. It is significant, however, that no identified sediments deriving from continental sources have so far been found to be represented in the volcanic arc besides of a lot of thin, conformable exhalative sedimentary layers. The Gjersvik massive sulphide deposits have thus been proposed to occur mainly within an immature volcanic arc which was built on the ocean floor in connection with rifting environments in where there are complete absence of the continental crust and no supply of normal sediments.

Geological and geochemical evidences have demonstrated that the Gjersvik volcano-stratigraphical succession can be further divided into three units, i.e., the dark and pale greenstones of tholeiitic composition as well as the keratophyric pyroclastic complexes of rhyolitic composition. The dark greenstone has evidently been proposed to be stratigraphically older than the pale greenstone, while the keratophyric pyroclastic complexes represent an episode of felsic volcanic processes between tholeiitic basalt activities at two stages, dark and pale greenstones as their present metamophised equivalents. Thus, it can be concluded that magmatic processes during construction of the Gjersvik volcanic arc are recyclic or multistage, and are all related to rift system development, during which the magmas were guided by extensional fault zones.

The massive sulphide mineralization are predominantly associated with the keratophyric pyroclastic complexes. Meanwhile, the veining and disseminated sulphide mineralization also occur extensively within the underlain dark greenstone but very few are associated with the overlain pale greenstone. And, the dark, pillowed greenstone is often accentuated by a pyrite-bearing rim around individual pillows, which is a good indication of distal mineralization. The exhalative sediments are extensively present just in junction between the dark and pale greenstones or within the pillowed greenstones. Thus, It can be further deduced that the massive sulphide mineralization within the Gjersvik volcanic arc are largely associated with an episode of the felsic volcanic processes between tholeiitic basalt activities at two stages, and are in some ways related to the dark greenstone, but it is very difficult to connect them with the pale greenstone.

The keratophyric pyroclastic complexes scattered extensively within the Gjersvik volcanic arc consist of felsic pyroclastic rocks, sills and dikes, and are characterized by small and variable scales in occurrences. The massive sulphide mineralization are mainly associated with the felsic pyroclastic complexes. Their distributions are mainly controlled by extensional fault zones in connection to the rift system development. Petrology and geochemistry of the metavolcanic rocks points out that the early rifting activity was characterized by volcanic process of the undifferentiated tholeiitic basalt related in some ways to the subduction between oceanic plates, while the late developing rifting environment was associated with new volcanic process of the differentiated tholeiitic basalts derived from deeper mantle source. The keratophyric pyroclastic complexes have been proposed to be formed at a stage during the rifting evolution between the early initial and late developing rifts.

4.5.2 Original evidences from distributions, types, zonation and chemistry of the ores

Mineralization associated with the Gjersvik volcanic arc can be apparently subdivided into three types: massive sulphide ores associated directly with a feeder zone, exhalative sediments and vein sulphide mineralization in the underlying dark greenstone, even though the later two types have no any recoverable value to have known so far. These different mineralization have a strict stratigraphic restriction and a distinctive host association in mode of occurrence to each other. The massive sulphide horizon is predominantly associated with the keratophyric pyroclastic complex within which often occurs a feeder zone characterized by both of apparent vein, stockwork sulphide mineralization and intense hydrothermal alterations directly below the massive sulphide orebody. The exhalative sediments are mainly present within the dark, pillowed greenstone as a distal extension of the exhalative massive sulphide horizon or in junction between the dark and pale greenstone although they can also occupy at level of the pale, pillowed greenstone near the boundary to the dark greenstone. The vein sulphide mineralization associated with apparent hydrothermal alterations are mainly limited to occur within the underlying dark greenstone.

Furthermore, the vein mineralization and the feeder zone directly below the massive sulphide horizon result mainly from reaction between solution and country rocks because they are all characterized by obvious hydrothermal alterations. It is more interesting that they are consistent and comparative in their metal and altered mineral assemblages and hydrothermal alteration types although the former occurs mainly within the underlying dark greenstone, while the latter is associated with the keratophyric pyroclastic complexes. This leads to a deduction that solution which passed to and reacted with country rocks of the dark greenstone or of the felsic pyroclastic complexes are similar in their compositions and natures. On the other hand, the exhalative sediments consisting mainly of magnetite, pyrite and quartz are comparative in mineral assemblages with the massive sulphide orebodies. Thus, these different types of mineralization have been proposed to have a primitive and systematic connection during ore-forming processes. The massive sulphides associated directly with a feeder zone have been considered to be formed at or near the discharge vents of a submarine hydrothermal systems, the veining sulphide mineralization in the underlying dark greenstone probably represent a product of seawater-rock reaction between the circulating hydrothermal solution and the underlying tholeiitic basalt pile within which they passed along fracture zones, while the exhalative sediments were very probably formed by silica and iron oxides precipitation of the discharge hydrothermal solution plumes in distal, or stratigraphically higher positions relative to the massive sulphide body within the reduced convenient basins on the ocean floor.

Mineralization in the Gjersvik volcanic arc has been interpreted to be formed mainly in a strong reduced environment in where they precipitated because the massive sulphide horizon consist predominantly of pyrite, chalcopyrite, pyrrhotite and sphalerite with minor but considerable amounts of magnetite, while exhalative sediments are also composed largely of pyrite and magnetite. The massive sulphide ores are mainly fine-grained, compact and massive in the central orebody, but they often become banded in texture upward and outward to the boundary near wall rocks of the dark greenstone, which display a feature of sedimentary processes. The exhalative sediments are also very fine-grained in texture and often reserve very good primary structures of the sedimentary bands or laminae although they have generally been folded by the late structure.

It is also important in understanding origin of the deposit that gangue mineral assemblages associated with the massive sulphide ores are mainly quartz and carbonate (calcite), which are also most essential altered mineral components in the feeder zone and in the underlying vein mineralization zone. It is interesting, however, that quartz and calcite in the massive sulphide ores occur mainly as thin bands alternating with sulphide bands or as paragenetic association with the sulphide gains, while they are present in the feeder zone and the vein mineralization as hydrothermal filling, replacements and precipitation associated with other altered minerals. Gangue mineral assemblages between feeder zone, vein mineralization zone and massive sulphide ores display an important nature rich Si, CO2 and Ca components of the solution from which the sulphides precipitated, while textures and occurrences of quartz and calcite between the two exhibit a difference of the environments in where they precipitated.

On the basis of systematic studies of the ores mainly in the Gjersvik massive sulphide horizon, the massive sulphide body displays a very good zonation which the pyrite + chalcopyrite ores located in the central part in direct contact to the feeder zone, through pyrite + pyrrhotite + chalcopyrite ores grade upward and outward to pyrite ores which grade outside to either the sphalerite-pyrite ores or magnetite-pyrite ores in contact to the outside unaltered wall rocks of the dark greenstone. This kind of zonation of the massive ores shows that the central facies of the pyrite + chalcopyrite and the pyrite + chalcopyrite + pyrrhotite ores were formed in condition of higher temperature relative to the outside and marginal other ore facies. Textural studies of the ores have demonstrated that chalcopyrite and pyrrhotite result largely from fractural filling and replacement along or between preexisting pyrite gains. On the other hand, chemical zonation of the massive ores is also obvious and comparative with their mineral zonation. For example, Cu and Fe decrease but Zn increases upward and outward from the central zone of the massive ores (Fig. 4.24), and Cu/Zn ratio has no big changes in the central zones of massive pyrite + chalcopyrite, pyrite + pyrrhotite + chalcopyrite and pyrite ores, but abruptly increases outward to the outside zones of pyrite + sphalerite and pyrite + magnetite ores.

Zonation of the massive sulphide ores both in ore mineral assemblages and metal compositions have been interpreted to be originally related to and to be formed during the accumulation of a sulphide mound around the vent (Franklin et. al., 1981). In the Gjersvik deposit, however, Cu increase in the central massive ore zones, i.e., pyrite + chalcopyrite and pyrite + pyrrhotite + chalcopyrite ores results mainly from the remobilization of previously deposited sulphides by the action of continued hydrothermal flow through the mound, while Cu/Zn ratios decrease toward and outward from the central massive ore zones, especially in outside massive ore zones such as from pyrite zone grading to pyrite + sphalerite and pyrite + magnetite zones is mainly due to deposition taking place by accumulation of sulphide precipitated in a hydrothermal plume. The zonation of the massive sulphide body indicates that the ores with the highest Cu/Zn ratios were deposited at higher temperature and lower Po2 than those with lower Cu/Zn ratios (Franklin et. al., 1981).

4.5.3 Feeder zone and hydrothermal alterations

The petrologically distinctive alteration zones in the Gjersvik volcanic arc occur either within the keratophyric pyroclastic complexes below directly the massive sulphide horizon or in the underlying dark greenstone. These zones have been interpreted to be formed by a progressive reaction of rising ore-forming fluids with the wall rocks in a circulating hydrothermal system.

The hydrothermal alterations are mainly silicification, sericitization and carbonatization. The sericitization was produced mainly by formation of the altered sericite due to breakdown of albite in the feeder zone or to K replacement to the chlorite in the underlying vein mineralization zone in condition of addition of the K-rich fluid during hydrothermal alteration processes, which are shown in following reactions:

$\mathrm{3NaAlSi_3O_8 + K^+ + 2H^+ \dashrightarrow 6SiO_2 + KAl_2(AlSi_3O_{10})(OH)_2 + 3Na^+}$ (albite)
(sericite)

$\mathrm{3(Mg,\ Fe)_5Al(AlSi_3O_{10})(OH)_8 + 2K^+ + 24H^+ \dashrightarrow}$
(chlorite)

$\mathrm{\dashrightarrow 3SiO_2 + 2KAl_2(AlSi_3O_{10})(OH)_2 + 15(Mg,\ Fe) + 24H_2O}$
(sericite)

The silicification and carbonitization resulted largely from precipitations of quartz and calcite during the hydrothermal alteration. Chemistry of the alteration zones have shown that K, Ca, Si and Mg are major addition components, while Na and Al are major loss compositions.

Experiment of chemical exchange during hydrothermal alteration between natural seawater and oceanic basalt in the conditions that are at 200 to 500 C, 500 - 800 bars, water/rock mass ratios of 1 - 3, and durations ranged from 2 to 20 months indicates that SiO_2, Ca, K, Ba, B and CO_2 were leached from basalt and enriched in the seawater, but Mg, Na and SO_4 were removed from seawater into solid phases as the Mg-rich alteration products such as smectite, tremolite-actinolite and into solids by formation of sodic feldspar and possibly analcime, respectively (Mottle et. al. 1978). Same experiment under nearly same conditions as Mottle (1978) but only two weeks duration also showed a comparable result, that is, Mg and Na net loss but Ca, K, Fe, Mn, and Si net addition to seawater (Hajash, 1975). Thus, K, Si, and Ca that extensely precipitate in the feeder zone and the underlying vein mineralization zone came mainly from the circulating seawater leaching through the underling dark greenstone pile in where they passed.

4.5.4 Source of ore-forming material

The essential constitutes of the massive sulphide deposits are the metals Fe, Cu, Zn, and Pb and sulphur, for which three major possibilities have been assumed in regard to the sources of metals and/or sulphur, that is, seawater, the rocks stratigraphically below the massive sulphide horizon and through which solutions of the ore-forming hydrothermal system have passed, and magmas either directly as the volatile components of a crystallizing magma or indirectly by a hydrothermal convection cell involved in the direct cooling of the magma body. Seawater as the main sources of sulfur have been supported from evidences of S, O, H, and Sr isotopes (Franklin, et. al., 1981). The concentration of the main ore metals Cu, Zn and Pb in modern seawater, however, is about 0.01 ppm, nearly four orders of magnitude smaller than the minimum concentration of about 10 ppm that is generally regards as being necessary for ore deposition (Barnes and Czamanski, 1967). This fact make it very difficult that the ore metals of massive sulphide deposits are presumed to be derived directly from seawater.

Cu and Zn as major ore metals of the Gjersvik deposits are here being proposed to be mainly leached from the underlying dark greenstone pile through which the ore-forming hydrothermal fluids passed. The close association between the massive sulphide orebodies and the keratophyric pyroclastic complexes have been considered to be very important for the felsic magma as heat source driving the convection cell in the circulating ore-forming system during formation of the massive sulphide deposits. This conclusion results mainly from the evidences in follow.

(1) Relation between the deposits and sizes of the keratophyric pyroclastic complexes

There is no positive interrelation between the deposits and size of the keratophyric pyroclastic complexes with which the massive sulphide bodies are generally associated. For example, the Gjersvik ore body as the biggest one in size in this area is only associated with a small keratophyric pyroclastic body about 700 m long and 400 m wide on the surface exposure, while the biggest keratophyric pyroclastic complex about 18000 m in length and 5000 m in width located in the southern shore of the Bjorkvatnet is associated with few massive sulphide mineralization although they do occur. At the same time, the massive sulphide bodies in the Annlifjellet and in the Tjiermajaevrieh areas are much bigger than those in the shore of the Bjorkvatnet, but the keratophyric pyroclastic complexes associated with them are much smaller than the Bjorkvatnet body. Otherwise, the keratophyric pyroclastic complexes associated with relative bigger massive sulphide bodies are usually characterized by apparent hydrothermal alterations. Thus, this phenomena becomes an unfavorable evidence that the major ore metals of the Gjersvik deposits should be assumed to be mainly derived from the keratophyric pyroclastic complexes with which they are associated.

(2) Ratio of Cu, Zn and Pb metals in the ores and major but different types of the rocks in the Gjersvik volcanic arc

Ratios of Cu, Zn and Pb metals in the different types of the rocks and the massive sulphide ores are compared, which is shown in Figure 4.27. Ratio of Cu, Zn and Pb in the massive sulphide orebodies is comparative with that in the dark and pale greenstones, i.e., they all have very low Pb, generally less 5 % percent although the Cu and Zn are variable in their ratio. In contrast to this, ratio of Cu, Zn and Pb metals in the massive sulphide ores are different from those in the felsic intrusive and extrusive rocks that are characterized by relative lead enrichments. The altered rocks have both properties of the massive sulphide ores and of the keratophyric pyroclastic rocks in ratio of the Cu, Zn and Pb, i.e., Cu-rich trend can be comparative with that in the massive sulphide ores, while Pb content is similar with that in the keratophyric pyroclastic rocks. This is due to that the altered rocks are mainly associated with the feeder zone occurring within the keratophyric pyroclastic complexes.

In addition, Cu contents are generally lower in the dark greenstone relative to those in the pale greenstone, being average about 30 ppm and 45 ppm, respectively. It is very interesting that the geological evidences have demonstrated that major mineralization related mainly to an episode of the felsic magmatic activities occurring between the tholeiitic basalts at two stages in the Gjersvik volcanic arc are present after the undifferentiated, but before the differentiated tholeiitic magma processes that led to formation of the dark and the pale greenstones, respectively and that the dark greenstone is stratigraphically lower than the massive sulphide horizon. Order of magnitude calculations (Solomon, 1976) have suggested that a convection cell model would require a depletion of 10 to 20 ppm in total ore metal of the source rocks.

