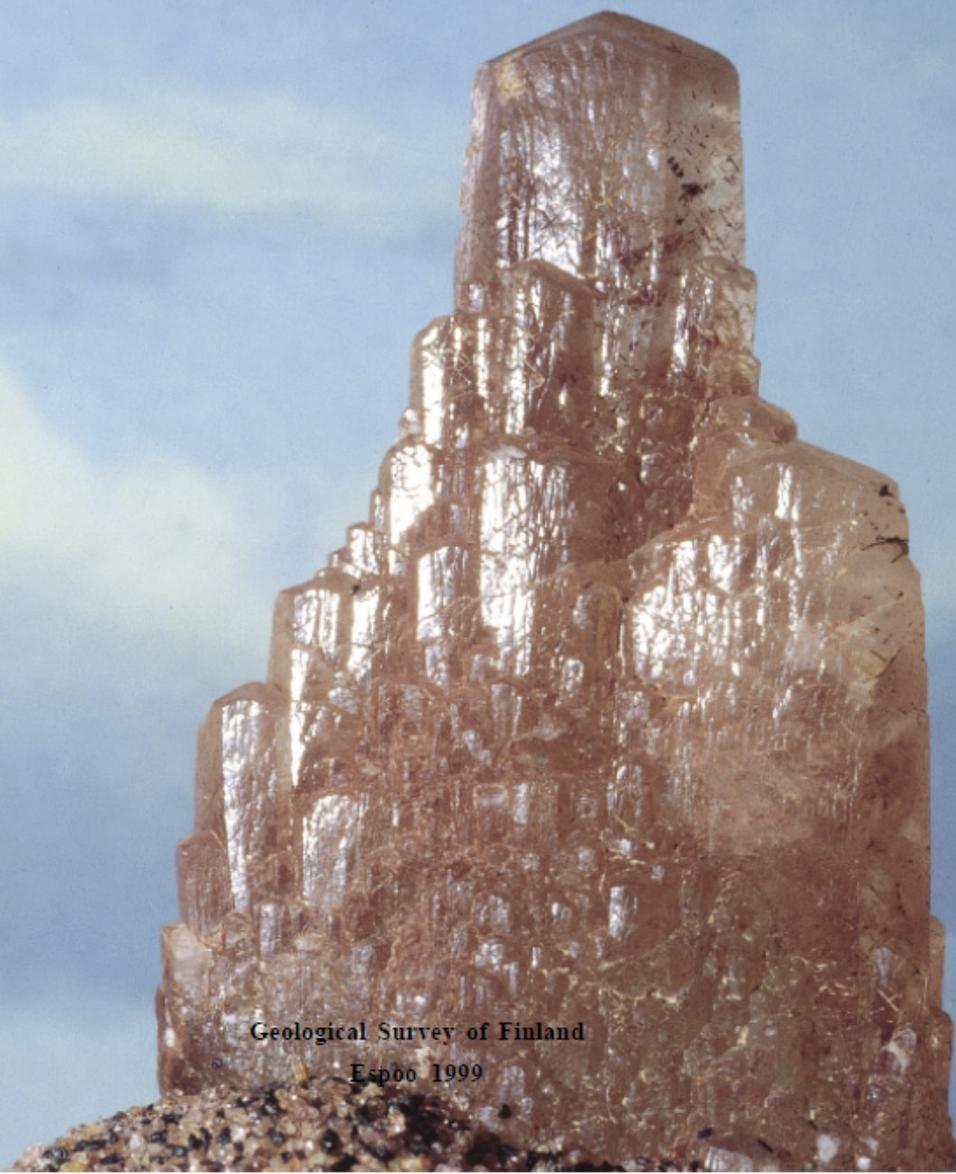


Geological Survey of Finland, Special Paper 27

**Geological Survey of Finland
Current Research 1997 - 1998**

edited by Sini Autio



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Espoo 1999

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The diversity of topics dealt with in this volume is a clear sign of the change under way. Along side traditional topics such as mineral studies and petrology, the search for fresh approaches is obvious. The volume sets a new trend in the range of research results it covers. The concern for human health is revealed in the studies of the toxic properties of Precambrian bedrock and arsenic in groundwater. Knowledge of the cultivability of soil is of practical importance as are the geophysical properties of clay, geophysical interpretations of the bedrock and physical properties of industrial minerals. International co-operation produces maps that extend across national borders.

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Raimo Matikainen

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Raimo Matikainen

CHEMICAL AND MODAL COMPOSITION OF GRANITOIDS IN THREE DIFFERENT GEOLOGICAL UNITS, SOUTH-POHJANMAA, WESTERN FINLAND

by

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Key words (GeoRef Thesaurus, AGI): granites, granodiorites, quartz monzonite, tonalite, granite gneiss, diatexite, mineral composition, chemical composition, Proterozoic, Paleoproterozoic, western Finland

Introduction

Chemical and mineral (modal) compositions are the two most used numerical and effective parameters in classifying and describing granitoid rocks (Streckeisen 1976, Streckeisen & Lemaitre 1979, Pearce et al. 1984, Barbarin 1990). These properties have relatively close relationships, but the mineral composition does not strictly correlate with the chemical composition of the granitoids. For example, the A/CNK values that are used to discriminate I- and S-type granitoids have no direct relationship to the modal composition of the rock. The chemical and modal composition of granitoids are related to a large number of factors, such as variable magmatic source and differentiation processes (e.g. Clarke 1992). Moreover, regional or contact metamorphism can later change the mineral modes of granitoids. The chemical composition of granitoids can, however, be used to establish genetic links between spatially associated granitoid rocks.

This paper gives an introduction to the chemical and modal compositions of the granitoids in three different, neighbouring geological units within a restricted area (4000 km²) in the Palaeoproterozoic Svecofennian domain (age 1.93-1.82 Ga), South-Pohjanmaa, western Finland (Fig. 1) (cf. Korsman et al. 1997). The different units of the research area are the Central Finland granitoid complex, the Pohjanmaa schist belt and the Vaasa granitoid complex (Fig. 1). The most abundant granitoids in the area are tonalites, granodioritic diatexites and

porphyritic granites. The less common rocks include granodiorites, pyroxene granitoids, granitic gneisses and pegmatites (cf. Laitakari 1942).

The term granitoid, as defined in the IUGS classification, refers to a plutonic rock with a quartz content between 20 and 60 volume% (see Bates & Jackson 1980). The authors have used in the present study the term granitoid in a wider sense and included in the granitoids also the quartz monzonites, diatexites and granitic gneisses.

Our chemical data consists of 143 bulk rock analyses. The modal composition of 135 rock samples was determined by point counting. The samples were collected from the various granitoid types and areas shown in the bedrock maps (cf. Saksela 1934, Lahti & Mäkitie 1990, Mäkitie et al. 1991, Lehtonen & Virransalo, in press). The chemical and modal composition of these granitoid types and areas are shown as average values (Table 1). The authors have collected the samples studied here in detail during bedrock mapping, ore prospecting and granitoid studies of the Geological Survey of Finland.

Regional geological setting

The research area in South-Pohjanmaa, Finland, is a part of the Palaeoproterozoic Svecofennian accretionary arc complex of central and western Finland (age 1.90-1.87 Ga) (Korsman et al. 1997). There are three major geological units in this area

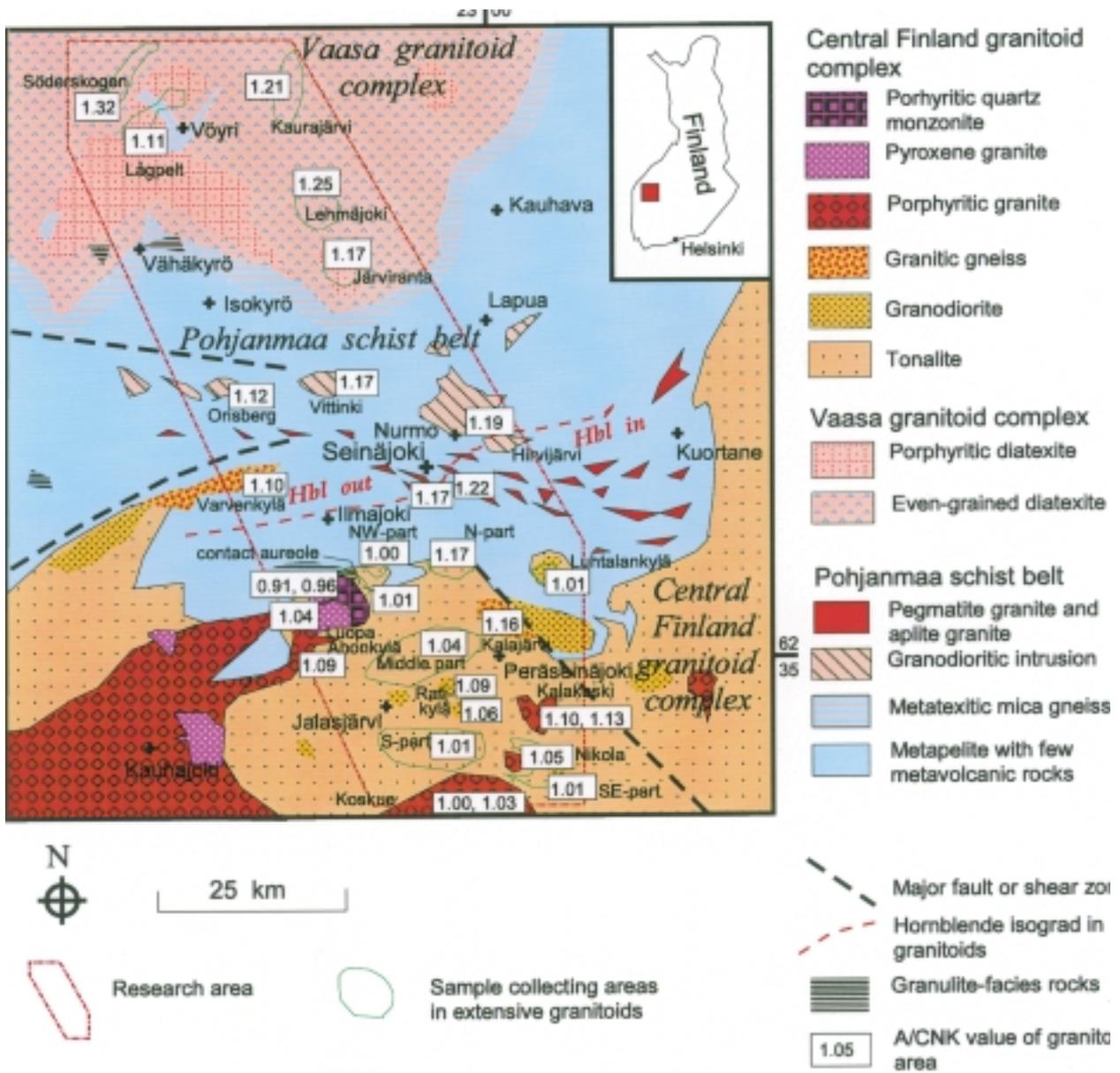


Fig. 1. Simplified geological map of the research area in South-Pohjanmaa. The numbers in boxes are A/CNK-values of the granitoid areas studied. The map is modified after Saksela (1934), Tyrväinen (1970, 1971), Lahti and Mäkitie (1990), Mäkitie et al. (1991) and Lehtonen and Virransalo (in press).

(Fig. 1) (cf. Korsman et al. 1997): A) the southern part that is a part of the Central Finland granitoid complex (CFG) (age 1.89-1.87 Ga) (cf. Väyrynen 1923, Nurmi & Haapala 1986), B) the middle part consists of supracrustal rocks of the Pohjanmaa schist belt (PSB) (cf. Laitakari 1942), and C) the northern part that is composed of granitoid rocks of the Vaasa granitoid complex (VGC) (earlier called the Vaasa granite) (age 1.89-1.88 Ga) (cf. Laitakari 1942).

The rocks of the Central Finland granitoid complex (ca. 45.000 km²) are mostly collision related granodiorites and tonalites with a lot of granites that mainly post-date the main stage of crustal thickening (Korsman et al. 1997, Elliott et al. 1998). Most

of the rocks of the CFGC in the research area are tonalites (age 1882±9 Ma) and little younger porphyritic granites occur as less abundant (Mäkitie & Lahti 1991).

The characteristic rocks in the about 50 km wide Pohjanmaa schist belt are mica schists and mica gneisses, originally pelites and greywackes metamorphosed in conditions of low pressure amphibolite facies. Mafic metavolcanic rocks are less abundant. Orogenic granitoids occur as small intrusions and locally granitic pegmatites are common (e.g. Mäkitie & Lahti 1991, Vaarma & Pipping 1997).

The Vaasa granitoid complex (ca. 6000 km²) is mainly composed of rather homogeneous, porphyritic to even-grained granodioritic rocks (Laitakari 1942),

Table 1. Chemical and modal composition of the studied granitoids. n.d. = not determined, + = rarely detected, - = not detected. 'Others' refers to zircon, opaque, chlorite etc. (continues on next page)

Geological unit	Central Finland granitoid complex (CFGC)														
	Tonalites							Granodiorites		Porphyritic granites					
Location	SE-part	S-part	Middle NW-part	N-part	Contact aureole	Luhtalan-kylä	Rati-kylä N	Rati-kylä S	Koskue inner part	Koskue border part	Nikola	Kalakoski inner part	Kalakoski border part	Ahon-kylä	
number of analyses	4	5	6	3	2	4	3	2	2	3	4	2	6	4	2
SiO ₂ wt%	62.33	65.69	64.94	62.04	69.97	63.82	69.09	69.69	69.64	70.95	68.45	72.45	72.66	68.73	73.78
TiO ₂	0.70	0.57	0.61	0.64	0.46	0.66	0.40	0.38	0.36	0.37	0.52	0.34	0.31	0.46	0.21
Al ₂ O ₃	16.34	15.93	16.69	17.15	14.29	16.28	15.40	15.14	14.70	13.30	14.44	13.61	13.89	14.53	13.52
Fe ₂ O ₃ tot	6.52	5.28	4.94	6.66	4.01	5.90	2.98	3.36	3.35	3.59	5.06	3.30	2.82	4.18	2.52
MnO	0.10	0.08	0.08	0.11	0.06	0.09	0.05	0.07	0.07	0.04	0.08	0.06	0.03	0.06	0.03
MgO	2.98	1.90	2.11	2.42	1.40	1.88	1.40	1.16	1.10	0.53	0.54	0.28	0.50	0.88	0.18
CaO	4.61	4.14	4.33	5.29	2.50	4.24	2.20	2.96	2.68	1.85	2.24	1.47	1.42	2.29	1.06
Na ₂ O	3.12	3.20	3.37	3.47	3.12	3.23	5.15	3.11	2.87	2.35	2.94	2.66	2.47	2.70	2.46
K ₂ O	2.45	2.73	2.39	1.73	2.38	2.86	2.60	3.10	3.92	5.20	5.16	5.48	5.21	4.21	5.92
P ₂ O ₅	0.21	0.16	0.20	0.23	0.13	0.34	0.09	0.05	0.12	0.10	0.15	0.07	0.07	0.13	0.07
Sum	99.34	99.69	99.65	99.74	98.29	99.28	99.36	98.99	98.78	98.29	99.57	99.69	99.38	98.16	99.74
Rb ppm	109	85	88	63	63	n.d.	72	133	131	117	148	216	145	150	196
Ba	857	903	852	685	813	700	683	1535	1070	1497	1653	1100	978	1185	629
Sr	482	400	563	550	586	250	443	420	460	213	197	115	153	230	95
Cs	5	4	4	3	2	n.d.	3	n.d.	5	2	2	3	n.d.	n.d.	1
Ta	1	3	1	n.d.	1	n.d.	n.d.	1	1	n.d.	2	2	n.d.	n.d.	1
U	2	2	3	n.d.	3	n.d.	5	n.d.	6	2	2	2	n.d.	n.d.	n.d.
Th	7	14	6	4	10	n.d.	7	6	25	9	8	10	n.d.	n.d.	15
La	27	28	21	n.d.	47	n.d.	n.d.	18	37	25	50	53	n.d.	n.d.	n.d.
Y	29	28	26	n.d.	14	n.d.	n.d.	23	14	31	53	41	28	30	n.d.
Sc	23	17	12	28	10	n.d.	6	11	13	11	15	11	8	n.d.	3
Ga	22	21	22	25	33	n.d.	29	19	16	17	23	17	22	25	17
Zr	148	142	112	123	110	153	150	130	130	213	370	280	207	260	195
A/CNK	1.01	1.01	1.04	1.00	1.17	1.01	1.01	1.09	1.06	1.03	1.00	1.05	1.13	1.10	1.09
NK/A	0.48	0.52	0.49	0.44	0.54	0.52	0.73	0.56	0.61	0.71	0.72	0.76	0.70	0.62	0.77
Rb/Sr	0.23	0.21	0.16	0.11	0.11	n.d.	0.16	0.32	0.28	0.55	0.75	1.88	0.94	0.65	2.06
Ba/Rb	7.84	10.62	9.73	10.87	12.90	n.d.	9.53	11.58	8.20	12.76	11.18	5.09	6.76	7.93	3.21
10000*K/Rb	186	267	226	228	313	n.d.	302	194	249	368	290	210	299	234	251
10000*Ga/Al	2.52	2.54	2.47	2.70	4.36	n.d.	3.60	2.37	2.06	n.d.	3.05	2.36	2.93	3.19	2.38
Modal composition															
Quartz vol%	19.5	24.2	24.3	25.8	28.8	16.0	31.4	32.9	30.4	40.6	35.1	33.1	38.7	35.0	29.0
K-feldspar	-	2.2	0.1	2.5	0.5	0.5	7.2	16.1	31.9	37.9	48.8	32.7	29.5	30.6	42.6
Plagioclase	52.0	51.0	52.5	50.6	53.7	60.8	48.8	38.9	29.2	13.3	8.4	25.7	26.3	27.0	16.0
Biotite	16.2	15.7	17.7	10.4	13.6	8.9	11.4	8.8	5.0	6.9	4.9	6.6	4.6	5.7	5.6
Muscovite	-	0.1	-	0.2	1.2	-	0.2	0.1	0.1	-	0.1	+	-	-	-
Hornblende	9.9	3.0	2.6	9.3	0.7	7.7	-	0.1	2.7	1.0	2.6	1.9	0.8	1.2	6.7
Fayalite	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Orthopyroxene	-	-	-	-	-	5.1	-	-	-	-	-	-	-	-	-
Clinopyroxene	-	-	-	-	-	0.7	+	-	-	-	-	-	-	-	-
Sphene	0.3	0.7	0.4	0.1	0.2	-	0.1	0.3	0.1	+	0.1	+	+	0.3	+
Epidote	1.5	2.8	2.1	-	-	-	-	2.8	0.6	+	0.1	+	+	0.2	0.2
Garnet	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Apatite	+	+	0.2	+	+	+	+	+	+	+	+	+	+	+	+
Others	0.6	0.4	0.2	1.1	1.3	0.4	0.9	0.1	0.1	0.3	+	+	0.1	0.1	+
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

which in the research area are diatexites according to the authors. Diatexite refers to a rock having a fairly plutonic texture, which is formed by complete or nearly complete melting of supracrustal source material (cf. Mehnert 1971). The VGC rocks locally

resemble plutonic rocks, but also various nebulitic migmatite types are known. The contact between the VGC and the PSB is gradual, and is composed of metatextitic garnet-cordierite-mica gneisses. Metatextitic is a textural term that is used to describe

Table 1. Continued.

Geological unit	CFGC					Pohjanmaa schist belt					Vaasa granitoid complex				
	Pyroxene granite	Porphyritic quartz monzonite		Granitic gneisses		Granodioritic intrusions			Pegmatite granite	Aplite granite	Porphyritic diatexites		Even-grained diatexites		
Location	Luopa	Greenish type	Pinkish type	Varvem-Kalajärvi kylä		Orisberg	Vittinki	Narmo-Hirvijärvi	Seinä-joki	Seinä-joki	Läppeli	Järvi-ranta	Söder-skogen	Kaana-järvi N	Lehmä-joki
number of analyses	5	18	7	2	3	4	3	3	23	5	3	6	3	3	3
SiO ₂ wt%	71.43	59.27	60.57	66.69	69.20	72.65	69.78	71.25	73.17	70.06	66.69	66.35	68.29	69.41	66.45
TiO ₂	0.33	0.80	0.68	0.46	0.45	0.39	0.53	0.31	0.06	0.21	0.71	0.71	0.53	0.41	0.60
Al ₂ O ₃	13.87	16.17	16.61	16.94	15.05	13.59	14.05	14.86	14.75	14.12	15.57	15.21	15.42	15.11	15.75
Fe ₂ O ₃ tot	3.21	9.69	8.09	3.60	4.36	2.12	3.98	2.87	0.62	2.00	4.55	4.71	5.17	3.31	4.29
MnO	0.05	0.17	0.13	0.04	0.06	0.04	0.06	0.05	0.03	0.04	0.05	0.05	0.08	0.03	0.05
MgO	0.29	0.64	0.62	0.83	0.84	0.62	1.08	1.14	0.27	0.72	1.86	1.78	1.81	1.29	1.61
CaO	1.63	4.03	3.56	2.05	1.50	1.30	1.60	1.59	0.63	1.08	2.32	2.26	1.85	1.66	2.17
Na ₂ O	2.57	3.29	3.13	4.14	3.36	3.30	2.45	3.34	3.92	3.23	2.89	2.94	2.70	2.97	3.06
K ₂ O	5.72	4.68	5.26	4.49	4.33	4.03	4.72	3.83	4.17	4.43	4.71	3.77	3.57	4.27	3.33
P ₂ O ₅	0.09	0.26	0.27	0.09	0.16	0.15	0.14	0.09	0.16	0.15	0.13	0.19	0.08	0.15	0.19
Sum	99.18	99.01	98.91	99.32	99.30	98.19	98.39	99.33	97.78	96.05	99.47	97.97	99.50	98.61	97.52
Rb ppm	120	69	80	172	255	181	155	132	178	192	189	145	159	204	145
Ba	1988	2816	3007	1299	806	413	848	471	150	670	749	886	484	523	657
Sr	174	423	406	237	157	113	127	175	71	152	204	238	185	197	239
Cs	1	1	1	10	25	11	6	6	23	9	n.d.	4	n.d.	n.d.	3
Ta	1	3	2	2	3	5	n.d.	n.d.	10	1	n.d.	1	n.d.	n.d.	1
U	n.d.	2	2	3	11	6	4	4	7	12	n.d.	4	n.d.	n.d.	2
Th	3	6	12	18	16	11	15	9	1	8	31	23	23	8	12
La	44	78	30	46	53	22	n.d.	n.d.	4	18	52	59	64	33	34
Y	20	47	35	16	45	15	0	n.d.	7	8	n.d.	12	n.d.	n.d.	7
Sc	9	39	25	10	10	8	10	10	3	8	n.d.	12	n.d.	n.d.	15
Ga	22	32	n.d.	n.d.	21	23	24	24	19	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zr	376	767	734	148	287	122	183	n.d.	n.d.	n.d.	237	294	255	175	n.d.
A/CNK	1.04	0.91	0.96	1.10	1.16	1.12	1.17	1.19	1.22	1.17	1.11	1.17	1.32	1.21	1.25
NK/A	0.75	0.65	0.65	0.69	0.68	0.72	0.65	0.65	0.74	0.72	0.63	0.59	0.54	0.63	0.55
Rb/Sr	0.69	0.16	0.20	0.73	1.63	1.61	1.22	0.76	2.51	1.27	0.93	0.61	0.86	1.03	0.61
Ba/Rb	16.57	40.71	37.66	7.55	3.16	2.28	5.48	3.56	2.11	3.49	3.96	6.12	3.05	2.57	4.52
10000*K/Rb	396	562	547	217	141	185	254	240	194	191	207	216	187	174	190
10000*Ga/Al	3.00	3.74	n.d.	n.d.	2.64	3.20	3.23	3.05	2.43	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Modal composition															
Quartz vol%	20.1	7.1	15.5	33.9	33.0	30.9	35.3	30.2	n.d.	n.d.	30.2	34.7	33.4	34.4	31.8
K-feldspar	38.3	37.2	26.7	28.2	18.3	20.1	14.3	4.3	n.d.	n.d.	10.6	14.7	18.5	9.0	8.0
Plagioclase	34.4	34.2	35.6	28.7	37.2	33.6	33.1	49.8	n.d.	n.d.	33.3	30.2	25.0	39.7	39.1
Biotite	4.0	2.1	8.5	7.8	6.5	15.2	14.3	11.5	n.d.	n.d.	24.7	19.3	20.3	16.0	17.8
Muscovite	-	-	-	+	1.1	0.2	+	2.3	n.d.	n.d.	0.4	0.5	0.9	0.5	2.1
Hornblende	1.2	13.6	12.8	-	-	-	-	1.0	n.d.	n.d.	-	-	-	-	-
Fayalite	-	1.6	0.1	-	-	-	-	-	n.d.	n.d.	-	-	-	-	-
Orthopyroxene	0.4	+	-	-	-	-	-	-	n.d.	n.d.	-	-	-	-	-
Clinopyroxene	1.2	1.5	0.1	-	-	-	-	-	n.d.	n.d.	-	-	-	-	-
Sphene	-	-	-	-	-	-	-	-	n.d.	n.d.	-	-	-	-	-
Epidote	-	-	-	-	1.0	-	-	-	n.d.	n.d.	-	-	-	-	-
Garnet	-	-	-	+	-	-	-	+	n.d.	n.d.	+	0.5	0.2	-	+
Apatite	+	0.4	0.3	+	0.1	+	+	0.1	n.d.	n.d.	0.5	0.1	0.2	0.2	0.4
Others	0.4	2.3	0.4	1.4	2.9	0.2	3.0	0.8	n.d.	n.d.	0.3	0.1	1.5	0.2	0.8
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	n.d.	n.d.	100.0	100.0	100.0	100.0	100.0