(3) Extensive mineralization and alteration zones within the dark greenstone

The detailing surface mapping and the drilling have revealed that the dark greenstone are often associated with the solution channelways that are characterized by both of extensive vein, stockwork and disseminated sulphide mineralization and hydrothermal alterations. They are

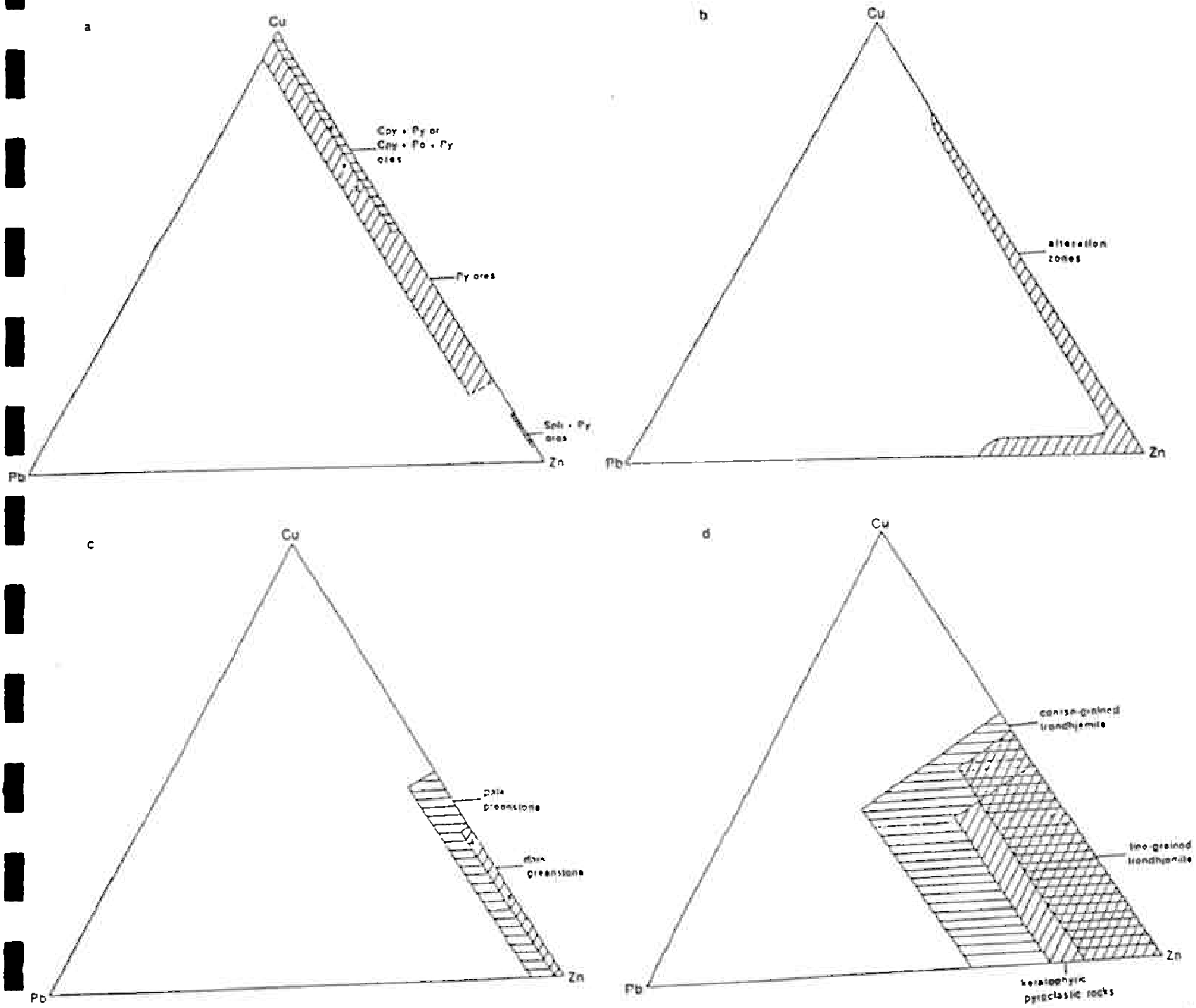


Fig. 4.27 Comparisons of Cu, Zn and Pb ratios in the massive sulphide ores, the alteration zones in the feeder zone, and the different types of the rocks in the Gjersvik volcanic arc

a, massive sulphide ores, + average value of the pyrite + chalcopyrite and pyrite + chalcopyrite + pyrrhotite ores, x average value of the pyrite ores, and o average value of the former two types of the ores; b, alteration zones within the feeder zone; c, dark and pale greenstones, + average value of the pale greenstone, x average value of the dark greenstone; d, felsic extrusive and intrusive rocks including the keratophyric pyroclastic complexes, fine-grained porphyritic trondhjemite and coarse-grained trondhjemite present as long, narrow zones within the dark greenstone, which are apparently controlled by fault zones, and are not associated with the massive sulphide mineralization and the felsic bodies. These altered and mineralized zones are similar with and comparative in metal and altered mineral assemblages and their fabrics to the feeder zone associated with the keratophyric pyroclastic complexes directly below the massive sulphide horizon. Obviously, they represent a product of the hydrothermal replacements, which very probably results from the reaction between seawater and wall rocks when the solution passed from channelways within the tholeiitic basalt pile. Experience of reaction between seawater and basalt has shown that Cu and Zn are leached from the basalt during hydrothermal alteration, and some Cu are precipitate as sulphides in the basalt (Humphris & Thompson, 1978).

4.5.5 Working model of the deposits

The Gjersvik massive sulphide deposits were formed in an immature volcanic arc which was built on and related to the rift system development in the intra-ocean floor environment. Main mineralization in the Gjercvik volcanic arc are related to an episode of the felsic magmatic activities between depositions of the tholeiitic basalts at two stages during the intra-ocean rift system development. The deposits have been proposed to be originally related to a circulating hydrothermal system occurring in the thick, undifferentiated tholeiitic basalt pile of the Gjersvik volcanic arc. The hydrothermal ore-forming system has been considered to be essentially a convective cell which consists mainly of sea-water, though magmatic water cannot be rule out. The major ore metals such as Cu, Zn and Fe have been interpreted to be derived predominantly from the underlying tholeiitic basalt pile within which the ore-forming solution passed. Due to the fact that the massive sulphide orebodies are generally associated with the keratophyric pyroclastic complexes which extensively scatter within the dark greenstone succession, heat energy driving the convection cell is thought to be mainly connected with the local felsic intrusive-extrusive complexes controlled by extensional fault zones in relation to the intra-ocean rift system development (Fig. 4.28).

When descending in the circulating ore-forming system in subsurface on the ocean floor, seawater gradually becomes heated and modified in chemical composition due to the bit-by-bit reaction between seawater and wall rocks of the undifferentiated tholeiitic basalts through

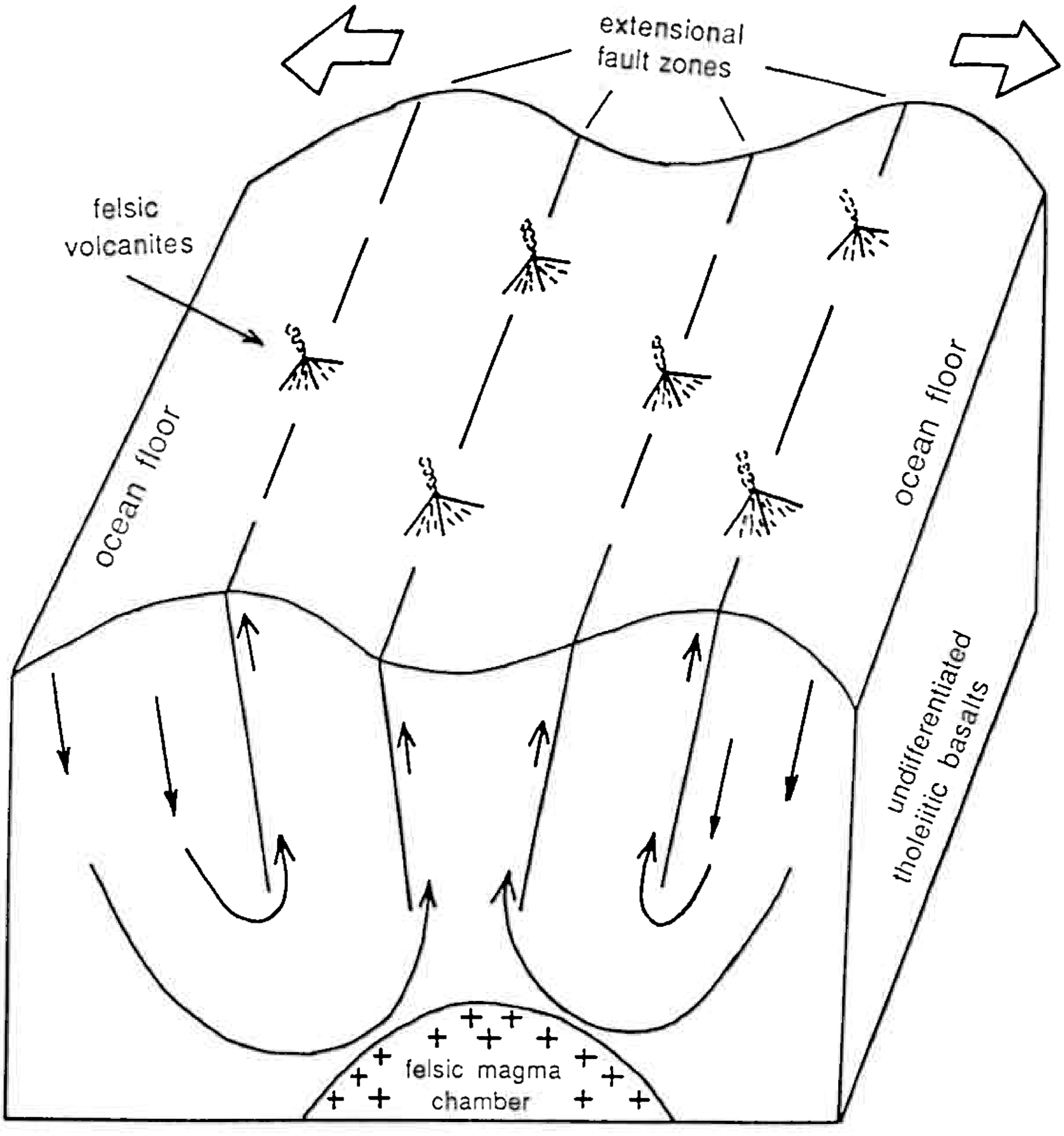


Fig. 4.28 A simplified diagram showing the geological and tectonic environmen related to formation of the deposits

which the solution passed, and hence some elements in the underlying tholeiitic basalt pile such as Cu, Zn, Ca, K, Fe, Mn, and Si begin net addition to solution of the convective cell, while Mg and Na net loss. After passing through the locations where there is the heat anomaly to be caused mainly by the cooling felsic magma chambers occurring along the extensional fault zones, the hydrothermal solutions rise along the extensional fault or fracture zones of high permeability following the felsic clastic volcanic eruption, which is obviously deducted from the closely spatial association of the massive sulphide mineralization with the felsic pyroclastic complexes in occurrence. On nearing the surface, physico-chemical changes to the hydrothermal solutions, induced by their mixing with ambient sea- or pore-water, boiling, or reaction with their wall rocks, cause the precipitation of ore and gangue minerals. Initial chemical reaction takes place in the subsurface and is characterized by potassium metasomatism, depositions of silica and carbonate, which leads to formation of the alteration pipe and precipitation of the sulphides such as pyrite, chalcopyrite and sphalerite within a stringer zone in the felsic pyroclastic complexes. At the seawater-rock interface, chemical precipitation is much more rapid and results in the accumulation of a sulphide mound around the vent and in the exhalative chemical sediments of the iron formation along a distal extension of the massive sulphide horizon in strong reduced environments on the ocean floor local basins. The ore-forming solution may rises along the fracture zones within the underlying tholeiitic basalts rather than following the felsic volcanic eruption, which leads the vein sulphide mineralization accompanying the hydrothermal alterations within the basalt pile due to reaction between the ore-forming fluid and the basaltic wall rocks (Fig. 4.29).

The ore-forming solution activity should be continue to keeps a certain period. At the early stage, the solution processes may mainly lead to the precipitation of pyrite in both massive sulphide phase on the seawater-rock interface and the disseminated phase in the feeder zone because the ore textures display that the chalcopyrite, pyrrhotite and part of sphalerite were formed mainly by replacements to the preexisting pyrite.

During the ore-forming processes, reactions between the moving solution and the wall rocks linking the channelways and boiling of the ore-forming fluid may be important in the subsurface because the feeder zone and the vein mineralization zone characterized by both of intensively hydrothermal alterations and stockwork and disseminated mineralization are

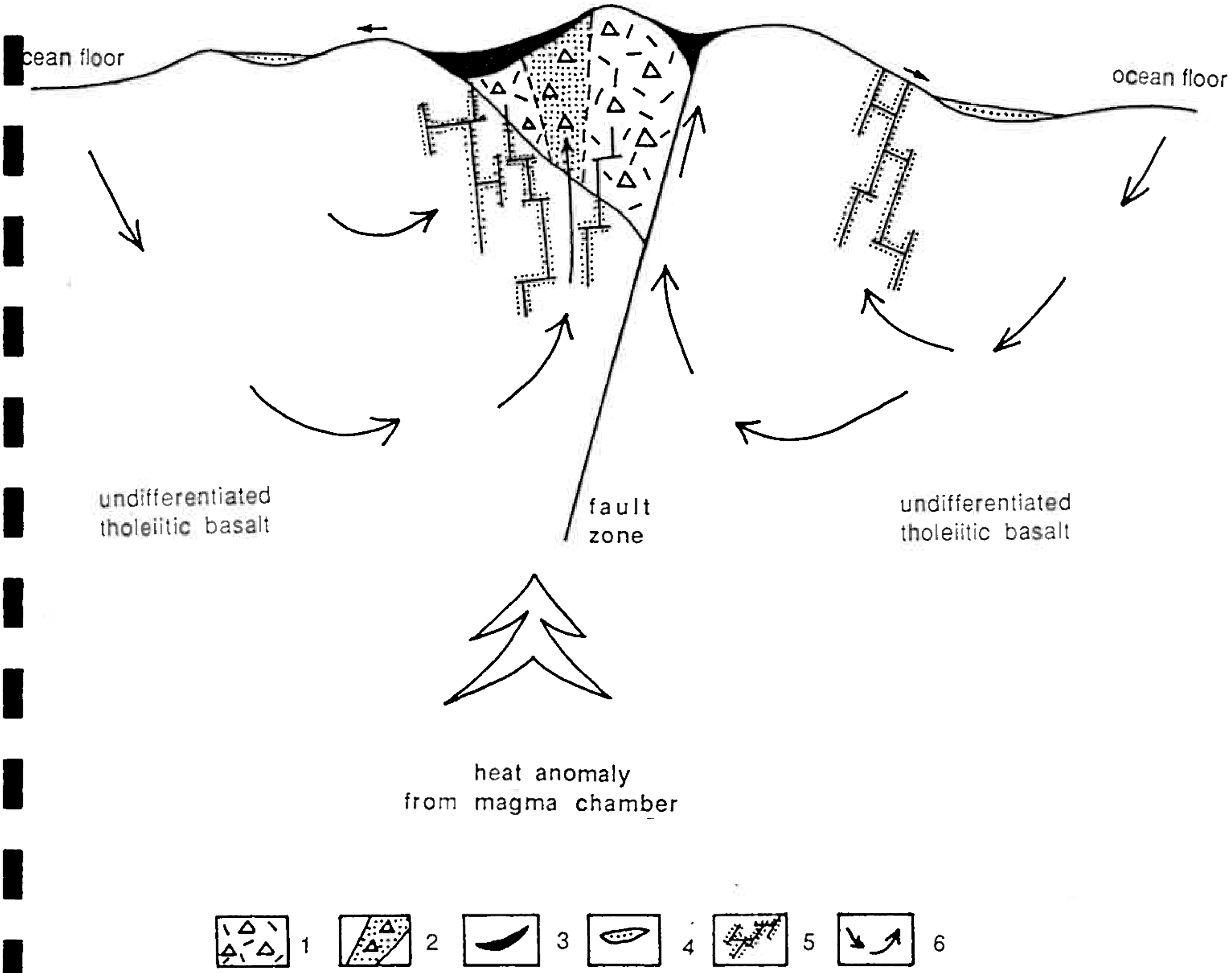


Fig. 4.29 An simplified original model of the Gjersvik massive sulphide deposits

1 - keratophyric pyroclastic complex; 2 - altered keratophyric pyroclastic complex (feeder zone); 3 - massive sulphide ore bodies; 4 - exhalative sediments; 5 - vein mineralization associated with the hydrothermal alterations occurring in the fracture zones within the underlying dark greenstone; 6 - circulating ore-forming hydrothermal system consisting of a convection cell