high-grade metamorphic migmatitic supracrustal rocks, which are partially melted (cf. Mehnert 1971).

The regional metamorphic grade in the research area varies from lower amphibolite facies to granulite facies with a low-pressure intermediate type (Mäkitie 1990, Mäkitie & Lahti 1991). The pyroxene-bearing granitoid intrusions have overprinting contact metamorphic aureoles. There are major shear zones in the area (see Korsman et al. 1997).

Granitoid types

Field classification and petrography

Granitoids of the research area were classified into three main groups on the basis of their geological unit (geological surroundings) (cf. Table 1). Each main group is further divided into several petrographical subgroups as follows:

A) Granitoids of the Central Finland granitoid complex:

1. Tonalites
2. Granodiorites
3. Porphyritic granites
4. Pyroxene granite
5. Porphyritic quartz monzonite
6. Granitic gneisses

B) Granitoids within the Pohjanmaa schist belt:

7. Granodioritic intrusions
8. Pegmatite granites and aplite granites

C) Granitoids of the Vaasa granitoid complex:

9. Porphyritic diatexites
10. Even-grained diatexites

Tonalites, porphyritic granites, porphyritic diatexites and even-grained diatexites, as the four most extensive granitoid types, were studied in still smaller subareas to understand the possible variation within the granitoid type (cf. Table 1). The boundaries of the subareas are shown by lines in Figure 1.

Tonalites (1). Tonalites are synkinematic, intrusive rocks belonging to the CFGC. The main rock type is a predominantly even-grained (1 - 3 mm) grayish tonalite, locally gneissic in texture, and typically containing more biotite than hornblende, and a few dark enclaves and granitic veins (Fig. 2a). Tonalite occupies large areas in the Jalasjärvi and Peräseinäjoki area (Lahti & Mäkitie 1990).

Tonalites were studied from seven different subareas, named after their geographic position: a) SE-part, b) S-part, c) middle part, d) NW-part, e) N-part, f) Luhtalankylä and g) contact aureole of Luopa quartz monzonite (cf. Fig. 1 and Table 1).

The Luhtalankylä tonalite, which locally grades into granodiorite, is situated inside PSB but very near the main body of the CFGC. Tonalite samples from the contact aureole have distances less than 100 m from the porphyritic quartz monzonite of Luopa.

Granodiorites (2). Limited areas near the tonalites contain even-grained or poorly porphyritic granodiorites, which locally intersect tonalites (cf. Fig. 2a) (Lahti & Mäkitie 1990). Often these granodiorites are weakly foliated and include 1-2 % epidote. The grain size of K-feldspar is usually slightly coarser than that of plagioclase. Two small granodiorite areas were studied, one of them is situated on the northern and the other on the southern side of the village of Ratikylä, about 10 km east of the church village of Jalasjärvi (Fig. 1).

There is also a variable group of chloritized tonalites and granodiorites, hornblende-rich quartz diorites and streaky gneissic granodiorites within the research area. The compositional variation of these minor rock types are not studied.

Porphyritic granites (3). Reddish gray, porphyritic hornblende-bearing granite occurs in four localities. The texture of the rock is characterized by phenocrysts (1-3 cm) of K-feldspar. The granites studied near the villages of Koskue and Ahonkylä are parts of large plutons that continue outside the research area. Those granites observed in the Nikola and Kalakoski villages form small intrusions (Fig. 1) (cf. Lahti & Mäkitie 1990). The Nikola granite is smaller in grain size (2-7 mm) than the other granites. These rocks intersect surrounding tonalites. The granites are usually weakly foliated.

Two sets of samples were taken from the Koskue and from the Kalakoski granites, one of them from the inner parts and the other from the border parts of the intrusions - to see the possible zoning within

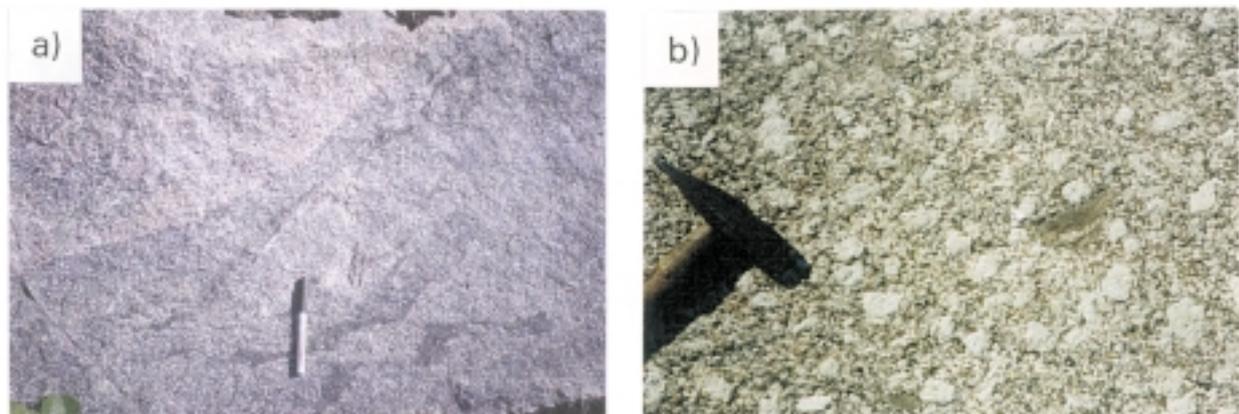


Fig. 2. Typical granitoids of the research area. a) Synkinematic tonalite (lower part of the figure) with few enclaves in contact to granodiorite. The rocks belong to the CFGC. Location; Peräseinäjoki, x = 6923.930, y = 2456.990. b) Porphyritic granodioritic diatexite from the VGC. The rock contains supracrustal inclusions. Location; Vöyri, x = 7005.010, y = 1558.650.

the intrusions (cf. Table 1).

Pyroxene granite (4). Reddish gray, pyroxene-bearing granite occurs at Luopa, about 30 km southwest of the town of Seinäjoki. It is weakly porphyritic and in places weakly deformed. Pyroxene granite is spatially closely associated with Luopa quartz monzonite. The contact between the pyroxene granite and the neighbouring porphyritic granite of Ahonkylä is not found.

Porphyritic quartz monzonite (5). Some 20 km southwest of the town of Seinäjoki and 5 km north-east of the village of Luopa there is an irregular, almost undeformed, post-kinematic porphyritic quartz monzonite stock (age 1871 ± 1 Ma) (Lahti & Mäkitie 1990, Mäkitie & Lahti 1991). Phenocrysts (1-4 cm) of the rock are composed of K-feldspar. The mafic main minerals in the quartz monzonite are hornblende, biotite, clinopyroxene and fayalite. The intrusion is composed of two different colour-types: a dark greenish variety and a gray pinkish variety that is less common (Table 1). The quartz monzonite is often strongly weathered. The rock intersects surrounding tonalites and pyroxene granite.

Granitic gneisses (6). Granitic gneisses, which have gradual contacts to the surrounding rocks occur in two localities, one of them at Varvenkylä, Ilmajoki and the other at Kalajärvi, Peräseinäjoki. These gneisses are located at the boundary of the CFGC and the PSB, and in the vicinity of major faults and deformation zones. The various granodioritic gneisses at Varvenkylä gradually change from meta-arkosites and mica gneisses. The relatively homogeneous granitic gneiss at Kalakoski has a gradual contact, associated with the increase of deformation, to the surrounding tonalite. Dark elongated inclusions, porphyroblastic K-feldspar grains, the absence of hornblende and strong deformation are typical features in the granitic gneisses.

Granodioritic intrusions within the PSB (7). There are relatively small (< 30 km²) separate, mostly granodioritic intrusions in the central parts of the Pohjanmaa schist belt (e.g. Mäkitie & Lahti 1991, Lehtonen & Virransalo, in press). In the research area they are called the Orisberg, Vittinki and Nurmo-Hirvijärvi intrusions (Fig. 1). Biotite is the characteristic mafic mineral. Hornblende is found only in the southeastern part of the Nurmo-Hirvijärvi intrusion.

These deformed granitoids are relative homogeneous in outcrop scale, but their texture and composition often differ between outcrops. The abundances of K-feldspar and plagioclase vary so widely that some variations are actually tonalites and gran-

ites.

Pegmatite granites and aplite granites (8). The granitic pegmatites in the research area have been described in many publications and reports (e.g. Haapala 1966, Oivanen 1983, Kärkkäinen 1986, 1993, Alviola 1989). In this study the chemistry of coarse-grained pegmatite granites and medium-grained aplite granites in the surroundings of the town of Seinäjoki are studied. Both rock types form tens of metres wide intrusions in the area. The smaller pegmatite dykes are mineralogically very complex and their composition is not discussed in this connection.

Porphyritic and even-grained diatexites (9-10). The granitoids studied in the VGC are typically fairly homogeneous, porphyritic or even-grained granodioritic diatexites (Fig. 2b), in places gneissic in texture. The contact between these diatexites is gradual. Biotite is a characteristic mineral, but hornblende, sphene and dark enclaves are absent. Relicts of concretions and schists are fairly common. Garnet and secondary muscovite are often common accessory minerals. As important accessory minerals the VGC granitoids locally contain minor monazite, sillimanite and andalusite. The porphyritic nature of the rocks varies; locally the diameter of phenocrysts can reach 6-7 cm, but there also occur poorly porphyritic types.

The VGC granitoid samples are from five localities. Even-grained (2-5 mm) rocks are from the Söderskogen, Kaurajärvi N and Lehmäjoki areas around the Vöyri commune (Fig. 1). Inclusions are rare in diatexites of the Kaurajärvi area. Porphyritic rocks are from the Lågpelt area, a few kilometers southwest of Vöyri, and from the Järviranta area about 20 km southeast of Vöyri.

Modal composition

At least three thin sections were point counted from each granitoid type or area (cf. Table 1). The pegmatite granites and aplite granites were not point counted. Granitoids from the VGC and from the PSB are mostly granodiorites by the classification of Streckeisen (1976) (Fig. 3a). Granitoids from the CFGC are more dispersed within four fields of Streckeisen's diagram (Fig. 3a).

At the boundary of the CFGC and the PSB there occur mineralogically two varieties of tonalites. Hornblende-rich tonalite is common near the pyroxene-bearing quartz monzonite of Luopa, but hornblende is rare in tonalites situating further away from the quartz monzonite (cf. Fig. 1 and Table 1). Also the granite of Ahonkylä, which situates near

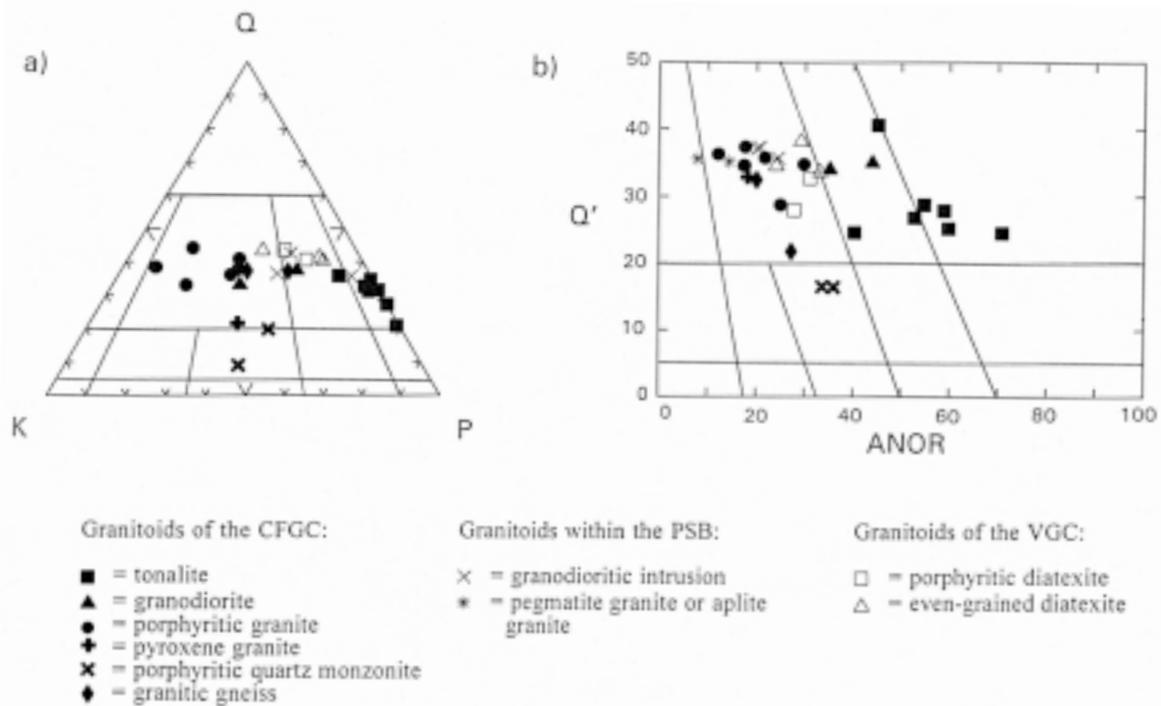


Fig. 3. Classification diagrams of the granitoids of South-Pohjanmaa. a) modal classification diagram after Streckeisen (1976), b) chemical (normative mineral) classification diagram after Streckeisen and Lemaitre (1979).

the Luopa pyroxene granitoids, includes relatively much hornblende compared to other granites (Table 1). Pyroxenes in the tonalites within the contact aureole of Luopa quartz monzonite are metamorphic minerals. Spheue and epidote in these pyroxene tonalites are not stable due to the high-grade metamorphic conditions of the aureole.

Chemical composition

General

The samples used for chemical analyses are drill powder, core samples and hand specimens weighing 1-3 kilograms. Samples were analysed in the Chemical Laboratory of Geological Survey of Finland, in the Technical Research Centre of Finland and in the Chemical Laboratory of the Rautaruukki Company. The major elements and Rb, Sr, Ba and Zr were analysed by the XRF- and ICP-MS-methods, Ga and Y by OES, and Cs, Sc, La, U and Th by INAA and XRF.

The average SiO₂ content of the granitoid types from the research area ranges from 59.27 to 73.78 wt% (Table 1). Standard deviations of the analyses are given in Appendix 1, and codes of all the analysed samples are in Appendix 2.

Only the quartz monzonite is classified in the field of alkaline rocks in the alkalis-silica diagram

of Irvine and Baragar (1971), even though in the Streckeisen diagram it is clearly not an alkaline rock. CIPW normative (weight norm, FeO and Fe₂O₃ after Irvine and Baragar 1971) mineral classification differs by some degree from Streckeisen's modal-based classification. Granodioritic diatexites of the VGC and granodioritic intrusions within the PSB are granodiorites by modal classification, but in normative mineral classification they are granites (Figs. 3a and 3b). These differences are mostly due to the relatively high mode of biotite in the rocks. Biotite contains much K₂O, which increases the amount of normative orthoclase (K-feldspar) so much that these granitoids plot in the field of granites in the normative mineral classification. Biotite belongs to mafic minerals in the diagrams of Streckeisen (1976), and is not used in the classification of granitoids.

Harker and minor element diagrams

In Harker diagrams the studied granitoids usually are distributed within a more or less linear trend (Fig. 4). In the CaO-SiO₂ diagram the VGC diatexites and the CFGC granitic gneisses cluster slightly separately compared to other granitoids (Fig. 4). In the Na₂O against SiO₂ diagram the linearity of the plots is poor. A clearly different group of Harker and other chemical diagrams is the quartz monzonite with, for example, the unexceptional high Fe/Mg

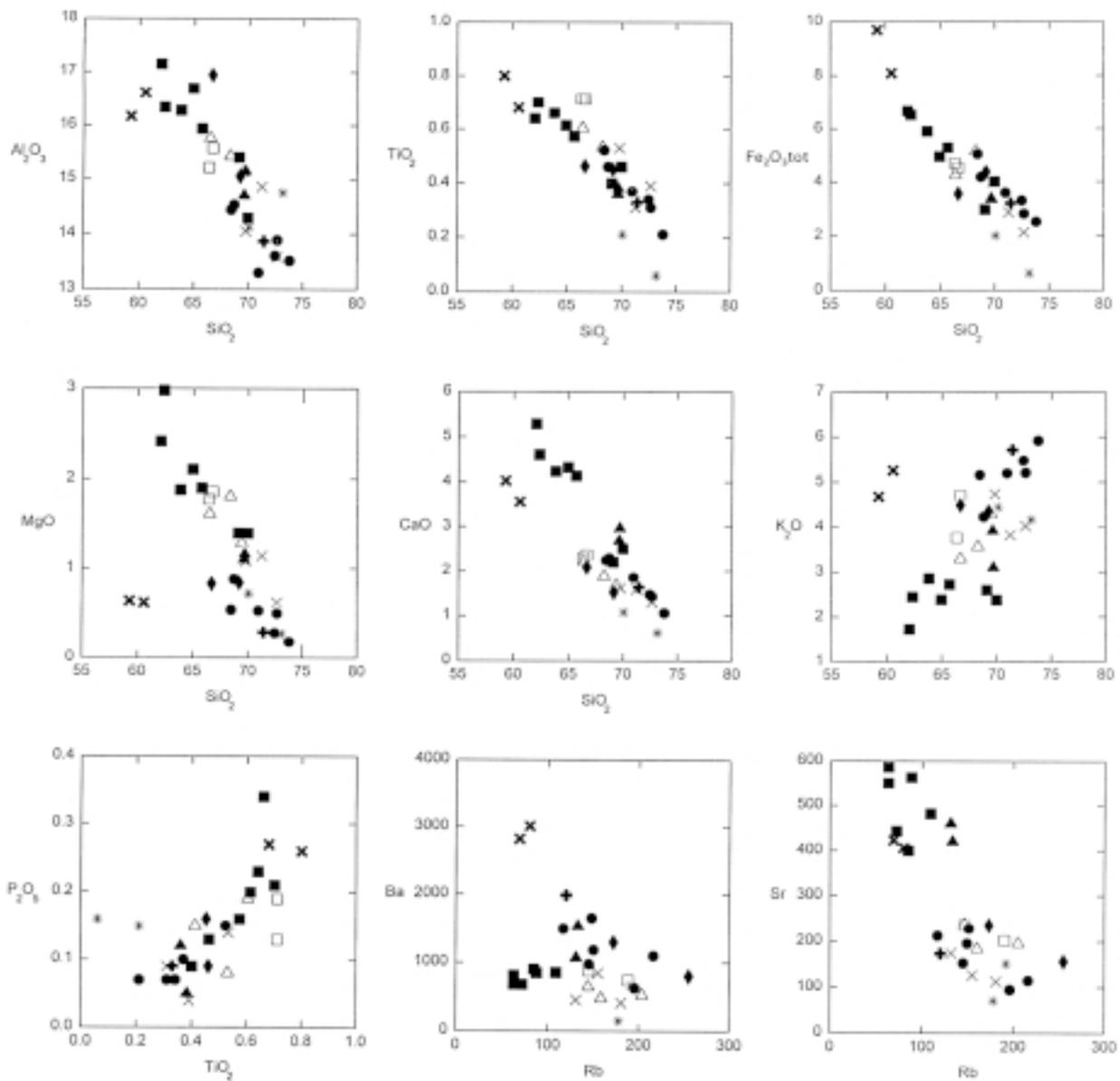


Fig. 4. Chemical variation diagrams of the main and trace elements in the granitoids. Symbols as in Figure 3.

ratio and Ba content (Fig. 4).

Phosphorus and Ti generally decrease during magmatic differentiation of granitoids, until an increase of P in the latest fractionation products, granitic pegmatites (Fig. 4). The granodioritic diatexites in VGC contain relatively much titanium and locally P. This is likely due to the composition of melted source material that is suggested to contain a high proportion of sedimentary rocks.