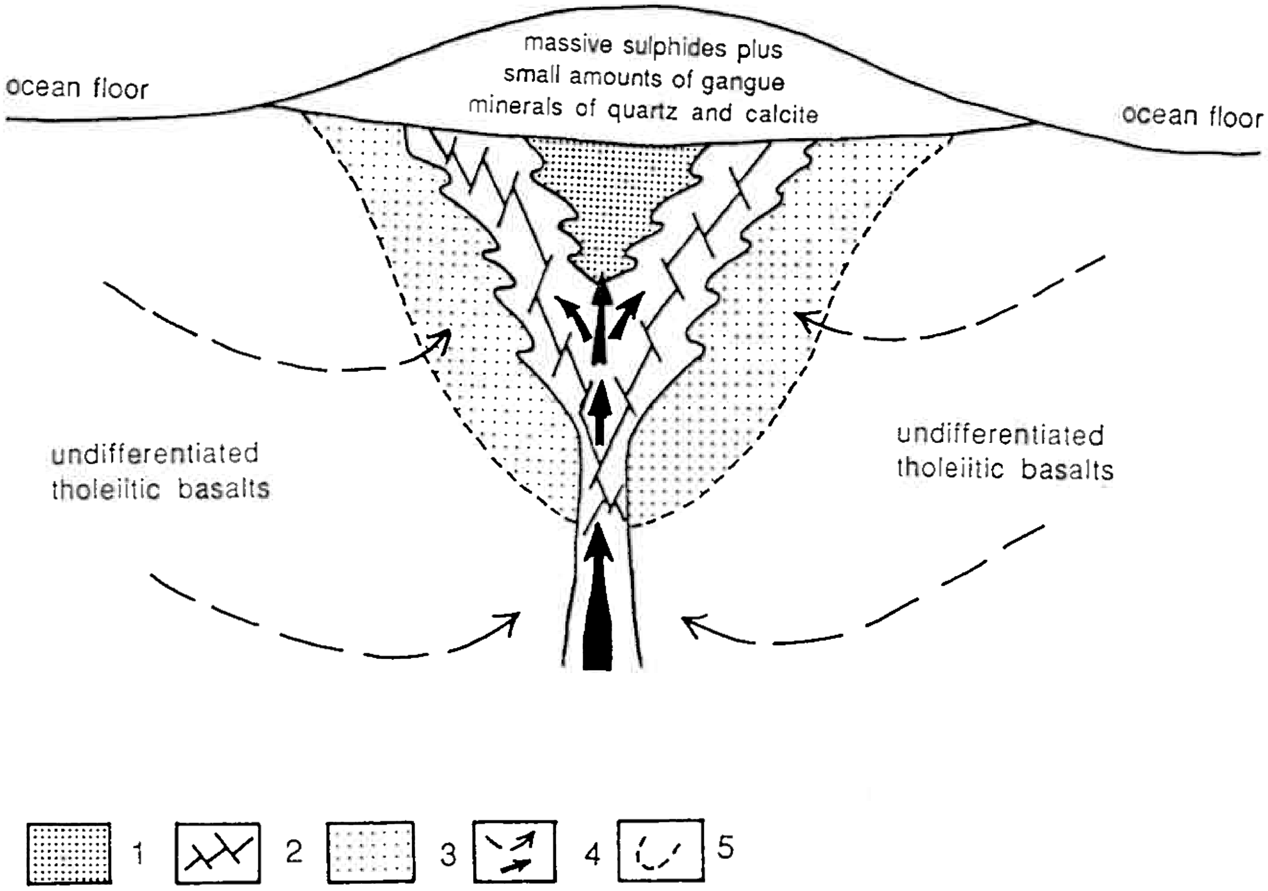


Fig. 4.30 An simplified model of reaction between ore-forming solution and wall rock in subsurface directly below the massive sulphide horizon, leading formation of the feeder zone

1 - strong hydrothermal alteration zone (silicification and sericitization) associated with disseminated sulphide mineralization; 2 - moderate hydrothermal alteration zone (silicification, sericitization and carbonitization) associated with vein, veinlet and stockwork sulphide mineralization; 3 - slight hydrothermal alteration (silicification) associated with weak pyritic mineralization; 4 - circulating ore-forming hydrothermal system consisting of a convection cell; 5 - boundary between the keratophyric pyroclastic complex and the dark greenstone

generally present directly below the massive sulphide horizon or occur extensively within the underlying dark greenstone, respectively. During the hydrothermal alterations, extraction of hydrogen ions from solution and potassium replacement to the wall rock tend to reduce the stability of chloride complexes and lead to sulphide mineral precipitation, about which an obvious evidence is that the intense sericitization owing to potassium replacement to the feldspar or chlorite in the wall rocks is often associated with the feeder zone within the keratophyric pyroclastic complexes diractly below the massive sulphide horizon (Fig. 4.30). On the other hand, temperature and pressure changes, rapid cooling and mixing of a hot, rising solution with a cold seawater mass may be major factors leading to precipitation of the sulphides in seawater-rocks interface on the ocean floor.

4.5.6 Comparison of the Gjersvik deposits to Kuroko-type deposits

It is significant to make a comparison of the Gjersvik massive sulphide deposits to the Kuroko-type deposit, for the Gjersvik deposit was proposed by Lutro (1979) to be comparative in stratigraphical succession of the deposit to Kuroko-type ore deposit that has been considered to be standard volcanic-hosted massive sulphide deposits to which virtually all other deposits are compared (Franklin et. al., 1981).

It is obvious that some macroscope to megascopic similarities do exist between the Gjersvik and the Kuroko deposits, such as their apparent volcanite-host association with felsic, and especially fragmental volcanic rocks, the tendency for orebodies to occur in clusters, the presence of a footwall alteration zone, the presence of both massive and stratigraphically lower stringer ore, the chemical zonation of the deposits, especially of the Cu/Zn ratio. It must be emphasized, however, that many important differences which are imposed on restrictions to a direct correlation of the Gjersvik to the Kuroko-type deposits have been distinguished (Table 4.4).

Some significant aspects in differences between the Gjersvik and the Kuroko-type deposits should be accentuated: (1) The continental crust is completely absent and no normal sediments deriving from the continental sources have so far been found to occur within the Gjersvik volcanic arc, while the continental crust is present in and sandstone and mudstone are associated

Table 4.4 Comparison of the Gjersvik deposits with the Kuroko-type deposits

	Gjersvik deposits	Kuroko deposits in Japan
Age	Early Palaeozoic	Miocene
metamorphism	greenschist facies	zeolite facies
deformation	strong	very weak
tectonic environments	intra-ocean rifting environment	intra-arc extensional environment
continental crust	complete absence	presence
development of the volcanic arcs	immature or primitive	mature
magma series	tholeiitic	calc-alkaline
volcanic rock assemblage	well-defined bimodal basalt-rhyolite volcanic assemblages that essentially lack andesites	basalt, andesite, dacite and rhyolite assemblages
dominant types of volcanites constituting volcanic arcs	tholeiites	andesite, dacite and rhoylite
chemistry of the host volcanic rocks	Na-richment	K-richment
sedimentary rocks associated with the volcanic succession	only small exhalative sediments	sandstone, mudstone
intrusive rocks associated with the volcanic arc	major trondhjemite plus small gabbro	quartz-diorite, granotoids
exhalative sediments associated with the massive sulphide ores	cryptocrystalline quartz and magnetite	cryptocrystalline quartz and hematite

Table 4.4 continued

	Gjersvik deposits	Kuroko deposits in Japan
tendency of ore bodies in occurrence	cluster	cluster
orebody morphology	massive sulphides horizon underlying directly a stringer mineralization	massive sulphides horizon underlying directly a stringer ore
ore-associated volcanics	keratophyric pyroclastic complexes of rhyolitic composition	dacite, rhyolite
rocks hosting the feeder zone	felsic pyroclastic complexes	rhyolitic dome
major alterations related to mineralization	silicification sericitization carbonitization	silicification sericitization montmorillonite
major ore textures	compact, massive	compact, massive
major metal mineral assemblages	pyrite, chalcopyrite, pyrite, pyrrhotite	pyrite, galena, sphalerite
minor metal mineral assemblages	sphalerite, magnetite	chalcopyrite, barite, tetrahedrite, tennantite
major gangue mineral assemblages	quartz, carbonate (calcite)	quartz
minor gangue mineral assemblages	chlorite	barite, gypsum, anhydrite
sulphates associated with the ores	none	barite, gypsum, anhydrite
major ore-forming element associations	Cu-Zn	Pb-Zn
minor ore-forming element associations	none	Ba, Cu

The Kuroko deposits are referenced mainly from Matsukuma & Horikoshi, 1970; and Franklin et. al., 1981 with the volcanic succession in which the Kuroko deposits occur. This nature has been proposed as an evidence that the Gjersvik volcanic arc was built on the intra-ocean floor distinct from the intra-arc environment in which occur the Kuroko-type deposits; (2) The Gjersvik deposits are typically associated with well-defined bimodal basalt-rhyolite volcanic assemblages that essentially lack andesites, which indicates an rifting environment distinctive from the extensional environments that generate Kuroko-type deposits; (3) The volcanic succession hosting the Gjersvik ores is tholeiitic in magma series, and dominated by the tholeiitic basalts, which display an immature volcanic arc environment. In contrast to this, the volcanic sequence hosting the Kuroko deposits is calc-alkaline, and comprises mainly the felsic volcanic rocks that have been proposed to represent a mature island arc environment; (4) The Gjersvik volcanites are characterized by Na-richment and extensively associated with their plutonic infrastructures of trondhjemite and gabbro, while the island arc volcanic succession in where the Kuroko-type deposits are located by K-richment and with quartz-diorite and granitoids; (5) the Kuroko-type deposit is originally related generally to the rhyolitic dome, while the Gjersvik deposits are mainly associated with the felsic pyroclastic volcanic rocks; (4) the exhalative sediments associated with the Gjersvik deposits consist predominantly of cryptocrystalline quartz and magnetite, while they are cryptocrystalline quartsz and hematite in the Kuroko-type deposits; (7) there are great differences in the ore mineral assemblages and in the ore compositions between these two types of the deposits. For example, main ore mineral assemblages in the Gjersvik deposits are pyrite, chalcopyrite and pyrrhotite plus minor amounts of sphalerite and magnetite that are essentially lack sulphate mineral assemblages, while the Kuroko-type deposit consist predominantly of pyrite, galena and sphalerite with small amounts of chalcopyrite, tetrahedrite and tennantite and the sulphate minerals such as barite, gypsum and anhydrite constitute an essential components of the ores. In ore compositions, the Gjersvik deposits are mainly Cu-Zn association and essentially lack Pb and Ba metals, while the Kuroko-type ores are Pb-Zn association with a small amount of Cu but an immense of Ba metal.

Section 5: Summary and conclusions

5.1 Stratigraphic sequence of the Gjersvik Group

The metavolcanic succession of the Gjersvik Group is subdivided into the Bjørkvatnet and the Gjersvik Formations. The former comprises mainly massive amphibolites with a MORB affinity, which has been proposed as the remnant of an ocean-floor based on which the Gjersvik volcanic arc consisting of the magmatic complexes of a thick bimodal meta-volcanic suite in association with the plutonic infrastructures of the Gjersvik Formation was built.

The Gjersvik Formation has been subdivided into three units: older unit of the dark greenstone, younger unit of the keratophyric pyroclastic rock, and youngest unit of the pale greenstone. The evidences for this subdivision result from that (1) these three stratigraphic units have a considerable scale for each one in their occurrences and distributions, and they can be apparently distinctive and separated to each other in the field based on a series of the considerable distinct features such as colour, magnetism, lithologies, mineral assemblages, textures and structures of the rocks; (2) contact between dark greenstone and pale greenstone is sharp but original because the exhalative sediments often occur conformably just in junction between the two. More importantly, the dark and pale greenstones can be distinctly distinguished in geochemical properties, especially in systematic differences of the immobile elements contents and their behaviors such as FeO, MgO, Ti, Cr and Ni; (3) The keratophyric pyroclastic complexes occur mainly between the dark and pale greenstones or are associated predominantly with the dark greenstone, but very few with the pale greenstone. This relation appears to display the keratophyric pyroclastic rock was largely formed later than the dark greenstone but earlier than the pale greenstone, and it has hence been interpreted to be related mainly to an episode of felsic magmatic activities between the basaltic magma processes at two stages; (4) The hydrothermal alterations and sulphide mineralization are mainly associated with the keratophyric pyroclastic complexes or extensively occur within the uinderlying dark greenstone but very few in the pale greenstone, which leads to a deduction that the main sulphide mineralization are predominantly related to an episode of the felsic volcanic processes between depositions of the tholeiitic basalts at two stages; and (5) the exhalative sediments such as magnetite-rich chert related in some ways to an episode of the felsic volcanic activities occurs extensively just in junction between the dark and pale greenstone successions, which become a very useful stratigraphic mark.

5.2 Paleotectonic environment of the Gjersvik deposits

It has been proposed that the Gjersvik massive sulphide deposits were formed mainly within an immature volcanic arc which was built on the ocean floor environment in connection with a rift system development in where there is a complete absence of the continental crust and no supply of normal sediments. Reconstruction of paleotectonic setting of the Gjersvik deposits is mainly based on the evidences in follow.

(1) Stratigraphic successions

Regional geological investigation has indicated the Gjersvik Nappe consists of a sequence of metasedimentary rocks of the Limingen Group and a metamagmatic complex of the Gjersvik Group. And, the Gjersvik Group has been evidently interpreted to be stratigraphically lower than the Limingen Group (Halls, et. al., 1977; Kollung, 1979; and Lutro, 1979). The Gjersvik Group has been subdivided into Bjørkvatnet and Gjersvik Formations, the former being stratigraphically older than the latter, and present a remnant of the ancient ocean crust on which the Gjersvik volcanic arc. The metavolcanic succession of the Gjersvik volcanic arc has been subdivided into three stratigraphic units, i.e., felsic volcanic complexes, dark and pale greenstones. The dark greenstone is evidently proposed to be stratigraphically older than the pale greenstone, whereas the keratophyric pyroclastic complexes represent an episode of felsic volcanic activity between tholeiitic basalts, the dark and pale greenstones being their present metamorphosed equivalents, respectively. This can be dedicated that the primary magma processes are multicyclic during construction of the Gjersvik volcanic arc, which can be divided into three main stages, i.e., early undifferentiated tholeiitic, felsic to late differentiated tholleiitic magma processes related to a rift system development in the intro-ocean floor environment.

(2) Bimodal compositions both in the metavolcanic and meta-intrusive rocks

The Gjersvik volcanic arc is characterized by well-defined bimodal basalt-rhyolite volcanic assemblages plus their plutonic infrastructures that are essentially lack of andesite and diorite. The metavolcanic rocks are composed mainly of the greenstones of tholeiitic composition and the keratophyric pyroclastic complexes of rhyolitic composition, while the meta-intrusive rocks comprise trondhjemite and gabbro. Martin and Piwinskii (1972) pointed out that igneous rocks generated at convergent plate boundaries tend to be characterized by unimodal petrochemistry, whereas those generated in rift zones are characterized by bimodal petrochemistry, especially in silica content of volcanics.

(3) Rock types and magma series

The metavolcanites in the Gjersvik volcanic arc are tholeiitic in magma series, and are dominated by tholeiitic lava, massive flow and volcanic clastic rocks, the greenstones being their present metamorphosed equivalents. The felsic pyroclastic volcanic rocks extensively scatter in the lower part of the mafic volcanic pile but are only about 20 % in volume of all volcanic rocks, which means the Gjersvik volcanic arc was made up mainly by tholeiitic basalts. It has been recognized that the typical volcanic-plutonic series of more mature island arcs and active continental margin is generally "andesitic" and "calc-alkaline", but basaltic rocks of the tholeiitic series may actually be the fundamental magma type in young or immature arcs in intro-oceanic settings (Coats, 1962, 1968; Ewart et al., 1973; Shiraki and Kuroda, 1977; Wilson, 1989). In addition, It is significant that no identified sediments deriving directly from continental sources and the continental crust have so far been found to be represented in the volcanic arc besides of a lot of thin, conformable exhalative sedimentary layers. These features have accentuated the Gjersvik volcanic arc as an immature volcanic arc in where there is an absence in supply of the normal sediments from the continental source.

(4) Meta-intrusive association

The Gjersvik volcanic arc is extensively associated with the plutonic infrastructures consisting mainly of trondhjemites and gabbro, which constitute respectively roots of the metavolcanic keratophyric pyroclastic complexes and the greenstone. Trondhjemite has in a global sense been known to occur mainly in three tectonic settings: Archean gneiss terraces and

Late Archean greenstone-granite terraces; Phanaeozoic and some Proterozoic extrusive and intrusive bodies in plate-tectonic environments of convergent oceanic-continental and oceanic-oceanic types; and as volumetrically minor component of many ophiolites (Barker, 1979). This kind of the magmatic complex associations in the Gjersvik volcanic arc can be distinct and different from those in the present mid-ocean ridge environments and in the present oceanic islands.

(5) Geochemistry of the metavolcanites

The dark and pale greenstones can be well distinct in geochemical properties to each other, especially in systematic differences of the immobile elements contents and their behaviors such as FeO, MgO, Ti, Cr and Ni. The pale greenstone has strong enrichment in Cr, Ni, and Mg, but depletion in Ti and Fe relative to the dark greenstone. This kind of systematic differences in trace element compositions reveals differences of the primary magma sources. Correlations of Mg against Cr and Ni point out that the pale greenstone was formed by differentiated tholeiitic magma, while the dark greenstone was originated from undifferentiated tholeiitic magma. In addition, the dark greenstone in the immobile elements contents and behaviors is in certain extent associated with the island arc and back-arc tholeiitic basalt affinity, but the pale greenstone tends to be comparative to the E-type MORB affinity. These features have accentuated the differences of tectonic environments and primary magma sources between the dark and pale greenstones.

5.3 Metavolcanic rocks and their plutonic infrastructures constituting the Gjersvik volcanic arc

5.3.1 Main rock types of the magmatic complexes

The Gjersvik volcanic arc consists predominantly of a magmatic complex plus small exhalative sediments. The metavolcanic rocks of the dark and pale greenstones are extensively associated with submarine sedimentary structures such as massive, pillowed, amygdaloidal and fragmental structures, whereas some of the felsic volcanic rocks often with felsic fragments and breccias, which indicate their primary origins mainly as basaltic flow, pillowed lava and clastic volcanic rocks and as felsic volcanic pyroclastic rocks in submarine environments. Chemically, the greenstones are consistent with the basaltic rocks in SiO2 contents, ranging from 47 to 53.5 wt. % SiO2, whereas the metafelsic volcanic rocks vary mainly from 71 to 75 wt.% SiO2 that can be comparative to rhyolitic compositions. Whether the greenstones or metafelsic volcanic rocks are all characterized by the Na-rick and K-poor features, being mainly from 4 to 6 wt.% Na2O and from 0.02 to 0.5 wt.% K2O in contents, and between 5.5 - 7 wt.% Na2O and between 0.1 - 0.9 wt.% K2O in the greenstones and in the felsic rocks, respectively. And, albite is one of the mostly dominate rock-forming minerals in these volcanic rocks but very few potassium feldspar has been distinguished. Furthermore, plots in Hughes'igneous spectrum indicate that almost greenstones and all metafelsic volcanic rocks fall outside in the normal igneous spectrum on the Na-enriched side but concentrate on field of the spilite and keratophyre. The original rocks of the greenstones and metafelsic volcanic rocks have hence been referred as the spilitized basalts and the keratophyric pyroclastic rocks of rhyolitic composition, respectively.

The plutons are composed of the mafic and felsic rocks. The felsic plutonic rocks are characteristic of Na rich and relative Al2O3 low, generally less 14.5 wt.%, and their mineral assemblages and chemical compositions are comparable with those of the trondhjemite defined by Goldschmidt (1916) and Barker (1979), but are distinct from granodiorite, which has further confirmed in terms of a normative An-Ab-Or classification diagram for common siliceous igneous rocks. The felsic plutons are hence proposed as a subtype of low-Al2O3 trondhjemite, thereas the mafic intrusives as gabbro.

5.3.2 Lithologies

(1) Metavolcanic rocks

Dark Greenstone

The dark greenstone is characterized by dark green in colour, massive to variable schistose, fine grain, rarely visibly porphyritic crystals, Fe-rich and slight-magnetism in hand specimen and field outcrops and by holocrystalline-porphyritic and holocrystalline-homogeneous textures. The porphyritic texture is mainly composed of lath-shaped albite setting in matrix consisting largely of felsic minerals, chlorite and epidote. Content of the porphyritic minerals ranges generally from 15 to 25 percent. Almost all porphyritic crystals of the albite are orientated and surrounded by schistosity. The dark greenstone consists mainly of chlorite and albite with considerable, but variable amounts of epidote, stilpnomelane, biotite, muscovite, sericite, quartz and carbonate. Occasionally, augite as a remnant of primary mineral phase has been recognized to occur within interior of the pillows with relative low-grade metamorphism and deformation. Magnetite and pyrite are common accessory minerals occurring as fine-grained anhedral or euhedral, with lessly abundant sphene. On the basis of major mineral assemblages, several subtypes can be separated, i.e., stilpnomelane- and biotite-bearing, epidote-rich and chloritic greenstones.

The epidote-bearing and chloritic greenstones constitute the most dominant types of the dark greenstone. They are often associated with some typical volcanic structures deposited in the submarine environment such as pillowed, clastic and amygdaloidal structures. The stilpnomelane- and biotite-bearing greenstones are restricted to occur in locations in where they tend to be associated with the fault zones. They can be distinct in appearance of the stilpnomelane and biotite and in relative massive structure to the epidote-bearing and chloritic greenstones. The stilpnomelane laths tend to occur without preferred orientation and to cut all existing textures and fabrics, including hydrothermal quartz and carbonate veins. Meanwhile, stilpnomelane can be not only limited to occur within the dark greenstone and but also be associated with the keratophyric pyroclastic complexes. These features appear to point out that the stilpnomelane must be very late in their form and are, perhaps, related in some ways to late fault tectonic activities after the regional low-grade metamorphism.

Pale greenstone

The pale greenstone is mainly holocrystalline-homogeneous and porphyritic in textures and characteristic of less pillowed and clastic structures relative to the dark greenstones, which appears to indicate an origin of the major massive basaltic flow. It is light green in colour, fine-grained, massive to schistose, Fe-poor and no magnetism, and carbonate-rich. Its main mineral assemblage is similar to that in the dark greenstones consisting predominantly of chlorite, epidote and albite, but is characterized by higher property of carbonate in content and by presence of iron-poor actinolite. Carbonate ranges generally from 10 to 15 percent, whereas actinolite varies among 0 to 20 percent in content.

keratophyric pyroclastic complexes

The keratophyric pyroclastic rocks scatter extensively as rather thin complexes within the dark greenstone. They are white to light grey or to light rose in color, very fine-grained, much hard and dense with associating, sometimes, recognizable free quartz in hand specimen. The relative large complexes consist apparently of the felsic volcanic pyroclastic rocks, while the smaller felsic bodies are generally dykes, sills or subvolcanic rocks. The massive sulphide deposits known so far in the Gjersvik area are mainly associated with the pyroclastic complexes.

The keratophyric pyroclastic complexes consist of albite, quartz with small amounts of sericite, carbonate, chlorite, epidote and biotite, among which the felsic minerals which are dominated by albite range usually from 80 to 95 percent. The complexes are characteristic of holocrystaline-porphyritic textures consisting of phenocrysts setting in a very fine-grained matrix of quartz and albite with subordinate chlorite and epidote. The phenocrysts, generally less 20 percent in content, are mainly composed of euhedron to subeuhedron tabular albite occurring as either individual crystal or aggregates with a few roundish quartz and subeuhedron biotite. All phenocrysts are in certain extent oriented and surrounded by schistosity.

(2) Plutonic complexes

The plutonic complexes are dominated by trondhjemites with minor amounts of gabbro. The trondhjemite is subdivided into two coarse-grained and fine-grained porphyritic phases. The intrusive bodies are various in scale, among which the relative large bodies comprise either the complexes consisting of the trondhjemite plus minor xenoliths of the gabbro or the coarse-grained trondhjemite, while the relative small bodies include fine-grained porphyritic trondhjemite and gabbro. Contact between the coarse-grained and fine-grained porphyritic trondhjemites has been revealed to be continue and immediately transitional, and the coarse-grained and fine-grained porphyritic trondhjemites are very similar in their mineral assemblages. Only distinction between the two is, perhaps, in their textures, being the relative fine-grained and porphyritic, and the coarse-grained, holocrystalline and approximately equigranular granitic textures, respectively. They have hence been interpreted to represent a shallow-seated and deep-seated phase of co-magmatic processes, respectively. However, contacts between the intrusive bodies and the greenstones are almost tectonic and no clear primary contact relations can be observed. It seems that the thrusts in the regional scale often exist in boundary between the intrusive bodies and the greenstones.

The trondhjemites consist predominantly of plagioclase dominating albite or oligoclase, quartz with small amounts of chloride, epidote, muscovite, sericite and carbonate plus very few potassic feldspar, and pyrite is are main accessory minerals, within which the mafic minerals (chlorite after epidote, chloritized biotite) are low, usually between 2 - 3 percent and occasionally up to 10 % in contents. The albite is about 60 percent in content, and mainly euhedron and tabular grains with obvious twinning but without zoning, about 1 - 3 mm in size. The albite is locally but often clotted with secondary sericite and muscovite. The quartz is anhedron grains, varying from 0.2 to 2 mm in size, and about 35 percent in content.

The gabbro is composed of chlorite, clinozoisite, chloritized biotite and amphibolite with small amounts of secondary quartz and carbonate. The clinozoisite often keep in pseudomorphs of the plagioclase and is about 40 - 50 percent in content. The biotite is anhedron, scaly, with perfect cleavage, but frequently chloritized. The amphibolite have two good cleavages.

5.3.3 Chemistry of the magmatic complexes

(1) metavolcanic rocks

Metavolcanic rock series

On the basis of a series of the rock chemical diagrams such as K2O - SiO2, Alkali Index (A.I.) -Al2O3, FeO*/MgO - TiO2 and F-M-A, the metavolcanic rocks are plotted on them to display a nature of the tholeiitic magma series. Due to the fact that the Gjersvik volcanic arc is dominated by the greenstones occupying probably about 80 per cent in volume, plus only small amounts of felsic volcanic rocks, it is hence proposed to be made up mainly by tholeiitic basalts. It has been shown that immature island arcs are usually made up of basaltic rocks of the tholeiitic series, whereas calc-alkaline magma are typical of more mature arcs and active continental margins (Wilson, 1989).

Bimodal feature

The metavolcanic rocks in the Gjersvik volcanic arc are characterized by a typical bimodal compositions, especially in SiO2 content. SiO2 content of the greenstones concentrates on the range of 50 - 52 percent and varies mainly among 46 to 56 percent, whereas the keratophyric pyroclastic rocks concentrates on 72 - 76 wt.% SiO2 and ranges largely from 70 to 78 percent. No typical volcanic rocks of andesitic composition have so far been found to occur within the Gjersvik volcanic arc. In recent review of magmatism and tectonic settings throughout the world, Martin and Piwinskii (1972) noted that two kinds of magmatism in orogenic and nonorogenic belts are associated with two tectonic settings, compressional and tensional (rifting) environments, the former being calc-alkaline or hypersthenic in magma series, consisting of andesitic volcanogenic sequences predominantly of andesite, high-alumina basalt, and dacite with fragmental volcanoclastic strata and of quartz monzonite, granodiorite, and quartz diorite with minor granite, diorite, and gabbro in batholithic belts, the latter obvious bimodal basalt-rhyolite volcanic assemblages that are essentially lack or volumetrically insignificant andesites.

Major elements

Generally, fields of major elements of the greenstones in variation diagrams of MgO versus Al2O3, CaO, TiO2, FeO, Na2O and K2O are not completely coincident with each of tholeiitic basalts occurring in typical but different tectonic environments such as MORB (Mid-ocean ridge basalts), HTB (Hawaiian tholeiitic basalts) and IATB (Island arc tholeiitic basalts). However, they, especially MgO versus Al2O3, TiO2 and FeO, tend to be concentrated on field between MORB and IATB. Relationships between pairs of the major elements show that MgO and TiO2 are immobile and can be used in inferring primary magmatic processes, the FeO, CaO and

Al2O3 are probably in certain extent mobile and can conditionally be used in petrogenetic interpretions, whereas Na2O and K2O are too mobile to be used in interpreting primary magmatic processes. The reason leading Na2O and K2O changes has been interpreted to be related mainly to the secondary geological processes. There is a big difference in a group of element populations such as MgO, TiO2 and FeO between the pale and dark greenstones. The pale greenstone is characterized by high magnesium but low iron and titanium in contents relative to the dark greenstone, which probably indicates a difference of their primary magma compositions.

Trace Elements

Interrelations of the pairs of some trace and minor elements point out that post-magmatic alterations related to the mineralization and the regional metamorphism are minimal and neglect in the most trace and minor immobile elements and that abundances of Ti, Zr, Cr, Ni and Y, most probably exhibit primary magmatic compositions, but the Nb and P, perhaps including some mobile elements such as Rb, Ba and Sr, were in certain extent changed during the second geological processes.

A group of immobile element populations in the pale and dark greenstones are very significant and distinct to each other. The pale greenstone is characterized by apparent high Cr, Ni, but low Ti and Y relative to the dark greenstone. And, Co is slightly high but the Zr and the V are low in the pale greenstone relative to those in the dark greenstone. The difference in the trace element populations between the dark and pale greenstones has been interpreted as the differences of their magma sources. In addition, plots of the greenstones on the diagrams of MgO against Ni and Cr show that the Ni and Cr increase systematically and apparently with the increase MgO in the pale greenstone, but they have no obvious variation with increase MgO in the dark greenstones. It has been revealed that the Ni abundances in MORB strongly controlled by olivine fractionation (Wilson, 1989). Thus, the different geochemical behaviors among the Cr, Ni and Mg display that the dark greenstone was originated from the undifferentiated tholeiitic basalt magma, while the pale greenstone from the differentiated tholeiitic basalt magma. These different differentiated trends are further revealed in plots of the dark and pale greenstones on the diagram of V - TiO2.