Ba/Rb-ratio, a common fractionation index, is generally lower in VGC diatexites and in PSB granodioritic intrusions compared to the CFGC plutonites (Fig. 4). Another fractionation index, Rb/Sr, separates nicely the tonalites, granodiorites and quartz monzonite from other granitoids (Fig. 4). The fractionation index, K/Rb, is rather similar in all granitoids except the quartz monzonite (Table 1).

Source and geotectonic diagrams

There exist many approaches to link the chemical composition of granitoids to their source rocks and tectonic setting (e.g. Barbarin 1990). In the research area A/CNK value, alumina saturation-index (after molar Al_2O_3 , CaO, Na_2O , K_2O , Shand 1947), varies between 0.91 and 1.32. Generally the A/CNK values increase from the Central Finland granitoid complex to the Vaasa granitoid complex (Figs. 1 and 5a). The CFGC is characterized by the I-type ($\text{A/CNK} < 1.1$) granitoids. The VGC is composed of S-type ($\text{A/CNK} > 1.1$) granitoids. Pegmatite granites, aplite granites and granodioritic intrusions within the PSB belong also among S-type granitoids. The quartz monzonite of Luopa is a metaluminous ($\text{A/CNK} < 1.0$) rock. Low A/CNK values (< 1.1) imply source

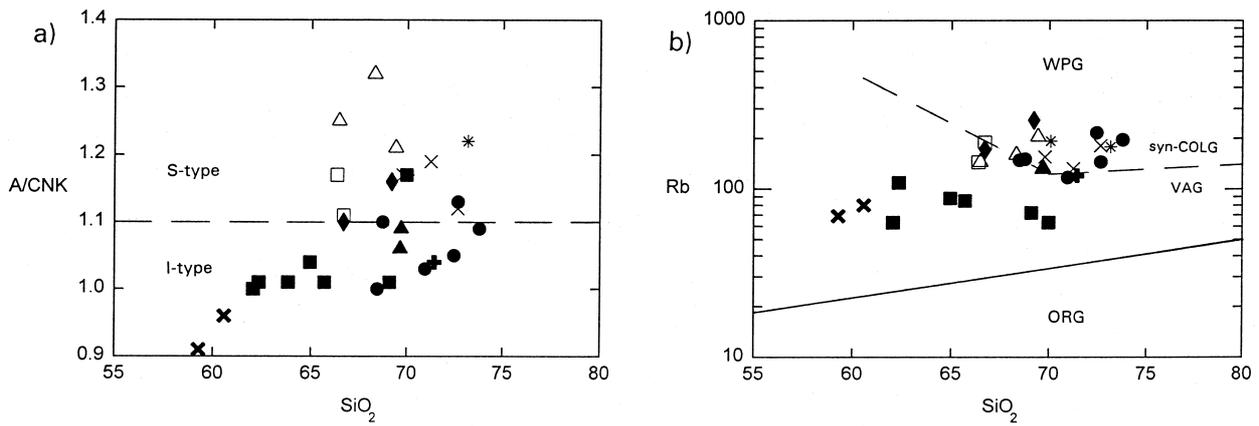


Fig. 5. Geotectonic classification diagrams of the granitoids. a) after Chappell and White (1974), b) after Pearce et al. (1984) (abbreviations: WPG = within plate granites, syn-COLG = syn-collision granites, VAG = volcanic arc granites, ORG = ocean ridge granites). Symbols as in Figure 3.

rocks of mafic to intermediate igneous composition or infracrustal derivation, but high A/CNK values (>1.1) imply source rocks of sedimentary or supracrustal protoliths (Chappell & White 1974). Noteworthy is that a 'hornblende out' isograd occurs in granitoids between CFGC and VGC (cf. Fig. 1).

The Koskue and Kalakoski porphyritic granites of CFGC seem to be zoned, because the border parts have lower A/CNK values compared to the inner parts of the intrusions (Table 1). This is consistent with the observation that the inner parts include less

hornblende compared to the border parts (which are more mafic). However, fractionation indexes (as Rb/Sr) do not clearly agree with interpretation that the inner parts of these intrusions represent a more fractionated granitic material.

In the Rb-SiO₂ diagram of Pearce et al. (1984), all rocks of the research area belong to within-plate granites (WPG) (Fig. 5b). Quartz monzonite and tonalites plot in the field of volcanic arc granites (VAG), but other granitoids are transitional between the syn-COLG and VAG granites (Fig. 5b).

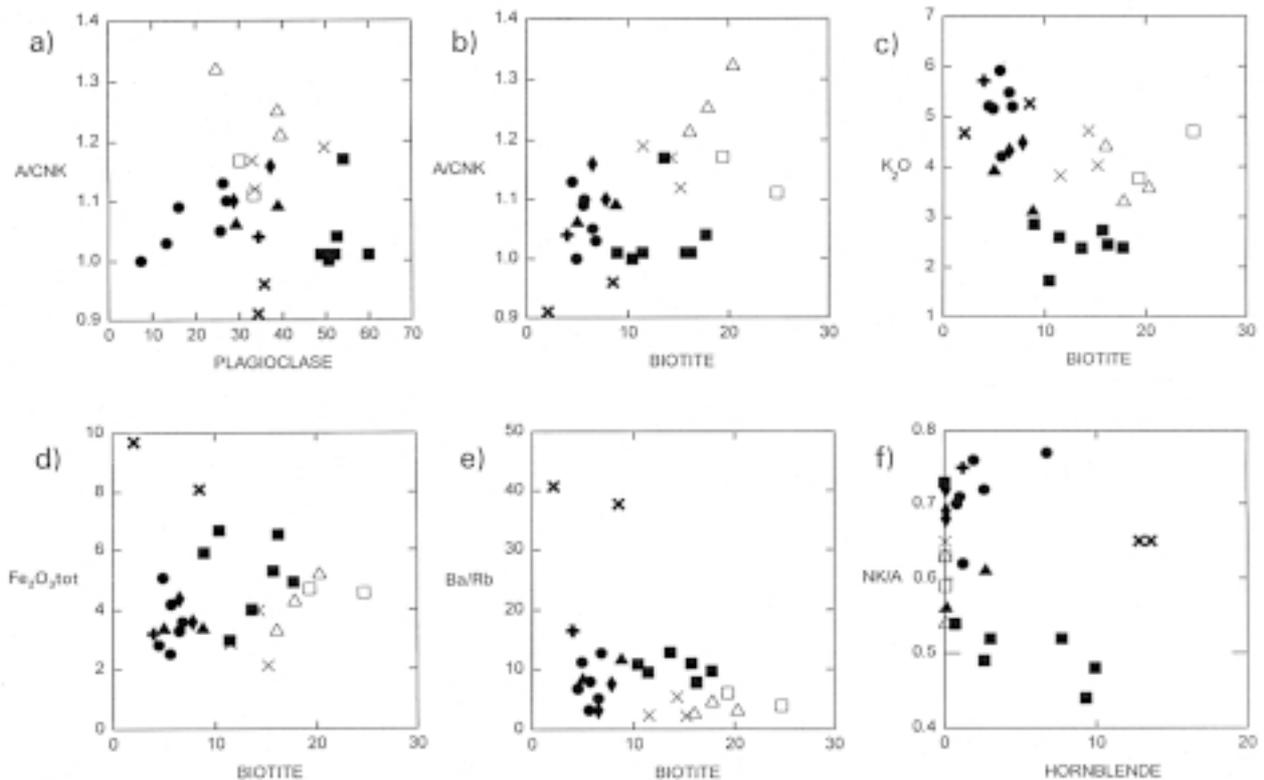


Fig. 6. Modal (vol %)-chemical variation diagrams of the granitoids. Symbols as in Figure 3.

The post-kinematic quartz monzonite of Luopa has some high Ga/Al ratios detected from the analysed granitoid samples. This supports (cf. Whalen et al. 1987) - with other chemical characteristics - the fact that Luopa quartz monzonite has a different source compared to other granitoids within the research area.

Modal-chemical diagrams

Many differences in the modal composition of granitoids in relation to the chemical composition depend on the concentrations of Ca, Na and K, which are components in the A/CNK ratio. The sum of CNK can be similar in different samples, but at the same time the element concentrations (Ca, Na, K) may vary widely. For example, tonalites have higher CaO but smaller K₂O than granites, and thus tonalites contain abundant andesitic plagioclase, but granites are enriched in K-feldspar.

The modal-chemical diagrams show that the tonalites and porphyritic granites have relatively similar A/CNK values, even though the modal variation of plagioclase is large (Fig. 6a). As opposite, in other granitoid types, the modal variation of plagioclase is often small, although the A/CNK values are largely different in the same samples.

Diatexites of the VGC separate from other granitoids by their high values both in the A/CNK and modal biotite (Fig. 6b). The granitoids of the VGC are characterized by high mode of biotite, however, simultaneously there is much overlap with other element concentrations (Figs. 6c-6e). For example, in the VGC granitoids all iron is predominantly concentrated into biotite, whereas the CFGC granitoids include also another Fe-bearing mineral, hornblende (Fig. 6d). The NK/A values in the CFGC granitoids do not correlate with the hornblende content of the rocks (Fig. 6f).

Discussion

The observed chemical and modal compositions of the main rock types in the Central Finland granitoid complex and in the Vaasa granitoid complex support the idea of a different source of the rocks. The granitoids from the CFGC have an igneous origin, whereas the VGC granitoids have a sedimentary source, even though many granitoids in the VGC are texturally almost plutonic indicating total melting and true magmatic stage. By contrast the granitoids of the CFGC are locally gneissic in appearance but their chemical composition

indicates plutonic source. The granodioritic intrusions within the Pohjanmaa schist belt differ from the granitoids of the CFGC and the VGC in that they mostly have clear plutonic texture but still they belong to S-type granitoids.

The modal and chemical classifications of the granitoids studied do not strictly correlate. Tonalites and porphyritic granites locally have similar A/CNK values, even though their modal composition varies. In addition, the chemical and modal compositions are regionally variable in the tonalites and porphyritic granites of the CFGC and in the VGC even-grained diatexites. Thus, it is important to have comprehensive field observations when studying the compositional data of granitoid rocks.

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Appendix 1. Standard deviations of the analyses shown in Table 1. - = not determined, 0 = very small.