Abundances of some immobile elements and their ratios in the dark and pale greenstones are used to make a comparison with tholeiitic basalts generated in distinct tectonic environments. The compatible trace elements Ni and Co in the pale greenstone are correlated to those in the E-Type MORB, and the Cr to that in the Back-arc tholeiitic basalts (BATB), while the Cr/Ni and Ni/Co ratios (Cr/Ni, Ni/Co) are very closed those in the N-type MORB and the E-type MORB, respectively. In contrast to this, the Ni and Cr contents as well as the Ni/Co ratio in the dark greenstone are correlated to those in the Island-arc tholeiitic basalts (IATB), but the Co and Cr/Ni ration are comparable with those in the N-Type MORB. The incompatible trace elements Ti in the pale greenstone is comparable to that in the IATB, Y is correlated to that in E-type MORB, and Zr lies between those in the E-type MORB and the IATB, but their rations (Zr/Y, Ti/Zr) are all correlated to that in the N-type MORB. However, the Ti and Y in the dark greenstone are very closed those in the BATB, while the Zr and Zr/Y ratio are comparable to that in the IATB. Furthermore, it is calculated that the correlative coefficient of the pale greenstone to E-type MORB is 0.45, to N-type MORB 0.27, to IATB 0.18, and to BATB 0.1, whereas the dark greenstone to IATB 0.5, to BATB 0.2, to N-type MORB 0.2, and to E-type MORB 0.1, which show that the pale greenstone tends to be related mainly with the E-type MORB and in certain extent to the N-type MORB, while the dark greenstone is in great extent correlated to the IATB and to, in some ways, the BATB. This nature demonstrates that the pale greenstone was probably originated from source of the E-Type MORB mantle, but it was probably in certain extent mixed by some material of island arc tholeiitic basalt, while the dark greenstone was mainly generated in the island arc environments.

In addition, the pale and dark greenstones are further discussed in terms of some tectonomagmatic discrimination diagrams of trace elements, especially immobile elements, such as Cr - Ti, Cr - Y, Zr - Ti, Ti/100 - Zr -Y.3, and Ti/100 - Zr - Sr/2 diagrams in order to reconstruct their paleotectonic environments. The results have demonstrated that the dark and pale greenstones are tholeiitic in magma series and were not originated from the calc-alkaline basalts associated uniquely with subduction, and they appear to be of a transitional nature, i.e., the dark greenstone tends to be correlated mainly to the IATB, but with in certain extent the MORB and BATB affinities, whereas the pale greenstone is comparable largely to the E-type MORB, but is also in some ways correlated to the N-type MORB, BATB and IATB.

(2) Intrusive rocks

Bimodal feature

The plutonic rocks are also characterized by bimodal composition, ranging 45 - 53 wt.% SiO2 in the gabbro and varying 70 - 78 percent in the trondhjemites that are obviously lack of diorite composition, which are comparable with the eruptive equivalences with which they are associated in the Gjersvik volcanic arc.

Chemical series

The trondhjemites exhibit a strong trondhjemitic trend that is rather different from the normal calc-alkaline suites in magma series. This feature is revealed in terms of plots of the felsic intrusive rocks in the K-Na-Ca and in the normal Q-Ab-Or diagram. It has been recognized that the trondhjemite represents a low-K\Na-ratio type of calc-alkaline rock (Barker and Arth, 1976) or a low-(FeO* + MgO) type (Barker, 1979), which is different from the calc-alkaline quartz diorite-tonalite-granodiorite-granite suites that form the bulk of the Mesozoic circum-Pacific batholiths. As the recent knowledge state, magma of the normal calc-alkaline series are generally restricted in their occurrence to subduction-related tectonic settings (Wilson, 1989), the trondhjemite and cogenetic, less siliceous and more mafic rocks are a major component of Archean greiss terranes, which occur in the volcanic and plutonic parts of Late Archean granite-greenstone terranes, or scatter widely within extrusive and intrusive bodies in plate-tectonic environments of convergent oceanic-continental and oceanic-oceanic types, or constitute a prominent if volumetrically minor component of many ophiolites (Barker, 1979).

Major elements

The trondhjemites are characterized by relative high Na2O but low K2O and Al2O3. For example, K2O content varies from 0.32 to 2.22 percent, Na2O from 4.49 to 6.88 percent, whereas granite usually contains about 4 percent or more K2O and less 4 percent Na2O in contents. And, Al2O3 content is generally less than 14 percent, which appears to indicate an ocean environment because the continental trondhjemite generally contains more than 14.5 to 15 percent Al2O3, whereas oceanic trondhjemite has less than 14.5 to 15 percent (Arth J.G. 1979).

Due to the fact that the keratophyric pyroclastic rock and the trondhjemites are completely comparative in their main mineralogy and bulk chemical compositions, the keratophyric pyroclastic rocks can be interpreted as an extrusive equivalent of the felsic plutons. This point may further be supported by Na2O, K2O and CaO systematic variations in these three kinds of the felsic rocks, i.e., K2O, Na2O and CaO contents in the fine-grained porphyritic trondhjemite generally lie between the coarse-grained trondhjemite, which is characterized by relative higher K2O and CaO but much low Na2O contents, and the keratophyric pyroclastic rocks with very low K2O and CaO but very high Na2O. And, the K2O and CaO gradually decrease with Na2O increase from the coarse-grained, via fine-grained porphyritic trondhjemites to the keratophyric pyroclastic rock, which show a good linear and negative correlation. This phenomena can be explained by evolution of the magma system and bit-by-bit reaction between magma and sea water during magma ascent processes.

Trace elements

Study of trace element behaviors during magmatic processes indicates that Ba and Rb are major substitutes for K in K-feldspar, hornblende and biotite, while Sr often substitutes readily for Ca in plagioclase and for K in K-feldspar. Thus, change in Ba or K/Ba ratio and Rb and K/Rb ratio may indicate the role of one of these phases in petrogenesis, whereas Sr or Ca/Sr ration is a useful indicator of plagioclase involvement at shallow levels (Wilson, 1989). These element changes in contents are gradual and systematic in the felsic intrusives and extrusives. Rb, Sr, and Ba concentrations gradually decrease from the coarse-grained (av. 41.63 ppm Rb, 211.5 ppm Sr, and 601.25 ppm Ba), via the fine-grained porphyritic trondhjemites (av. 27.2 ppm Rb, 104.4 ppm Sr, and 172.6 ppm Ba) to the keratophyric pyroclastic rock (av. 3 ppm Rb, 90 ppm Sr, and 63 ppm Ba) (see Table 3.3, 3.6), while their substitutes K and Ca display parallel geochemical behaviors. For example, variations of K2O versus Ba and Rb show display very well positive correlations in the coarse-grained, the fine-grained porphyritic trondhjemites and the keratophyric pyroclastic rocks. Parallel trends are also shown in diagrams of CaO versus Sr and Rb versus Sr. Property of the element correlations and their systematic variation behaviors indicate an evolution of the trondhjemitic magma from relative deep-seated, via shallow-seated levels to extrusive phase and the co-magmatic affinity between the trondhjemites and keratophyric pyroclastic complexes.

5.3.4 Relationship among different types of the magmatic rocks

(1) Relationship between dark and pale greenstones

The pale and dark greenstones are very characteristic of and distinct ro each other in geology and geochemistry. Contact between the dark and pale greenstones is sharp but original because the exhalative sediment layers often occur conformably just in junction between the two. The pale greenstone are characterized by much high Cr, Ni, and relative high Mg, but low Fe and Ti relative to the dark greenstone. Cr content in the pale greenstone is generally higher than 130 ppm, Ni higher than 65 ppm, and MgO higher than 6 wt.%, but FeO less than 12 wt.%, and TiO2 less than 1.2 wt.%, while Cr and Ni in the dark greenstone are usually less than 50 ppm, MgO less than 6 wt.%, but FeO higher than 13 wt.%, and TiO2 higher than 1.2 wt.%. Especially, average Cr and Ni contents in the pale greenstone are roughly eight times as much as those in the dark greenstone, respectively. These distinct and systematic differences in chemical compositions very probably imply a difference of magma sources between the dark and pale greenstones, respectively. In addition, correlations of MgO against Ni and Cr point out that the pale greenstone was generated by more evolved tholeiitic magma, while the dark greenstone was produced from undifferentiated tholeiitic magma.

(2) Relationship between greenstones and keratophyric pyroclastic rocks

The keratophyric pyroclastic complexes are stratigraphically interpreted to occur mainly between the dark and pale greenstones, which represent an episode of felsic magma processes between depositions of tholeiitic basalts. Major massive sulphide mineralization occurring within the Gjersvik volcanic arc are predominantly associated with the keratophyric pyroclastic complexes.

(3) Relationship between felsic intrusive and extrusive rocks

The geological evidence from detailing surface mapping shows that the coarse-grained trondhjemite is transitional and continue in contact with the fine-grained porphyritic trondhjemite, which indicate a co-magmatic origin. The fine-grained porphyritic trondhjemite most probably represent a shallow-seated phase in connection with relative deep-seated coarse-grained trondhjemite. This conclusion is further confirmed by major and trace element compositions.

Relationship between the trondhjemite and the keratophyric pyroclastic complexes is further accentuated on two aspects. One is that the keratophyric pyroclastic rocks and the trondhjemites are completely comparative in mineralogy and chemical compositions, and only different in rock textures to each other. Another that correlations between some major elements such as Na2O, K2O and CaO and trace elements including Rb, Sr, Ba, Nb, and Y exhibit strongly systematic and linear variations from deep-seated coarse-grained, via shallow-seated fine-grained porphyritic trondhjemites to extrusive keratophyric pyroclastic complexes. These properties have been interpreted as a result both felsic magma evolution in the crust higher level and of reactions between ocean water and felsic magma system during magma ascent processes towards the surface from relative deep portion. The felsic rocks associated with the Gjersvik volcanic arc have hence been proposed to be mainly co-magmatic and the keratophyric pyroclastic rocks can be interpreted as an extrusive equivalent of the deep-seated coarse-grained and the shallow-seated fine-grained porphyritic trondhjemites.

It must be emphasized, however, that some felsic intrusives associated with the pale greenstone probably represent later felsic magma activities. The felsic magmatic activity is probably multystage, which has been shown in terms of U-Pb zircon absolute dating for the felsic plutons associated with the Gjersvik volcanic arc on the regional scape (Roberts & Tucker, 1991; Kullerud, et. al., 1988).

5.3.5 Petrogenetic and paleotectonic model

A simplified petrogenic and paleotectonic model for the Gjersvik volcanic arc proposed here has accentuated mainly on several aspects in follow.

(1) The Gjersvik volcanic arc represents an immature or primitive volcanic arc which was formed in and built on the ocean floor environments in connection with a rift system development, in where there are a complete absence of the continental crust and no a voluminous sediment supply, perhaps, far away from the continents. And, the fundamental tectonic environments during construction of the Gjersvik volcanic arc is extensive or rifting rather than compressive.

(2) The Gjersvik volcanic arc consists of bimodal volcanic-plutonic complexes, which are definitely different in lithologies and geochemistry from those in mature island arc or continental margin related to convergent plate, and are also distinct from those in typical mid-ocean ridge and within ocean island arc environments related to divergent plate

(3) Magma processes of the Gjersvik volcanic arc must be multi-cyclic, probably major three stages, and each magma cycle may corresponds to a limited rifting environment related to the rift system development. At the early and late stages, magma processes are characterized respectively by the undifferentiated and the differentiated tholeiitic basalts, while the felsic magmatic processes are mainly present in an interval between depositions of the tholeiitic basalts.

(4) The early undifferentiated tholeiitic basalts were derived mainly from the depleted mantle source and were in some ways related to the initial rifting over the subduction zone between the ocean-floor plates, whereas the late tholeiitic basalts were generated as a consequence of the diapiric upwelling of deeper, enriched mantle source and were connected with the deeper, developing rift system. Due to the fact that the keratophyric pyroclastic complexes and their plutonic equivalents are mainly associated with the dark greenstones and gabbro within the Gjersvik volcanic arc, the felsic magma processes are thought to occur by partial melting of the undifferentiated tholeiitic basaltic or gabbro sources at shallow depths, which is also related to the rift system development.

5.4 Massive sulphide mineralization

5.4.1 Distribution and size

The massive Cu-Zn sulphide deposits have so far been found to occur extensively as a part of the bimodal metavolcanic sequence in the Gjersvik volcanic arc. Of them the Gjersvik and the Skorovas deposits are most important both in sizes and in economic value. The Gjersvik ore deposit as second big one following the Skorovas orebody in size is associated with c. 1.6 m.t. of ores (massive and disseminated) with an average of 31 % S, 1.6 % Cu and 0.9 % Zn with few amounts of Pb and precious metals (Oftedahl, 1958). The Skorovas orebody, located in about 40 km to the south of the Gjersvik deposit, with c.10 m.t. of ores massive and disseminated predominantly pyritic ore with an average grade of 1.3 % Zn and 1.0 % Cu, together with trace amounts of Pb, As and Ag (Halls et. al. 1977) used to be in production, but was closed in 1986. The Skorovas deposit was proposed to be comparative with and very similar to the Gjersvik ore body in tectonic setting, stratigraphic horizon, geological and lithological environments, as well as geology of ore bodies by Reinsbakken (1980, 1981). Some considerable differences, however, do exist between the two deposits. On the one hand, for example, the Skorovas massive sulphide ore body is associated with relative more Zn and Pb metals and is lack of pyrrhotite, while the Gjersvik ore body is dominated by Cu plus minor Zn but without Pb metals and the pyrrhotite is one of the most important components of ore mineral assemblages; on the other hand, a lot of jasper has been distinguished to occur as distal exhalative sediments in the mineralization horizon in the Skorovas area, whereas magnetite-rich cherts constitute the most important distal exhalative sediments extending in the mineralization horizon, but very few jasper have so far been found in the Gjersvik area. In addition, the other smaller deposits such as Annlifjellet, Tjiermajaevrieh, Gjersvikklumpen and those in the southern and northern shore of the Bjorkvatnet Lake, have been found to have less importantly economic value. These deposits are comparative and similar to the Gjersvik deposit.

5.4.2 Types and main features of the mineralization

The sulphide mineralization can be subdivided into three types, i.e., massive sulphide, exhalative, and veining mineralization.

<u>Massive sulphide mineralization</u>

Massive sulphide mineralization are generally situated at an interface between metavolcanic stratigraphic units of the greenstones and of the keratophyric pyroclastic complexes and the ore horizon consists of massive sulphide ores (sulphides generally over 60 vol.%) associated initially with a stringer (so-called feeder zone) characterized both by intensive wall-rock hydrothermal alterations and by extensively interconnected and disseminated sulphide mineralization which occur within and cut through the keratophyric pyroclastic complexes directly below the massive orebody. The association relationship between massive sulphide ores and altered stringer is intimated and the feeder zone has been interpreted as a path leading the mineralized solution flow towards the surface on the ocean floor in where accumulate the massive sulphides.

The massive sulphide ore bodies are generally stratiform, lensoid, and plate-like, varying from tens cm to several meters in thickness and from tens to several hundred meters in length and are conformable with their wall rock, while the feeder zone underlying directly below massive orebody is usually pipe-like or irregular, and is discordant with the host keratophyric pyroclastic complex. For example, present geometry of the Gjersvik orebody consists of an asymmetrical, spoon-shaped, synformal structure which plunges southerly with the eastern limb more steeply dipping than the western. The horizon of massive ores itself is an irregular 1 - 5 m thick and occurs just in junction between felsic pyroclastic complex and the greenstone, extending into within the greenstone. The road sections (both old and new roads) cutting through both limbs of this structure exhibit clearly outcrops of the massive orebody which is directly overlain by the interconnected network of sulphide veining and sulphide disseminated mineralization associated with intensive hydrothermal wall-rock alterations cutting and occurring within the felsic pyroclastic complex. The present sequence that the massive sulphide horizon is overlain by the altered, pyritic felsic complex but underlain by unaltered dark greenstone most probably indicates an inverted stratigraphic position.

Exhalative sedimentary mineralization

A thin, iron- and silica-rich, base-metal-depleted facies occurs extensively either in or near junction between the dark and pale greenstones or within the dark pillowed greenstone. They are usually characterized by obvious sedimentary structures and no hydrothermal alterations. This kind of mineralized horizon is interpreted as an exhalative sediment of setting of colloidal iron and silica hydrosol following explosive dispersal into the submarine environment related either to a volcanic episode of the keratophyrical pyroclastic eruption occurring between basic magmatic activities of dark and pale greenstones or to the pillowed tholeiitic basalts during construction of the Gjersvik volcanic arc.

The exhalative sediments occur mainly as thin, sheet- or plate-like layers or lenses, generally several tens cm to meters in thickness and several to tens meters in length or width. They are very regular in occurrence and conformable with the metavolcanic host succession and some of them are obviously synchronously folded together with their wall rocks. These thin, exhalative sedimentary layers can in places be traced about several hundreds to thousand meters along an identical stratigraphic horizon either between the dark and pale greenstones or within the dark pillowed greenstone, which have frequently been used as an useful key horizon that separates the metamorphosed volcanic-stratigraphic units formed in different episodes of tholeiitic basaltic magma activities. The exhalative sediments are simple in mineralogy and consist predominantly of magnetite, quartz and pyrite associated with or without subordinate sericite or muscovite and carbonate minerals. They are characterized by both of very well laminated structure, consisting predominantly of alternating laminae of pyrite, magnetite and chert, which are often superimposed by later fold structure, and of very fine-grained, paragenetic texture, generally less 0.05 mm in size, which appear to point out a circumstance of their primary chemical sedimentary processes.

Veining mineralization

This kind of mineralization, which were well revealed by the surface detailing mapping and the drilling core, occurs mainly as thin vein, stockwork and disseminated sulphide mineralization associated with intensive hydrothermal alterations within the underlying dark greenstone. They are present mainly as long belts, generally several to tens meters wide and tens to hundreds meters long, which cut through the dark greenstone and are sharp in contact with their wall rocks, which shows that they are apparently controlled by fault or fissure structures.

The vein mineralization are mainly veining, stockwork and linear-type disseminated in structures, and consist mainly of pyrite with varying amounts of chalcopyrite and sphalerite plus small magnetite. Sulphide content within the mineralization zones generally varies from 20 to 30 percent. It is significant to mention that the metal mineral assemblages and hydrothermal alterations in the vein mineralization are very similar and comparative with those in the feeder zone.

5.4.3 Ore mineralogy, textures and zoning

Massive sulphide horizon consists of massive sulphides associated with a stringer zone (feeder zone) characterized by interconnected pyritic mineralization plus intense hydrothermal alterations.

Massive sulphide phase

The massive sulphide phase comprises largely massive ores containing sulphides generally over 90 vol.% with less importantly banded sulphide ores containing sulphides about 50 - 70 vol.%. The ores comprise predominantly pyrite, pyrrhotite, chalcopyrite, and sphalerite with a considerable amount of magnetite. Non-metal minerals include quartz and carbonate as well as minor chlorite and sericite. Quartz is generally less 0.05 mm, but some up to 0.1 - 0.3 mm in size. Chlorite often occur as aggregate or recrystalline big crystal and tends to increase in places near the greenstone wall rocks. Sericite is mainly associated with chlorite. The quartz and calcite are all anhedron, generally 0.2 - 0.5 mm in size, and often intergrowth to each other to constitute a paragenetic texture.

Textures of the ores indicate an extensive and intense affection of metamorphism and deformation on the deposits. For example, typical foam texture of massive pyrite indicate an affection of slow heating during metamorphism to the ores, and recrystallization of the sphalerite related to the metamorphism was observed to occur extensively in the massive ores, while cataclastic texture of the pyrite and compressive strain texture in the massive pyrite ores are regarded as en evidence of the ore deformation. It must be emphasized, however, that some primary textures can still be reserved in the ores even though metamorphic and deformed textures are most dominant within the ores. For example, the texture which small pyrrhotite crystal occur as discontinue circling drops within big pyrite crystal most probably reflects a primary paragenetic relationship between pyrite and pyrrhotite during the pyrite crystallization from mineralized fluid, and also indicates a relative high temperature condition when they formed.

On the basis of major metal mineral assemblages, mineral content, their spatial relationship to each other and to the adjacent host rocks, the ore horizon of the Gjersvik massive orebody can be subdivided into five major ore facies or ore types, and their distribution and zonation constitute a part of volcanic stratigraphic succession. Succession of the massive sulphide horizon and relationship to their wall rocks are shown in follow:

greenstone (in top)

Type V: fine-grained, massive, banded pyrite-magnetite facies
Type IV: fine-grained, compact, massive pyrite-sphalerite (with magnetite) facies
Type III: fine-grained, massive to banded pyrite facies
Type II: fine- and coarse grained, compact, massive pyrrhotite-pyrite-chalcopyrite facies
Type I: fine-grained, compact, massive Cu-rich pyrite facies

keratophyric pyroclastic complex associated with a feeder zone (in bottom)

The massive sulphide horizon is dominated by type I, II, and III, and the massive Cu-rich pyrite (chalcopyrite + pyrite) and the massive pyrrhotite + chalcopyrite + pyrite phases which tend to occur in side of the massive orebody immediately overlying or adjacent to the altered pyritic feeder zone associated with keratophyric pyroclastic complex, grading upward and outward to the massive pyrite phase, while the type IV and V are only present in local places in where they occur as part of marginal zone or of lateral extent of the massive orebody bordering to the greenstone. The former is characteristic of very compact, massive, whereas the latter of massive and banded textures. The type I and II are the most important Cu-bearing ores, whereas the type III is dominated by pyrite with small amounts of Cu-bearing minerals. The ores are mainly fine-grained, but become in places relative coarse-grained in texture. It appears that the coarser the sulphides are in size, the higher the chalcopyrite is in content. The chalcopyrite and pyrrhotite often replace the pyrite to occur along edges and fractures of or as intergranular minerals within pyrite grains, as well as between boundaries of pyrite grains.

Sulphide stringer phase or feeder zone

A stockwork system of interconnected pyritic quartz-calcite veining with associated extensive wall-rock hydrothermal alterations occurs within and cuts through the metafelsic volcanic complex directly beneath the massive sulphide horizon, which has been interpreted as `feeder zone' or `root zone'.

In the case of the Gjersvik ore body, the individual thin sulphide vein within the feeder zone, generally several to tens mm wide, often coalesces upwards the sulphide horizon into larger mineralized zones about several meters in width, consisting of sulphide veins or channels associated with intermediate alterations or of dense disseminated sulphide mineralization with intense alterations in the keratophyric pyroclastic complex. Generally, the intense alteration zone is often associated with relative strong mineralization characterized by disseminated sulphides, varying from several to approximate 40 percent in content, consisting mainly of pyrite (generally over 80 percent) with small amounts of chalcopyrite with trace sphalerite and pyrrhotite, the intermediate alteration zone is characteristic of veining and veinlet sulphide mineralization consisting either of dominant pyrite or of approximately equal pyrite and sphalerite plus minor chalcopyrite, while the weak alteration zone is only associated with weak pyritic mineralization, which pyrite is usually less 5 percent in content. Gangue minerals include quartz, sericite, albite and calcite with small chlorite.

5.4.4 Hydrothermal wall-rock alterations

The hydrothermal alterations are mainly but extensively associated with the feeder zone and the vein mineralization occurring underlying the dark greenstone and consist largely of silicification, sericitization, carbonitization and chloritization. Based on main mineral assemblages, alteration grades as well as their spatial distribution, three alteration zones associated with the feeder zone within the keratophyric pyroclastic complexes directly under massive sulphide horizon can be subdivided: weak, intermediate and intense alteration zones. Distribution of the hydrothermal alteration zones tends to increase gradually in alteration grade towards the massive sulphide horizon. The weak alteration zone directly grades into intermediate or into intense alteration zones. The weak alteration zone is characterized by less differences from the unaltered metafelsic pyroclastic rocks in mineralogy, whereas the intense alteration zone almostly consists of altered minerals.

The weak alteration zone is characterized by slight alteration consisting of silicification and trends to occur in outside of the felsic complex adjacent to intermediate or intense alteration zone, but generally doesn't contacts directly with the massive sulphide body. It, in fact, has no big difference in mineral assemblages and textures to the regional metafelsic rocks and is generally associated with slight mineralization consisting predominantly of disseminated pyrite about 3 - 5 percent in content. The intermediate alteration zone is mainly silicification, sericitization and carbonitization, and characterized by obvious veining, veinlet and stockwork sulphide mineralization. This altered zone consists mainly of altered minerals of quartz, sericite, and calcite with minor amounts of albite, chlorite and epidote, being up, sometimes, to 80 percent in their contents. This altered zone is often characterized by obvious veining, veinlet and stockwork sulphide mineralization consisting mainly of pyrite with minor amounts of chalcopyrite and sphalerite. The intense alteration zone is dominated by silicification and sericitization ana almost entirely composed of altered minerals consisting of quartz and sericite together with small chlorite, carbonate and muscovite as well as varying sulphides. It is often associated with disseminated sulphide mineralization but the mineralization grade is various, ranging from very weak to 20 - 50 percent of sulphides.

Variation of bulk chemical compositions of the alteration zones in comparison with unaltered rocks shows that Si and Al appear to be relatively immobile during hydrothermal alteration process although they are rather gained or lost, to a certain extent, in different alteration zones. Fe has no much change in each alteration zone but becomes very apparently additional component only in intense alteration zone associated with strong mineralization, which is obviously caused by immense precipitation of pyrite in this zone. However, K, Na, Ca, and Mg are very mobile during the hydrothermal alteration process. Na is a mostly principal lost component, whereas K is a mostly principal gained component. Changes in Na and K compositions are consistent with bit-by-bit albite decomposition and step-by-step sericite addition from weak, via intermediate to intense alteration zones during the hydrothermal alteration processes. Similarly, Ca displays an exceptional trend that it loses about 40 % and 83 - 97 % in weak and intense alteration zones, respectively, but extraordinarily increases up to 200 % in intermediate alteration zone, which was most probably caused by calcite vast growth in intermediate alteration zone. Mg is a largely grained component in weak and intermediate alteration zones, but is grained or lost in great extent in intense alteration zone, which mainly reflects chlorite variation in different alteration zones.

5.4.5 Chemistry of the ores

The Gjersvik deposit comprises mainly Cu-Zn ore association with average grade of 1.55 % Cu and 0.84 % Zn, but no valuable Pb metal is associated with the ores. Plots of the different ore types in triangular Cu-Zn-Pb diagram show that Pb content is very low, generally less 5 percent, and hence the ores all belong to Cu-Zn association. However, ratio of Cu and Zn is different from type to type of the ores. The ores of pyrite + chalcopyrite and pyrite + chalcopyrite + pyrrhotite assemblages have highest ratio of Cu:Zn about 5.5, while the ores of pyrite + sphalerite assemblages have lowest ratio of Cu:Zn about 0.09. The pyrite ores have a variable scope in ratio of Cu: Zn, but their average value is about 5.5. And, chemistry of the ores displays that variety of the ore-forming metals depend mainly on the ore types. It seems clear that Cu is the most dominant component in the ores of pyrite + chalcopyrite and pyrite + pyrrhotite + chalcopyrite assemblages, within which Cu content is generally over 1 percent, but is low and variable in the ore of pyrite and pyrite + sphalerite assemblages, within which Cu is generally less 1 but over 0.1 percent in content. Zn is the most dominant component in the ores of pyrite + sphalerite ores, up to 4 - 7 percent in content, but varies in the ores, ranging generally between 1 and 0.1 percent of pyrite + chalcopyrite and pyrite + pyrrhotite + chalcopyrite assemblages, while it is very low in the ores of pyrite and pyrite + magnetite assemblages.

Metal contents and variations in the ores are mainly related to zonation of the ore types. For example, Cu tends to decrease and Fe gradually decreases in contents, while Zn tends to increase, and Pb seems to have a parallel behavior with Zn from the core ore zone grating towards outside zones, i.e., from pyrite + chalcopyrite, and pyrite + pyrrhotite + chalcopyrite, via pyrite, to most outside pyrite + sphalerite or pyrite + magnetite ore zones. Zonation of the ores and systematic variety of their chemical compositions in the different ore zones are most probably primary and related to chemico-physical conditions during precipitation of the ores.

Furthermore, Cu has the highest content in the strong alteration zone, but gradually decreases from strong, via moderate to weak alteration zones within the feeder zone. Zn and Pb display a similar geochemical behavior in different alteration zones, i.e., they are low in the weak and strong alteration zones, but abruptly increase in contents in moderate alteration zone. The reason is that the moderate alteration zone is mainly associated with vein and veinlet mineralization, within which sphalerite and galena are relative higher in contents than in the weak and strong alteration zones.

5.4.6 Origin of the deposits

It has been compared that the Gjersvik deposits are associated with much more differences rather than similarity relative to the Kuroko-type deposit. Origin of the Gjersvik deposits has hence been accentuated on the several aspects in follow.

Geological environments

The deposits have been proposed to occur mainly within an immature or primitive volcanic arc which was built on the ocean floor in connection with rifting environments in where there are complete absence of the continental crust and no supply of normal sediments. Study of the volcano-stratigraphic succession, petrology and geochemistry points out that the early rifting activity was characterized by volcanic process of the undifferentiated tholeiitic basalt related in some ways to the subduction between oceanic plates, the late developing rifting environment was associated with new volcanic process of the differentiated tholeiitic basalts derived from deeper mantle source, while the keratophyric pyroclastic complexes were formed mainly at a stage between the early initial and the late developing rifts during construction of the Gjersvik volcanic arc.

The keratophyric pyroclastic complexes extensively scatter as small and variable scales in occurrences within the Gjersvik volcanic arc and consist of felsic pyroclastic rocks, sills and dikes. The massive sulphide mineralization are mainly associated with the relative big keratophyric pyroclastic rocks. Distribution of the felsic complexes is mainly controlled by extensional fault zones, and the massive sulphide mineralization are hence also thought to be related to extensional fault zones in connection with the rifting system development.

Ore-forming system

Mineralization in the Gjersvik volcanic arc can be apparently subdivided into three types: massive sulphide ores associated directly with a feeder zone, exhalative sediments and vein sulphide mineralization, even though the later two types have no any recoverable value to have known so far. The massive sulphide horizon is predominantly associated with the keratophyric pyroclastic complex within which often occurs a feeder zone characterized by both of apparent vein, stockwork sulphide mineralization and intense hydrothermal alterations directly below the massive sulphide orebody. The exhalative sediments are mainly present within the dark, pillowed greenstone as a distal extension of the exhalative massive sulphide horizon or in junction between the dark and pale greenstone, although they can also occupy at level of the pale, pillowed greenstone near the boundary to the dark greenstone. The vein sulphide mineralization associated with apparent hydrothermal alterations are mainly limited to occur within the underlying dark greenstone. It is more interesting that the vein mineralization and the feeder zone directly below the massive sulphide horizon are consistent in both of their metal and altered mineral assemblages as well as hydrothermal alteration types and that the exhalative sediments are comparative in mineral assemblages with the massive sulphide orebodies. Furthermore, the massive sulphide ores are mainly fine-grained, compact and massive in the central phases of the orebody, which often grades into the banded ores upward and outward to the boundary near wall rocks of the dark greenstone, while the exhalative sediments are very fine-grained in texture and often reserve very good primary sedimentary bands or laminae in structure although they have generally been folded by the late structure. Zonation of the massive sulphide ores both in ore mineral assemblages and metal compositions have shown an original and genetic feature related to the accumulation of a sulphide mound around the vent. Thus, these three types of the mineralization have been considered to have a primitive and genetic connection during ore-forming processes. The massive sulphides with the feeder zone have been proposed to be formed at or near the discharge vents of a submarine hydrothermal systems, the veining sulphide mineralization probably represent a product of seawater-rock reaction between the circulating hydrothermal solution and the underlying tholeiitic basalt pile within which they passed along fracture zones, while the exhalative sediments is interpreted to be formed by chemical precipitation of colloidal iron and silica hydrosol or their oxides of the discharge hydrothermal solution plumes in distal, or stratigraphically higher positions relative to the massive sulphide body following explosive dispersal into the reduced submarine environment.