Geological unit	Central Finland granitoid complex (CFGC)														
	Tonalites							Granodiorites		Porphyritic granites					
	SE-part	S-part	Middle part	NW-part	N-part	Contact aureole	Luhatala-kylä	Rati-kylä N	Rati-kylä S	Koskue inner part	Nikola border part	Kalakeski inner part	border part	Ahen-kylä	
number of analyses	4	5	6	3	2	4	3	2	2	3	4	2	6	4	2
SiO ₂ wt%	1.7	4.9	2.9	1.3	5.4	3.5	1.1	0.9	0.1	3.6	3.7	0.5	1.9	1.1	1.0
TiO ₂	0.1	0.2	0.1	0.0	0.1	0.4	0.0	0.0	0.0	0.2	0.2	0.0	0.1	0.1	0.1
Al ₂ O ₃	0.6	0.8	0.6	0.4	3.3	0.8	0.2	0.2	0.1	1.0	1.1	0.2	0.6	0.6	0.0
Fe ₂ O ₃ tot	0.7	1.7	0.9	0.2	0.0	1.5	0.3	0.2	0.4	1.5	2.2	0.2	0.7	0.7	0.8
MnO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MgO	1.4	1.2	0.5	0.1	0.2	0.6	0.1	0.2	0.1	0.3	0.2	0.1	0.2	0.2	0.1
CaO	0.6	1.2	0.8	0.2	1.7	0.5	0.2	0.0	0.2	0.5	0.9	0.1	0.4	0.4	0.3
Na ₂ O	0.4	0.1	0.1	0.2	0.4	0.2	0.1	0.0	0.1	0.4	0.3	0.0	0.3	0.4	0.1
K ₂ O	0.3	0.6	0.4	0.1	0.8	0.8	0.3	0.4	0.1	0.3	1.2	0.1	0.6	0.3	0.2
P ₂ O ₅	0.0	0.1	0.0	0.1	0.0	0.2	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Rb ppm	16	15	19	3	19	-	7	18	10	8	36	0	36	51	41
Ba	184	409	103	31	57	297	21	435	70	466	500	210	72	262	442
Sr	168	126	123	85	385	39	19	61	130	48	30	15	46	21	31
Cs	2	1	2	1	1	-	1	-	-	0	0	1	-	-	-
Ta	0	3	0	-	0	-	-	-	-	0	0	0	-	-	-
U	1	1	2	-	1	-	2	-	-	0	0	-	-	-	-
Th	4	5	3	1	8	-	0	-	-	4	1	1	-	-	3
La	6	6	8	-	0	-	-	-	-	0	14	2	-	-	-
Y	9	3	7	-	0	-	-	7	-	0	17	1	6	6	-
Sc	8	7	5	12	3	-	0	-	0	3	5	2	3	-	1
Ga	3	3	2	2	0	-	2	2	2	0	1	0	4	3	3
Zr	23	17	17	5	52	28	16	10	0	33	115	20	45	56	65

Geological unit	CFGC					Pohjanmaa schist belt					Vaasa granitoid complex				
	Pyroxene granite		Porphyritic quartz monzonite		Granitic gneisses	Granodioritic intrusions			Pegmatite Aplite granite		Porphyritic diatexites		Even-grained diatexites		
	Luopa	Greenish type	Pinkish type	Varven-kylä	Kalajoki	Orisberg	Vittiski	Nurmo-Hirvijävi	Seinäjoki	Seinäjoki	Läggelt	Järvi-ranta	Söder-skogen	Kaura-järvi N	Lehmä-joki
number of analyses	5	18	7	2	3	4	3	3	23	5	3	6	3	3	3
SiO ₂ wt%	2.9	1.6	1.1	6.3	2.3	1.9	1.8	2.1	1.8	1.8	1.2	1.4	1.3	2.0	0.3
TiO ₂	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.0	0.2	0.0	0.2	0.1	0.1	0.1
Al ₂ O ₃	0.9	0.7	0.7	2.3	0.7	0.4	0.5	0.2	1.1	0.5	0.5	0.4	0.3	0.7	1.0
Fe ₂ O ₃ tot	0.7	1.9	0.9	0.3	0.5	1.0	0.8	1.9	0.3	1.7	0.7	1.2	0.4	1.0	0.2
MnO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MgO	0.2	0.1	0.0	0.4	0.2	0.4	0.2	0.8	0.2	0.8	0.3	0.4	0.2	0.3	0.2
CaO	0.6	0.5	0.5	0.5	0.2	0.5	0.5	0.4	0.2	0.4	0.3	0.6	0.7	0.5	0.7
Na ₂ O	0.2	0.3	0.3	1.2	0.5	0.4	0.1	0.3	0.8	0.7	0.4	0.2	0.4	0.6	0.4
K ₂ O	0.4	0.8	0.7	0.3	0.4	0.3	0.3	1.0	1.8	0.8	0.0	0.8	0.6	0.8	0.9
P ₂ O ₅	0.1	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.1	0.1
Rb ppm	18	19	18	21	77	72	10	36	113	81	7	39	11	25	28
Ba	343	512	382	311	209	193	164	178	249	504	48	180	156	123	208
Sr	84	84	69	97	33	59	17	34	67	92	24	30	10	56	25
Cs	0	0	0	1	15	8	1	1	21	5	-	1	-	-	1
Ta	0	1	0	1	0	7	-	-	22	1	-	21	-	-	0
U	-	1	1	-	4	3	1	0	6	15	-	2	-	-	2
Th	1	4	5	1	1	7	2	-	1	7	12	10	8	3	5
La	6	45	20	2	7	13	-	-	2	12	16	23	21	18	9
Y	6	24	5	-	4	7	-	-	4	3	-	5	-	-	5
Sc	3	14	11	0	1	3	0	8	3	7	-	3	-	-	2
Ga	1	0	-	-	3	3	0	-	7	-	-	-	-	-	-
Zr	122	170	170	-	47	3	21	-	-	-	50	19	82	37	-

Appendix 2. Codes of the chemical analyses used in the present study (cf. Table 1). Analyses are archived in the Geological Survey of Finland (KALTIE-database).

Granitoid type	Codes of the analysed samples
Tonalites:	
SE-part	57-VOP-81, 199-VOP-81, 17-HMM-84, 82-HMM-84
S-part	15-SLH-81, 165-SLH-81, 18-VOP-81, 49-VOP-81, 92-VOP-81
Middle part	51-EGN-80, 58-EGN-80, 189-EGN-80, 33-SLH-81, 66-SLH-81, 168-CLF-83
NW-part	917A-SIL-83, 917B-SIL-83, 50L-HMM-85
N-part	11.1-NKK-83, 892-SIL-83
Contact aureole	600-HMM-86, 52L-HMM-85, 53L-HMM-85, 54L-HMM-85
Luhtalankylä	887-SIL-83, 889-SIL-83, 891-SIL-83
Granodiorites:	
Ratikylä N	276-CLF-83, 412-JVK-84
Ratikylä S	331-CLF-83, 337-CLF-83
Porphyritic granites:	
Koskue (inner part)	52A-VOP-81, 271-VOP-81, 272-VOP-81
Koskue (border part)	95-SIL-81, 5-VOP-81, 53-VOP-81, 231-HMM-84
Nikola	97-HMM-84, 173-HMM-84
Kalakoski (inner part)	2A-CLF-83, 2B-CLF-83, 6-CLF-83, 8-CLF-83, 24-CLF-83, 20-HMM-84
Kalakoski (border part)	18-CLF-83, 36-CLF-83, 48-CLF-83, 49-CLF-83
Ahonkylä	153-HMM-82, 171-HMM-82
Pyroxene granite:	
Luopa	140-HMM-82, 141A-HMM-82, 205A-HMM-82, 233-HMM-82, 266-HMM-82
Porphyritic quartz monzonite:	
Greenish type	652-SIL-81, 233-VOP-81, 234-VOP-81, 238B-VOP-81, 290-VOP-81, 1-HMM-82, 11A-HMM-82, 11C-HMM-82, 18-HMM-82, 141B-HMM-82, 157-HMM-82, 167-HMM-82, 196-HMM-82, 199-HMM-82, 254-HMM-82, 178-NKK-83, 202-HMM-87, 205B-HMM-87
Pinkish type	238A-VOP-81, 256-VOP-81, 11B-HMM-82, 11D-HMM-82, 11E-HMM-82, 200B-HMM-87, 201-HMM-87
Granitic gneisses:	
Varvenkylä	140-NKK-84, 141-NKK-84
Kalajärvi	2-EGN-80, 11-EGN-80, 13-SIL-80
Granodioritic intrusions:	
Orisberg	171-NKK-84, 173-NKK-84, 174-NKK-84, 175-NKK-84
Vittinki	918-SIL-83, 919A-SIL-83, 920-SIL-83
Nurmo-Hirvijärvi	105-NKK-83, 906-SIL-83, 911-SIL-83
Pegmatite granites:	
Seinäjoki	75-NKK-83, 78-NKK-83, 79-NKK-83, 80.1-NKK-83, 80.3-NKK-83, 82.1-NKK-83, 82.2-NKK-83, 879A-SIL-83, 879B-SIL-83, 879C-SIL-83, 902A-SIL-83, 902B-SIL-83, 903A-SIL-83, 903B-SIL-83, 903C-SIL-83, 903D-SIL-83, 904AC-SIL-83, 905AC-SIL-83, 913A-SIL-83, 913B-SIL-83, 913C-SIL-83, 913D-SIL-83, 913E-SIL-83
Aplite granites:	
Seinäjoki	31-NKK-83, 89.1-NKK-83, 105-NKK-83, 164-NKK-83, 128.2-PMK-83
Porphyritic diatexites:	
Läggelt	14.1-MIL-89, 20-MIL-89, 25-MIL-89
Järviranta	150-NKK-83, 152-NKK-83, 153-NKK-83, 154-NKK-83, 36-MIL-89, 37-MIL-89
Even-grained diatexites:	
Söderskogen	26-MIL-89, 31-MIL-89, 34-MIL-89
Kaurajärvi N	43-MIL-89, 44-MIL-89, 158-NKK-83
Lehmäjoki	155-NKK-83, 156-NKK-83, 157-NKK-83

PETROLOGY OF THE KAIPOLA LAYERED INTRUSION, SOUTHERN FINLAND

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Key words (GeoRef Thesaurus, AGI): layered intrusions, gabbros, diorites, petrography, petrophysics, gravity anomalies, Proterozoic, Kaipola, Finland

Introduction

The Kaipola Layered Intrusion is located close to the easternmost tip of the Tampere Schist Belt (TSB) close to the boundary zone between the TSB and the Central Finland Granitoid Complex (Sandholm 1970). The intrusion is situated between two NW-SE trending faults about 20 km to the north of the roughly E-W trending shearzone separating the relatively strongly deformed and metamorphosed rocks of the Pori-Mikkeli migmatite-belt (middle crustal milieu) from the better preserved rocks of the Tampere Schist Belt (upper crustal milieu) on their northern side (Fig. 1). The Kaipola Layered Intrusion is a 4.6 km long and 2.2 km wide oval shaped gabbro-diorite intrusion which, as beautifully displayed in the aeromagnetic map in Figure 1, has experienced relatively little deformation but has been tilted so that the bottom is exposed in the SE with the top being in the NW. The associated volcanic rocks give rise to magnetic maxima on the NW side of the intrusion.

Field relationships

Unlike most other Svecofennian mafic-ultramafic intrusions, most of the Kaipola Layered Intrusion is enclosed by syn- and postkinematic granitoids. Gabbro–granite relationships are well exposed at a road cut close to the western tip of the intrusion where the contact zone is characterised by ameboidal gabbro fragments in the granite, their number in-

creasing towards the contact, and small mica-rich knots in the gabbro - both features implying the immiscibility of two melts. Two distinct types of granitoid dykes intrude the gabbro: a) “older” fine grained, 5-50 cm wide, anastomosing and deformed dykes with smooth and irregular boundaries with the

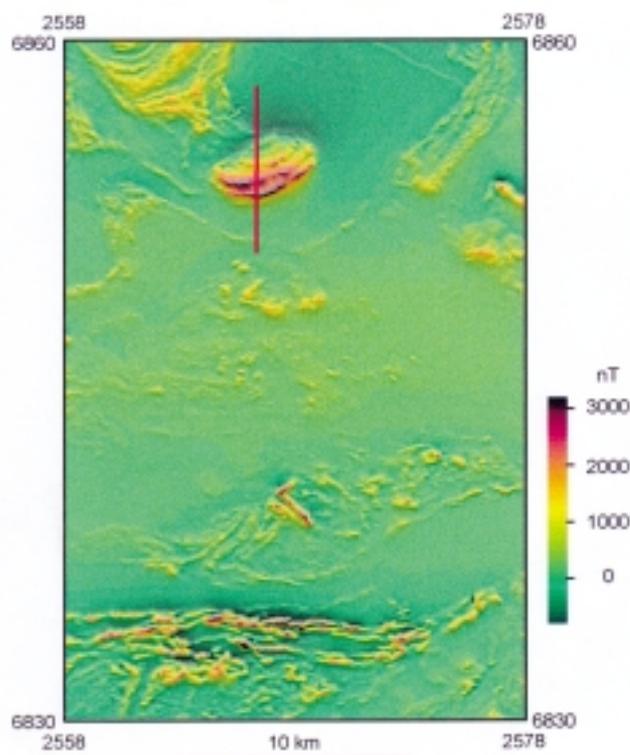


Fig. 1. Aeromagnetic total intensity anomaly map based on the low-altitude data of the Geological Survey of Finland. Flight altitude is 40 m and line spacing is 200 m. The red line shows the location of the gravity anomaly profile.

enclosing gabbro, and b) “younger” coarse grained pegmatite dykes which sharply cut both the gabbro and the “older” fine grained granite dykes. While the relationship of the gabbro with the “older” dykes gives an impression of immiscibility and co-existence of felsic and mafic magmas, the emplacement of “younger” dykes clearly postdates the solidification and deformation of the gabbro. It is very possible that the “older” dykes are of the same age as the synkinematic granitoids enclosing the gabbro while the “younger” dykes are related to the emplacement of somewhat younger, postkinematic, Kaipola and Jämsä plutons nearby (Nironen et al. 1999).

Petrography

The Kaipola Layered Intrusion is characterised by well-preserved primary igneous layering and cumulus textures showing distinctive large-scale repetitive layering, with at least seven megacyclic units being identified (Fig. 2). Thin olivine-bearing (augite-bronzite-olivine cumulates, aboC) and pyroxenitic layers (augite or augite-bronzite cumulates, aC/abC)

represent the most primitive fractionation products of the magma and have been located at the base of some of the megacyclic units. However, most of the cumulus sequence is composed of more evolved leucocratic-mesocratic plagioclase-dominated orthocumulates (paC/pabC/pbC/pC), where apatite and ilmeno-magnetite occur as minor but ubiquitous cumulus phases (Fig. 3a). A striking feature of the Kaipola Layered Intrusion is the extensive growth of large oikocrysts of green and brown amphibole, indicative of circulation of volatile-rich magma or fluid at the postcumulus stage, also suggesting that the parental melt of the intrusion was relatively hydrous (arc-type basalt?). On the basis of mineral textures, some of the poikilitic amphibole formed by interstitial crystallization, but most of it was produced by peritectic replacement of cumulus pyroxenes and plagioclase (Fig. 3b). Other intercumulus minerals include ilmenite, apatite, phlogopite, quartz, zircon, and plagioclase in the most primitive cumulates. Sulphides are uncommon which together with reconnaissance PGE analyses (unpublished) imply that Kaipola Layered Intrusion has low potential for magmatic sulphide deposits.

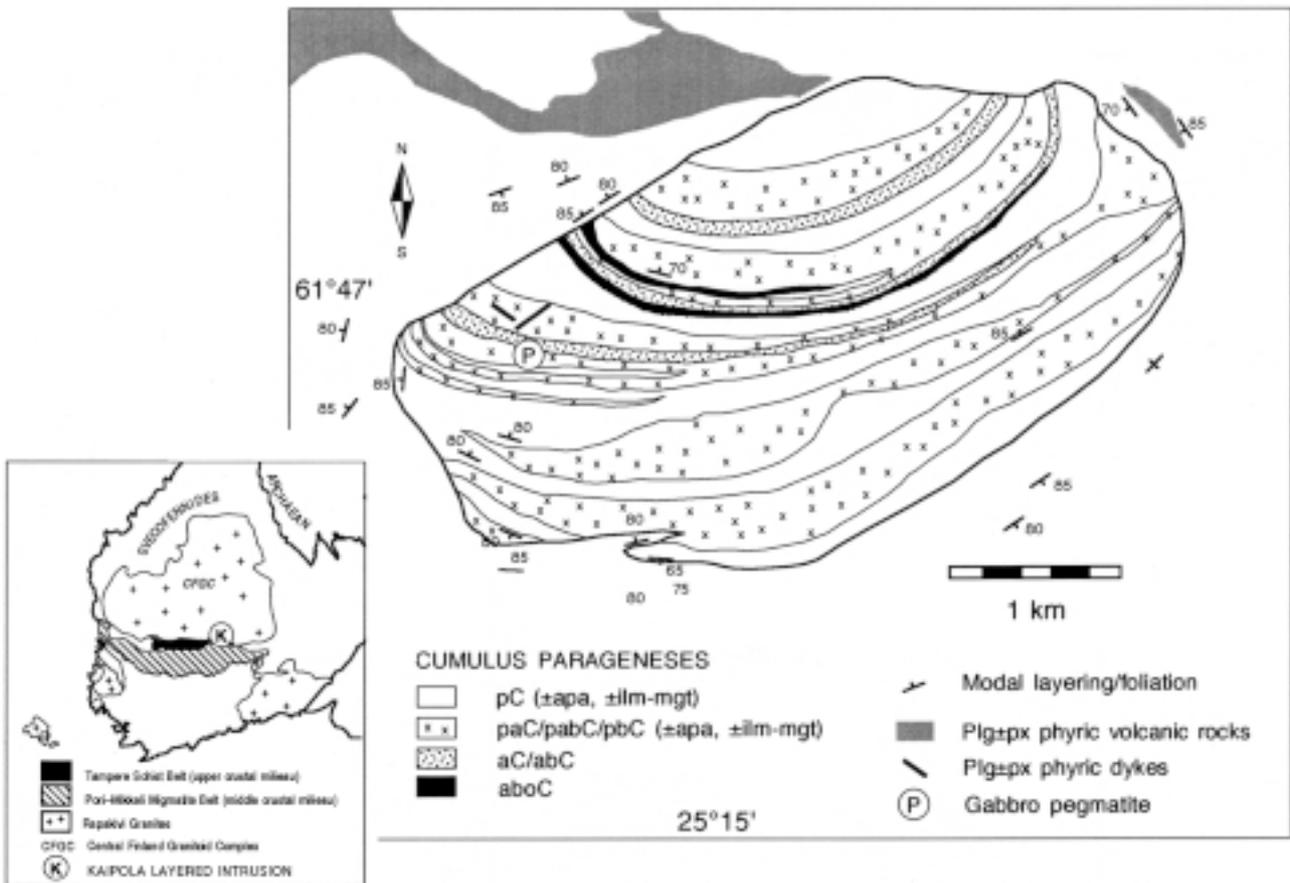


Fig. 2. Geological map of the Kaipola Layered Intrusion.

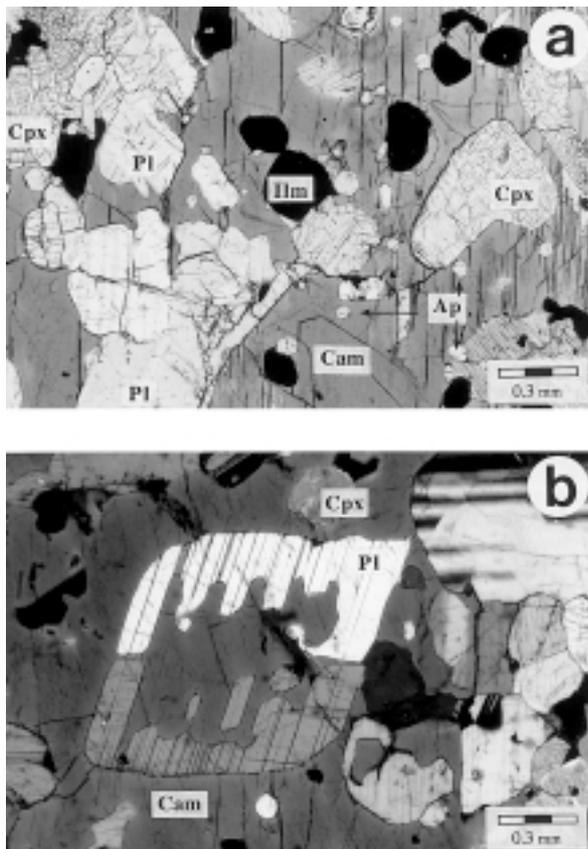


Fig. 3. a) Poikilitic plagioclase-clinopyroxene-orthopyroxene cumulate (pabC) with abundant subhedral ilmenite (ilm) and euhedral apatite (ap) crystals mainly enclosed by postcumulus calcic amphibole (cam). b) Poikilitic plagioclase-clinopyroxene orthocumulate. Note the prominent resorption of plagioclase grains as a result of their peritectic reaction with postcumulus amphibole (cam, pargasite).

Petrophysics and gravity modelling

Although the petrophysical data is somewhat sparse due to the fact that a major part of the intrusion lies below a lake, it clearly shows that the Kaipola intrusion is both dense and partially strongly magnetized. The density histogram can be divided into two normally distributed components a) $3017 \text{ (mean)} \pm 64 \text{ (st.dev.) kg/m}^3$ and b) $3187 \pm 21 \text{ kg/m}^3$, with most of the samples belonging to the first group. The magnetic susceptibility histogram can be divided into four log-normally distributed components a) 0.0011 ± 0.0001 , b) 0.0047 ± 0.0017 , c) 0.0123 ± 0.0034 , and d) $0.0735 \pm 0.0230 \text{ SI}$, with most of the samples belonging to the last group. The remanent magnetization histogram can be divided into three log-normally distributed components a) 195 ± 61 , b) 826 ± 349 , and c) $2897 \pm 931 \text{ mA/m}$, with most of the samples belonging to the last two groups. A majority of the samples has Koenigsberger ratios less than 1, but a minority has

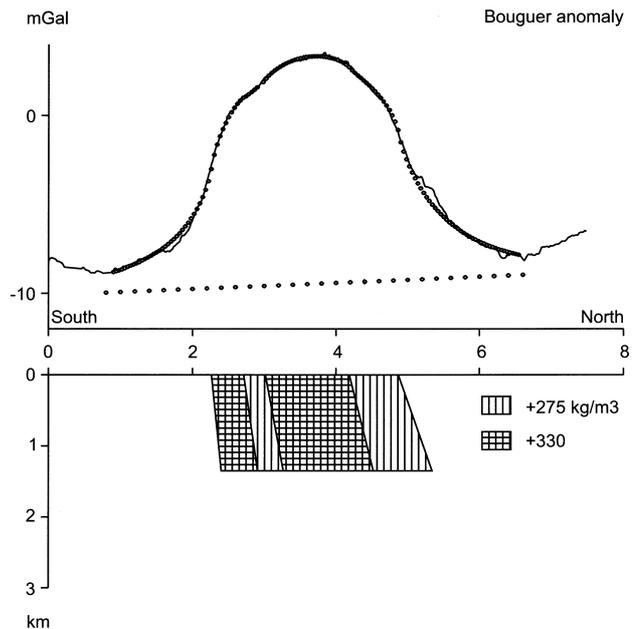


Fig. 4. The gravity anomaly profile and a quantitative density model derived from it. The continuous line represents the measured Bouguer anomaly, the small circles represent the calculated anomaly and its zero level. The model is 2-dimensional with a half-width of 2.5 km.

ratios ranging from 3 to 10.