Physico-chemical conditions

Mineralization in the Gjersvik volcanic arc are mainly related to an episode of the felsic magmatic processes between depositions of the tholeiitic basalts. The metabasalts, especially the relative older dark greenstone, are extensively associated with submarine pillowed and vesicular textures that indicate a deep water environment. And, pillow rims of the dark greenstone are often associated with pyrite, which is a good indicator of the distal mineralization.

The mineralization has been interpreted to be formed mainly in a strong reduced environment in where they precipitated, since the massive sulphide horizon consist predominantly of pyrite, chalcopyrite, pyrrhotite and sphalerite with minor but considerable amounts of magnetite, while exhalative sediments are composed largely of pyrite and magnetite. Metal mineral assemblages of the ores have shown that the deposits were formed at a relative high temperature condition, probably over 300 C, while zonation of the massive sulphide horizon displays the central facies of pyrite + chalcopyrite and the pyrite + chalcopyrite + pyrrhotite ores were formed in condition of the higher temperature relative to the outside massive pyrite ores and the marginal massive sphalerite + pyrite and pyrite + magnetite ore facies.

The massive sulphide orebodies are generally associated with the keratophyric pyroclastic complexes but not related to the scales of the felsic complexes, which has been considered as an important evidence that heat energy driving the convection cell is mainly connected with the local felsic intrusive-extrusive complexes controlled by extensional fault zones in relation to the intra-ocean rifting system development.

Ore-forming solution

The petrologically distinctive alteration zones occurring in the keratophyric pyroclastic complexes below directly the massive sulphide horizon or within the underlying dark greenstone have been interpreted to be formed by a progressive reaction of rising ore-forming fluids with the wall rocks in a circulating hydrothermal system. The hydrothermal alterations are mainly silicification, sericitization and carbonatization plus minor and variable chloritization. The sericitization was produced mainly by formation of the altered sericite due to breakdown of albite in the feeder zone or to K replacement to the chlorite in the underlying vein mineralization zone in condition of addition of the K-rich fluid, while the silicification and carbonitization resulted largely from precipitations of quartz and calcite during the hydrothermal alteration. Chemistry of the alteration zones have shown that K, Ca, Si and Mg are major addition components, while Na and Al are major loss compositions.

On the other hand, gangue mineral assemblages of the massive sulphide ores are mainly quartz and calcite. It is interesting that these minerals are also most essential components of the altered minerals in the feeder zone and in the underlying vein mineralization zone. However, quartz and calcite in the massive sulphide ores have the paragenetic textures with the sulphide gains and occur mainly as thin bands alternating with sulphide bands, which display an apparent sedimentary feature, while they are present in the feeder zone and the vein mineralization mainly as hydrothermal filling, replacements and precipitation in association with other altered minerals. The affinity of mineral components between the massive sulphide ores and the feeder zone points out that the Si, CO2 and Ca play an important role in the ore-forming solution from which the sulphides precipitated, while difference in their textures and occurrences exhibits different ways and conditions when they precipitated.

Experiment of chemical exchange during hydrothermal alteration between natural seawater and oceanic basalt indicates that SiO2, Ca, K, Ba, B and CO2 were leached from basalt and enriched in the seawater, but Mg, Na and SO4 were removed from seawater into solid phases as the Mg-rich alteration products such as smectite, tremolite-actinolite and into solids by formation of sodic feldspar and possibly analcime, respectively. Thus, K, Si, and Ca that extensely precipitate in the feeder zone and the underlying vein mineralization zone probably came mainly from the circulating seawater leaching through the underling dark greenstone pile in where they passed.

During the ore-forming processes, reactions between the moving solution and the wall rocks linking the channelways and boiling of the ore-forming fluid may be important in the subsurface. During the hydrothermal alterations, extraction of hydrogen ions from solution and potassium replacement to the wall rock tend to reduce the stability of chloride complexes and lead to sulphide mineral precipitation, about which an obvious evidence is potassium replacement to the feldspar or chlorite in the wall rocks to form sericitization. On the other hand, temperature and pressure changes, rapid cooling and mixing of a hot, rising solution with a cold seawater mass may be major factors leading to precipitation of the sulphides in seawater-rocks interface on the ocean floor.

Sources of ore-forming material

Cu, Zn and Fe as major ore metals of the Gjersvik deposits have been proposed to be mainly leached from the underlying dark greenstone pile through which the ore-forming fluids passed, which is concluded on the basis of the comparison of ratios of Cu, Zn and Pb metals in the ores with the major but different types of the rocks in the Gjersvik volcanic arc.

5.5 Possible application for further prospecting and evaluation in the Gjersvik area

5.5.1 Restriction of the stratigraphic succession for mineralization within the Gjersvik volcanic arc

The regional geological investigations have revealed that the volcano-stratigraphical succession of the Gjersvik volcanic arc can evidently be subdivided into three units, i.e., older dark greenstone, younger keratophyric pyroclastic complexes and youngest pale greenstone. And, the mineralization are predominantly associated with the underlying dark greenstone and the keratophyric pyroclastic complexes, but very few with the overlying pale greenstone. The Gjersvik deposits have thus been considered to be mainly related to an episode of the felsic magmatic processes between depositions of the tholeiitic basalts, the dark and pale greenstones being their present metamorphosed equivalents at the early and the late stages, respectively. This point is extended to an opinion that attention of the further prospecting work for finding the new, valuable massive sulphide bodies should focus on the underlying stratigraphic units of the dark greenstone and the felsic complexes rather than the overlying pale greenstone.

5.5.2 Types of mineralization and their significance

The sulphide mineralization have been subdivided into three types, i.e., massive sulphide, exhalative, and veining mineralization. The massive sulphide mineralization refers to those that the ore horizon, situated generally at an interface between metavolcanic stratigraphic units of the greenstone and of the keratophyric pyroclastic rock, consists of massive sulphide ores (sulphides generally over 60 vol.%) associated initially with feeder zone characterized both by intensive wall-rock hydrothermal alterations and by extensively interconnected and disseminated sulphide mineralization which occur within and cut through the keratophyric pyroclastic complexes directly below the massive orebody. The exhalative sediments consist predominantly of magnetite-rich chert, pyritic chert and chert which occur extensively as thin, small, and conformable layers or lenses in the metabasaltic succession. The veining mineralization are restricted to occur in the underlying dark greenstone and characterized by obvious hydrothermal alterations and veining, stockwork and disseminated sulphide mineralization. It must be emphasized that only massive sulphide mineralization have so far been found to be valuable in size and economic potential, while the later two types of mineralization have no any considerable value.

It should mention that the exhalative sediments are present either in junction between the dark and pale greenstones or within the dark and pale pillowed greenstones. Of them the exhalites which occur within the dark, pillowed greenstone and in boundary between two types of the greenstones are composed mainly of pyritic chert and magnetite-rich chert, which probably represent a distal extend of the exhalative massive sulphide horizon, while others within the pale, pillowed greenstone are characteristic of chert and hematite- and magnetite-bearing chert. The exhalites can be also composed mainly of massive pyrite ores such as those occurring in the northern shore and the southeastern part of the Bjorkvatnet. However, they are generally small in size and contain very few Cu metal because they consist almost of pure pyrite.

The veining mineralization have been interpreted to be formed by reaction between ore-forming solution and the underlying tholeiitic pile through which the fluid passed. They are generally not associated with the massive sulphide bodies. Thus, their importance are most probably in understanding origin of the deposits rather than in taking them as a direct indicator for further prospecting.

5.5.3 Close association of the massive sulphide horizon to the keratophyric pyroclastic complexes

It is significant that massive sulphide deposits with considerable economic potential have so far been known to be associated with the keratophyric pyroclastic complexes. This closely associated relationship has been connected in terms of an interpretion of the felsic magma as heat source or as ` heat machine ' driving ore-forming system of the connective cell that is necessary for formation of the ores. On the other hand, the keratophyric pyroclastic complexes are distributed along and controlled mainly by extensional fault zones in relation to the rift system development, and hence the massive sulphide orebodies associated with the felsic complexes should more or less be controlled by the extensional fault zones. The fault zones are also of the convenient structure paths leading to ascent of the mineralized solution toward the ocean floor surface in where the massive sulphides were precipitated.

5.5.4 Indicator of the hydrothermal alterations

Another important indicator for further prospecting is that the petrologically distinctive alteration zones generally occur within and cut through the felsic complex directly below the massive sulphide body. The main alterations are silicification, sericitization and carbonatization, which were produced by reaction of the ore-forming fluid with the felsic volcanic wall rocks. Furthermore, recognition of the mineralogical and chemical attributes of these alteration zones is also important as an indicator in exploration for these deposits, since the intense silicification + sericitization and silicification + sericitization + carbonitization zones generally occur directly below the massive sulphide orebody, while weak alteration, mainly silicification, away from the massive sulphide orebody. It seems that the relative large massive sulphide orebodies are often associated with relative stronger and apparent hydrothermal alterations. Thus, the hydrothermal alterations, especially intense alterations occurring within the keratophyric pyroclastic complexes may be a highly significant exploration guide.

5.5.5 Types and fabric of the ores and their zonation

It is valuable and useful in evaluation of the deposits that the massive sulphide orebodies with considerable economic potential such as the Gjersvik orebody are associated with good zonation of the ores and with high chalcopyrite and pyrrhotite in contents, while the massive sulphide bodies which were probably formed by distal exhalative sediments are generally small in size and consist almost of pyrite with very low Cu content, such as exposures of the massive pyrite bodies in the northern shore of the Bjorkvatnet along the Gjersvik-Ryorvik road, in the southeastern and northeastern parts of the Bjorkvatnet.

In the case of the Gjersvik deposit, the massive sulphide orebody consists mainly of massive pyrite + chalcopyrite, pyrite + chalcopyrite + pyrrhotite, pyrite ores with small amounts of massive to banded pyrite + sphalerite and pyrite + magnetite ores. It is, perhaps, important to pay more attentions in three aspects for further exploration. The first is zonation of the massive sulphide orebody. The ores constituting the massive sulphide body has been divided into five ore types or phases. Type I and II, i.e., massive pyrite + chalcopyrite, and pyrrhotite + chalcopyrite + pyrite phases tend to occur in side of the massive orebody immediately overlying or adjacent to the altered pyritic feeder zone associated with keratophyric pyroclastic complex, grading upward and outward to the massive Cu-low pyrite ore phase (Type III), while the pyrite + sphalerite and the pyrite + magnetite phases (Type IV and V) are only located in places where they occur as part of marginal zone or of lateral extent of the massive orebody bordering to the greenstone. The second is Cu metal distribution in the orebody. Chemistry of the ores displays that Cu metal is largely associated with the pyrite + chalcopyrite and pyrite + chalcopyrite + pyrrhotite ores (Type I and II), being generally over 1 %, whereas the pyrite ores are usually less 1 % and very variable in Cu content, and the pyrite + sphalerite and pyrite + magnetite ores only contain few Cu metal. The third, Cu content in the ores also depends in certain extent on the ore textures. For example, the pyrite + chalcopyrite and pyrite + chalcopyrite + pyrrhotite ores as most dominant Cu-bearing ore types can be subdivided into fine-grained and coarse-grained two phases. It appears that the coarser are the grains of the metal minerals, the higher are the Cu contents.

5.5.6 Possible potential target area for further prospecting

Present suggestion of the potential target area for further prospecting is mainly based on the surface mapping work in combination with some indicators associated with the known deposits in the Gjersvik area, for instance, volcano-stratigraphic succession in where occurs the massive sulphide horizon, close association of the massive sulphide orebodies with the keratophyric pyroclastic complexes, mineralization types, and alteration associated with the feeder zone directly, perhaps, below the massive sulphide horizon. It appears that the keratophyric pyroclastic complexes associated with the dark greenstone tend to occur in two belts with NE-SW trends in the east and the west of the Gjersvik village, respectively, and the massive sulphide orebodies to have so far known are all associated with them. It is being suggested that the attention for further prospecting would focus on the western area from about Sorvatnet, via Bjorkvatnet to Kirma Luvlie Tjierme-laevrie, especially in the north of the Gjersvik-Royrvik road, although the Gjersvik orebody occurs in the eastern area. This suggestion is based on several considerable reasons.

(1) In the eastern area, the belt consists of some bodies of the keratophyric pyroclastic complexes such as at Gjersvik, Gjersvikklumpen and Royrvatnet and many small, felsic sill, dike or subvolcanic rocks, while the belt in the western area is composed mainly of the keratophyric pyroclastic complexes.

(2) It is obvious that mineralization in the west is more extensive and intense than that in

the east but the Gjersvik deposit. For example, most of the keratophyric pyroclastic complex bodies in the western belt, each of them is associated with a series of exposures of the massive sulphide mineralization such as exposures of the massive sulphides at the southern and the northern shores of the Bjorkvatnet, at the Annlifjellet, and at the Tjiermajaevrieh, but only a small massive sulphide mineralization in the eastern belt has been known to be associated with the Gjersvikklumpen keratophyric pyroclastic complex besides of the Gjersvik body. And, indicators of the distal mineralization such as exhalative magnetite-rich chert, pyritic chert and the pyrite-bearing rims of the pillowes extensively occur in the underlying dark greenstone succession in the west relative to the east. Furthermore, the veining mineralization associated with the underlying dark greenstone are much more extensive in the western than in the eastern area.

(3) Some of the keratophyric pyroclastic complexes accompanying the massive sulphide mineralization in the western belt such as the Annlifjellet are associate with apparent wall rock alterations such as silicification and sericitization, but they in the eastern area generally with very weak alterations if they are present in local places such as at Gjersvikklumpen.

Acknowledgements

The project had been carried out while the author has held about two years, N.T.N.F. post-doctoral fellowship since October 1989 to December, 1991. The financial support for the project were jointly from N.T.N.F. and Grong Gruber A/S. The author is very grateful to Grong Gruber A/S, especially to A. Haugen for their help and support in accommodate, traffic and finance for duration of the field work. A. Reinsbakken is especially thanked for his assistance and some cooperative geological investigations during whole field work. He is indebted to Prof. F. M. Vokes for his assistance, discussion and advice throughout the life of the project.

I would like to thank I. Romme and I. Vokes for their help in chemical analyses; K. Isachsen and A. Monsoy in obtaining thin and polished sections; and A. I. Johannessen in drawing part of the diagrams.

Reference

Akiho Miyashiro, 1974. Volcanic rock series in island arcs and active continental margins. American Journal of Science, 274:321-355

Alt, J.C., Lonsdale, P., Haymon, R. and Muehlenbacks, K., 1987. Hydrothermal sulphide and oxide deposits on seamounts near 21 N East Pacific Rise: Geological Society of America, Bulletin, v. 98, p. 157-168

Amstutz, G. C. edit., 1974. Spilites and spilitic rocks. International Union of Geological Sciences Series A, Number 4. Springer-Verlag Berlin. Heidelberg. New York

Arth, J. G., 1979. Some trace elements in trondhjemites - their implications to magma genesis and paleotectonic setting. in Trondhjemites, Dacites, and Related Rocks. edit. by Barker, p. 123-132, Elsevier Scientific Publishing Company

Barker, F. 1979. Trondhjemites, Dacites, and Related Rocks. Developments in Petrology 6. Elsvier Scientific Publishing Company

Barker, F. and Arth, J. G., 1976. Generation of trondhjemitic-tonalitic liquids and Archean bimodal trondhjemite-basalt suites. Geology, 4, 596-600

Barnes, H. L., and Czamanske, G. K., 1967. Solubilities and transport of ore minerals, in Barnes, H. L., ed., Geochemistry of hydrothermal ore deposits. New York, Holt, Rinehart and Winston, pp. 336 - 381

Bjorlykke, A., Greene,T., Rui,I., and Vokes,F.M. 1980. A review of Caledonian stratabound sulphides in Norway. In Review of Caledonian-Appalachian Stratabound Sulphides, Geological Survey of Ireland, Special Paper 5:29-46

Bryan, W. B., Thompson, B. G., Frey, F. A., and Dickey, J. S., 1976. Inferred settings and differentiation in basalts from the Deep Sea Drilling Project. J. Geophys. Res. 81:4248-4304

Burnham, C.W., 1983. Deep submarine pyroclastic eruptions, in Ohmoto, H. and Skinner, B.J., edit., Kuroko and Related Volcanogenic Massive Sulphide Deposits, Economic Geology, Monograph 5, p. 142-148

Canadian American Seamount Expedition, 1985. Hydrothermal vents on an axis seamount of the Juan de Fuca ridge. Nature. 313:212-214

Cathles, L.M., 1978. Hydrothermal constraints on the formation of Kuroko deposits: Mining Geology, 28:257-265

Coats, R. R., 1962. Magma type and crustal structure in the Aleutian arc. In Crust of the Pacific Basin, edited by MacDonald, G. A. and Kuno, H. Geophys. Monogr., Am. Geophys. Union, 6:92-109

Coleman, R. G. and Donato, M. M., 1979. Oceanic plagiogranite revisited. In Trondhjemites, Dacites, and Related Rocks. edit. by Barker, p. 149-168, Elsevier Scientific Publishing Company

Cook, N. J., Halls, C., and Kaspersen, P. O., 1990. The Geology of the Sulitjelma Ore Field, Northern Norway - Some New Interpretations, Econ. Geol. 85:1720-1737

Date, J., Watanabe, Y. and Saeki, Y., 1983. Zonal alteration around the Fukazawa kuroko deposits, Akity Prefecture, northern Japan, in Ohmoto, H. and Skinner, B.J., eds., Kuroko and Related Volcanogenic Massive Sulphide deposits: Economic geology, Monography 5, p. 365-386

Donato, M. M., 1991. Geochemical recognition of a captures back-arc basin metabasaltic complex. southwestern oregon. J. of Geology, 99, 711-728

Ewart, A., Bryan, W. B. and Gill, J. B., 1973. Mineralogy and chemistry of the younger volcanic island of Tonga, SW Pacific. J. Petrology, 14:429-465

Floyd, P. A., and Winchester, J. A., 1975. Magma type and tectonic setting discrimination using immobile elements. Earth and Planetary Science Letters, 27:211-218

Foslie, S. 1926. Norges svovelkisforekomster. Norges. Geol. Unders. 98:27-42

Foslie, S., and Strand, T., 1956. Namsvatnet med en del av Froyningsfjell. Norg. Geol. Unders., 196:82

Franklin, J.M., Sangster, D.F. and Lydon, J.W., 1981. Volcanic-associated massive sulphide deposits. In Econ.Geol., Seventh-Fifth Anniversary Volume. 485-627

Gale, & Roberts, 1974. Trace element geochemistry of Norwegian Lower Palaeozoic basic volcanites and its tectonic implication. Earth Planet. Sci, Lett. 22:380-390

Gale, G.H., and Pearce, J.A. 1982. Geochemical patterns in Norwegian greenstones. Can. J. Earth Sci., 19:3:385-397

Goldschimidt, V. M., 1916. Geologisch-petrographische studien im hochgebirge des sudlichen Norwegens, IV. Ubersicht der eruptivgesteine im Keledonischen Gebirge zwischen Stavanger und Trondhjem. Vid. Skr. I. Mat.-Nat. Klasse, 2:75-112

Gustavson, M. 1975. The low-grade rocks of the Skalvar area, S. Helgeland, and their relationship to the high-grade rocks of the Helgeland Nappe Complex. Norge geol. Unders., 322:13-33

Hajash, A., 1975. Hydrothermal processes along mid-ocean ridges: an experimental investigation: Contribution to Mineralogy and Petrology, 53:3:205-226

Halls, C., Reinsbakken, A., Ferriday, I., Haugen, A., and Rankin, A., 1977. Geological setting of the Skorovas orebody within the allochthonom stratigraphy of the Gjersvik nappe, central

Norway. In: Volcanic Processes in Ore Genesis. Spec. Pap. No. 7. Inst. Min. Met. Geol. Soc. London, 128 - 151

Hawkins, J.W., Bloomer,S.H., Evans, C., and Melchior,J.T. 1984. Evolution of intra-oceanic arc-trench systems; Technophysics, 102:175-205

Hekinian, R and Fouquent, Y., 1985. Volcanism and metallogenesis of axial and off-axial structures on the East Pacific Rise near 13 N: Econ.Geol. 80:221-249

Hochstaedter, A.G. etc. 1990. Volcanism in the Sumisu Rift, I, Major elements, volatile, and stable isotope geochemistry. Earth and Planetary Science Letter, 100:179-194

Hochstaedter, A.G. etc. 1990. Volcanism in the Sumisu Rift, II, Subduction and non-subduction related components. Earth and Planetary Science Letter, 100:195-209

Hughes, V. J., 1972. Spilites, keratophyres and the igneous spectrum. Geol. Mag. 109:513-527

Humphris, S., and Thompson, G., 1978. Trace element mobility during hydrothermal alteration of oceanic basalts. Geochim. Cosmochim. Acta., 42:127-136

Kollung, S., 1979. Stratigraphy and major structures of the Grong District, Nord-Trondelag. Norges Geologiske Undersokelse (NGU), 354:1-52

Kullerud, K., Stephens, M. B., & Claesson, S., 1988. Age constraints on exotic arc-basin and tectonic implications, central Scandinavian Caledonides. (Extended abstract), Geol. Foren. Stockh. Forn. 110:402-403

Le Roex, A.P., Dick, H.J.B., Reid, A.M., Frey, F.A., Erlank, and Hart, S.R. 1985. Petrology and Geochemistry of Basalts from the American-Antarctic Ridge, Southern Ocean: Implications for the Westward Influence of the Bouvet Mantle Plume. Contri. Mineral Petrol. 90:4:367-380

Lutro, O. 1979. The geology of the Gjersvik Area, Nord-Trondelag, Central Norway. Norges Geologiske Undersokelse (NGU), 354:53-100

Lowell, R.P. and Rona, P.A., 1985. Hydrothermal models for generation of massive sulphide ore deposits: Journal of Geophysical Research, 90:8769-8783

Lydon J.W. 1988. Ore deposit models #14. volcanogenic massive sulphide deposits part 2: genetic models, Geoscience Canada. Volume 15. No. 1. pp.43-65

MacDonald, G. A., 1968. Forms and structures of extrusive basaltic rocks. In Basalts: Treatise on rocks of basaltic composition. Hess & Poldervaart ed. 1:1-16, Wiley Intersciences Pub. New York

Martin, R. F., and Piwinskii, A. J., 1972. Magmatism and Tectonic Setting. Journal of Geophysical Research. 77:26:4966-4975

Marshall, B. (Broadway, N.S.W., Australia), 1990. "Pseudostratigraphy" and thrusting in relation to the structural evolution of the Joma ore body, North Trondlag, Norway. Ore Geology Reviews, 5:3:175-210

Matsukuma, T., and Horikoshi, E., 1970. Kuroko deposits in Japan, a review. in Monograph of Volcanism and Ore Genesis, edited by Tatsuo Tatsumi, pp.153 - 180

Mellin, A.C., 1979. The geology of the Gjersvik area, Central Norway and a study of the chemistry and occurrence of stilpnomelane and biotite in the eruptive rocks in this region., A thesis for the degree of B.Sc. unpublished, in Grong Gruber A\S

Middlemost, E. A. K., 1975. The basalt clan. Earth Sci. Rev., 11:337-364

Middlemost, E. A.K., 1985. Magmas and magmatic rocks. Longman

Mottl, M.J. and Holland, H.D., 1978. Chemical exchange during hydrothermal alteration of basalt by seawater: 1. Experimental results for major and minor components of seawater and basalt: Geochimica et Cosmochimica Acta, 42:8:1103-1116

Mottl, M.J., 1983. Metabasalts, axial hot springs and the structure of hydrothermal systems at mid-ocean ridges: Geological Society of America, Bulletin, 94:161-180

O'Connor, J. T., 1965. A classification for quartz-rich igneous rocks based on feldspar ratios. U.S. geol. Surv. Prof. Pap., 525-B, 79-84

Odling, N. E., 1986. The geology of the Joma sulphide deposit, Nord-Trondelag, Norway, Part I Structural studies of the ore and surrounding area, Unpublishing research report, in Department of Geology and Mineral Resources Engineering, University of Trondheim-Norwegian Institute of Technology

Odling, N.E., 1989. The structural history of the Leipikvattnet Nappe in the Joma area of Nord Trondelag, central Scandinavian Caledonides, Norway. Norsk Geologisk Tidsskrift, 69:3:141-162

Oftedahl, C., 1956. Oversikt over Grongfeltets Skyvedekker, Norges. Geol. Unders., 195:57-64

Oftedahl, C., 1958. Oversikt over Grongkulminasjonen og Grongfeltets Skyvedekker. Norg. Geol. Unders. 202:76

Oftedahl, C., 1958. a theory of exhalative-sedimentary ores. Geol. Foren. Stockholm Forh., 80:1-19

Olsen, J. 1980. Genesis of the Joma stratiform sulphide deposit, Central Norwegian Caledonides, In Proceedings of the Fifth Quadrennial IAGOD Symposium, E.Schweizerbart'sche Verlagsbuchhandlung Germany, Stuttgart 1980

Pearce, J. A., and Cann, J. R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. Earth Planet. Sci. Letters, 19:290-300

Pettersen, O., 1972. unpublished report. in Grong Gruber A/S

Plimer, I.R., 1978. Proximal and distal stratabound ore deposits: Mineralium Deposits, 13:345-353

Ramberg, I. B., 1967. Kongsfjellomradets geologi, en petrografisk og strukturell undersokelse i Helgeland, Nord-Norge. Norges geol. Unders. 240

Read, M.H., 1983. Seawater-basalt reaction and the origin of greenstones and related ore deposits: Econ.Geol. 78:446-485

Reinsbakken, A., 1980. Geology of the Skorovass Mine: a volcanogenic massive sulphide deposit in the Central Norwegian Caledonides, Norges Geologiske Undersokelse (NGU), 360:123-154

Reinsbakken, A., 1986. The geology of the Joma sulphide deposit, Nord-Trondelag, Norway, Part II Stratigraphical, petrographical, mineralogical and geochemical studies of the ore and its surroundings, Unpublished report in Department of Geology and Mineral Resources Engineering, University of Norwegian-Trondheim Institute of Technology

Riverin, G., and Hodgson, C. J., 1980. Wall-rock alteration at the Millenbach Cu-Zn mine, Noranda, Quebec. Econ. Geol., 75:424-444

Roberts, D. & Tucher, R. D., 1991. U-Pb zircon age of the Moklevatnet granodiorite, Gjersvik Nappe, central Norwegian Caledonides. NGU (Geological Survey of Norway), 421:33-38

Sawkins, F.J., 1984. Metal deposits in relation to plate tectonics. Springer-Verlag

Sclater, J.G., Jaupart, C., and Galson, D., 1980. The heat flow through oceanic and continental crust and the heat loss of the earth. Rev. Geophys. Space Phys., 18:269-311

Schilling, J.G., Zajac, M., Evans, R., Johnston,T., White,W., Devine, J.D., and Kingsley, R. 1983. Petrology and Geochemical Variations along the Mid-Atlantic Ridge from 29 N to 73 N. American Journal of Sciences, 283:510-586

Shiraki, K. and Kuroda, N. 1977. The boninite revisited. J. Geogr. (Tokyo), 86:34-50 (in Japanese)

Sinton, J. M. and Freyer, P., 1987. Mariana trough lavas from 18 N: implications for the origin of backarc basin basalts. J. Geophys. Res. 92:12:782-12

Smith, J. R., Taylor, B., Malahoff, A., and Petersen, A., 1990. Submarine volcanism in the Sumisu Rift, Izu-Bonin arc: submersible and deep-tow camera results. Earth and Plene. Sci. Lett. 100:148-160

Solomn, M., 1976. "Volcanic" massive sulphide deposits and their host rocks: a review and an explanation. In Wolf, K.A., Handbook of Stratabound and Stratiform Ore Deposits, Regional studies and specific deposits. Amsterdom, Elsevier. 21-50

Strand, T., 1960. The Pre-Devonian rocks and structures in the region of Caledonian deformation. In Geology of Norway, Holtedahl, O., ed. Norg. geol. Unders. 208:170-284

Stephen, M. B., 1980. Spilitization, element release and formation of massive sulphide in the Stekenjokk volcanites, Central Swedish Caledonides. Norges Geol. Under. 360:159-194

Stephen, M.B. & Reinsbakken. A. 1981. UCS Excusion No.B14., Successions related to island arcs in the Koli. nappes, Central Scandinavian Caledonides. In Excursions in the Scandinavian Caledonides. Uppsala Caledonide Symposium 1981.

Stephens, M.B., and Swinden,S. H., and Slack,J.F. 1984. Correlation of Massive Sulphide Deposits in the Appalachian-Caledonian Orogen on the Basis of Paleotectonic Setting. Econ. Geol. 79:1442-1478

Stephens, M. B., Gustavson, M., Ramberg, I. B., and Zachrisson, E., 1985. The Caledonides of central-north Scandinavia - a tectonostratigraphic overview. in Gee, D. G., and Sturt, B. A., eds., The Caledonide orogeny - Scandinavian and related area: London, John Wiley and Sons, p.135-162

Stephens, M. B. (Ed), 1986. Stratabound sulphide deposits in the Central Scandinavian Caledonides, 7th IAGOD Symposium and Nordkalott Project Meeting, Uppsala.

Sun Shensu, Robert W.Nesbitt, 1979. Geochemical characteristics of mid-ocean ridge basalts. Earth and Planetary Science Letter, 44:119-138

Toshinori Matsukuma and Ei Horikoshi, 1970. Kuroko deposits in Japan, a Review. in Volcanism and Ore Genesis, edit. Takeo Watanabe, University of Tokyo Press

Urabe, T., and Kusakabe, M., 1990. Barite silica chimneys from the Sumisu Rift, Izu-Bonin Arc: possible analog to hematinic chert associated with Kuroko deposits. Earth and Planetary Science Letter, 100:283-290

Vaughan, D. J. and Craig, J. R., 1978. Mineral chemistry of metal sulphides. Cambridge University Press, Cambridge, England

Vokes, F. M., 1968. Regional metamorphism of the Palaeozoic geosynclinal sulphide ore deposits of Norway. Insi. Mining Metallurgy, sec. B, 77:53-143

Vokes, F.M. 1969. A review of the metamorphism of sulphide deposits. Earth-Sci. Rev., 5:99-143

Vokes, F. M., 1976, Caledonian massive sulphide deposits in Scandinavia: A comparative review, in Wolf, K. H., ed., Handbook of stratabound and stratiform ore deposits. Amsterdam, Elsevier, 6:79-127

Vokes, F. M. 1986. Latest Proterozoic and Phanerozoic metallogeny in Fennoscandia. Proceedings of the Seventh Quadrennial IAGOD Sympsonium (1986), Schweizerbart'sche Verlagsbuchhandlung, 1988

Wilson, A. C., 1960. Origin of pillow structure in early Precambrian lavas of western Quebec. J. Geol. 68:97-102

Wilson, M. 1989. Igneous petrogenesis, a global tectonic approach. Unwin Hyman

Winchester, J. A. and Floyd, P. A., 1976. Geochemical magma type discrimination: application to altered and metamorphosed basic igneous rocks. Earth Planet. Sci. Letters, 50:11-30

Zachrisson, E. 1971. The structural setting of the Stekenjokk ore bodies, Central Swedish Caledonides. Econ. Geol., 66:641-52

Zachrisson, E. 1982. Spilitization, mineralization and vertical metal zonation at the Stekenjokk stratabound sulphide deposit, central Scandinavian Caledonides. Inst. Mining Metallurgy Trans. 91:B192-199