The ground gravity profile shown in Figure 4 was measured across the intrusion with a station interval of 20 metres with insignificant gaps at both ends. The residual anomaly due to the intrusion is about 13 mGal. According to the gravity modelling, the body dips to the north-northwest with an average depth extent of about 1.4 km. Density variations between the magmatic layers are reflected by small changes in gravity anomaly. The two most magnetic layers cause low-altitude aeromagnetic anomalies of 3800 and 2600 nT. According to the quantitative modelling these two layers are found at the bottom of the dense layers. Altogether, the Kaipola Layered Intrusion shares the typical geophysical characteristics of other Svecofennian intrusions in this type of upper crustal geological environment.

Relationship with the spatially associated volcanics

Several lines of evidence suggest that the Kaipola Layered Intrusion could be a synvolcanic intrusion, comagmatic with the spatially associated volcanic rocks (upper volcanics of the Tampere Schist Belt). These include: a) volcanic rocks occur at the northern tip of the intrusion, in the direction that is also the stratigraphic top of the igneous layering, b) the phenocrysts phases of the volcanic rocks are the same as those which occur as cumulus phases in the

intrusions (plg and px), c) the presence of fine-grained plg-px pyritic dykes within the gabbro, and d) radiometric U-Pb age (1877 ± 30 Ma, unpubl.) of the Kaipola Layered Intrusion, although with large error, is correlative with the age of the volcanism within the Tampere Schist Belt (Kähkönen et al. 1989).

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NEW RESULTS FROM CALCITE AND ILMENITE EXPLORATION IN FINLAND

by

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Introduction

The Geological Survey of Finland (GTK) has increased exploration capacity of industrial minerals during last few years. The main motive has been the significantly increased domestic use of paper pigments of up to 2.6 million tonnes in 1997. Kaolin is the most important paper pigment. Of the total of 1.8 Mt of imported paper pigments, 1.3 million tonnes is kaolin. Potential kaolin deposits have been reported from Virtasalmi (Sarapää 1996) and they are still under development. The import of carbonates is more than 0.5 Mt, while domestic production of micronised calcite (GCC) and precipitated calcium carbonate (PCC) is 0.7 Mt (Pekkala 1998). The production of micronised calcite from domestic mines has increased to 0.4 Mt and still more than 0.35 Mt was imported. GCC is mainly used for paper coating. Talc production is more than 0.4 Mt, and about half is exported. Ilmenite is a raw material for TiO₂-pigment and it is imported from Tellnes, Norway. The export value of TiO₂ pigment in 1997 was about 724 million Finnish marks. Considering the above it is clear that calcite, ilmenite, kaolin and talc are of greatest interest in exploration and future perspectives of the industrial mineral's sector in Finland.

In southern and western Finland the main minerals explored by GTK are calcite and ilmenite. In eastern Finland talc and soapstone are the main targets and kaolin in northern Finland. In early 1999, the GTK reported two calcite-marble depos-

its, Norrjammala and Genböle, to the Ministry of Trade and Industry. In addition to these there are several promising calcite marble deposits under exploration. The deposits are located within 50 km from the GCC plant of Omya Oy (Plüss Staufer) at Förby, where calcite rock is quarried from the nearby underground mine of K. Forsström Ab. The search for domestic ilmenite deposits has been ongoing for several years. The Koivusaarenneva ilmenite deposit in Midwestern Finland (Kärkkäinen et al. 1997) has the resource estimate of 16 Mt with 20% or 3.5 Mt with 30% ilmenite to +150 m. At present Kalvinit Oy has the claim right for Koivusaarenneva. The GTK has discovered a new ilmenite deposit, at Peräneva, 3 km SW from Koivusaarenneva.

Calcite exploration in southwestern Finland

The GTK has carried out calcite exploration for five years in the Uusimaa Belt, SW-Finland. The aim is to find calcite marble deposits, which are suitable for the production of micronised calcite for the paper industry. Several promising deposits have been found (Fig. 1). The Uusimaa Belt forms a part of the Svecofennian Domain, and it belongs to an accretionary arc complex of southern Finland (1.90–1.82 Ma, Korsman et al. 1998). The Uusimaa Belt is comprised of highly metamorphosed felsic and mafic volcanic rocks (quartz-feldspar gneiss and amphibolite), abundant carbonate marbles, mica gneiss, granite and gabbro. It is a continuation of the famous mining district of Bergslagen in central

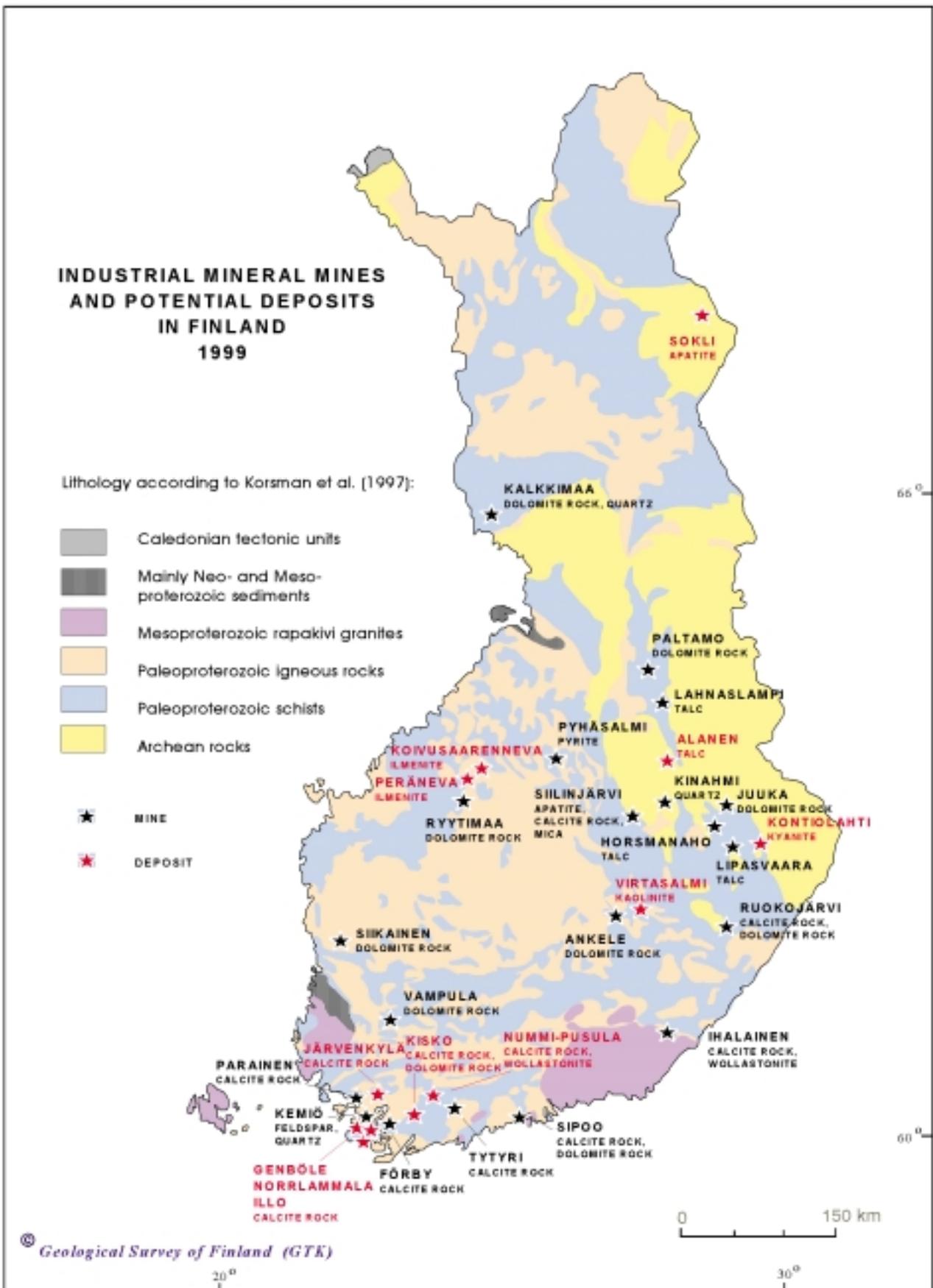


Fig. 1. The industrial mineral mines and potential deposits in Finland.

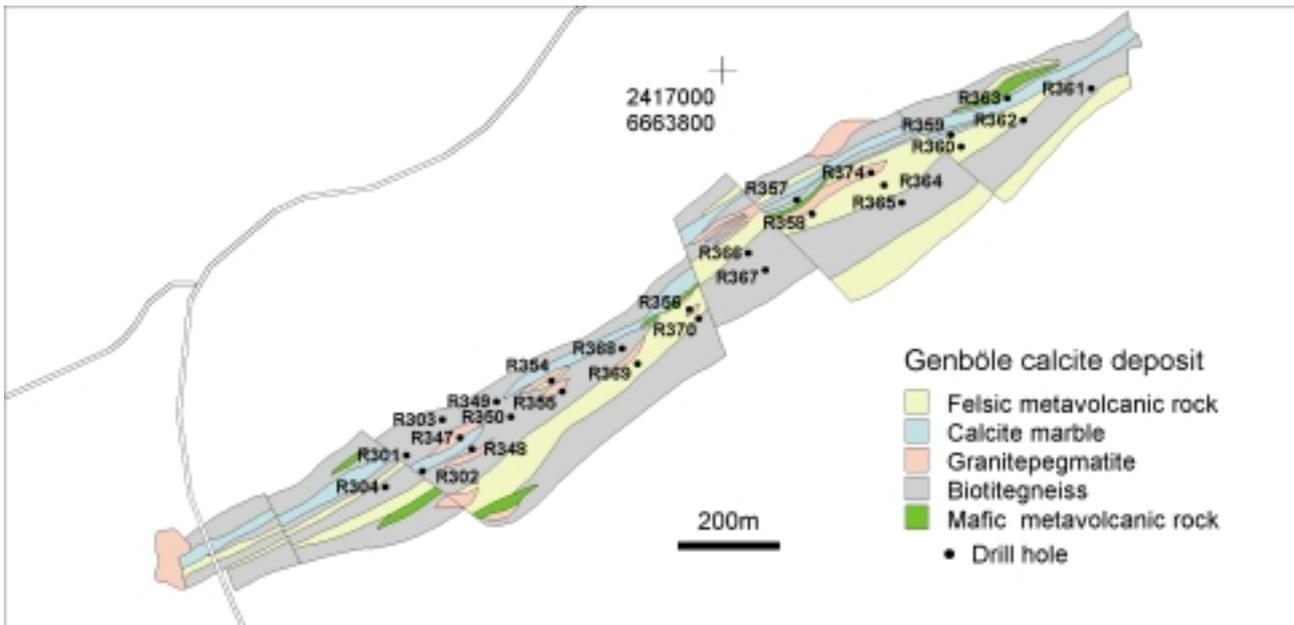


Fig. 2. The calcite marble deposit at Genböle.

Sweden, where large oxide and sulphide ores occur in metavolcanic rocks, carbonate marbles and skarns (Allen et al. 1996).

Genböle deposit

The Genböle deposit consists of a SW-NE trending, 2 km long and 10-40 m wide calcite marble layer. Fault zones cut the deposit in a SE-NW direction into six parts (Figs. 2 and 3). The deposit is composed of nearly vertical calcite marble layers dipping 80° NW. The deposit is partially controlled by a gently dipping lineation to 15-20° NE. There are few amphibolite, quartz-feldspar gneiss and skarn intercalations in the calcite marble. The country rocks are comprised of sillimanite and garnet-bearing biotite-gneiss and granite pegmatites, which occasionally also cut the calcite marble. The contacts between the marble and country rocks are sharp.

Calcite marble is a white or light grey, medium-grained (2-3 mm) and granoblastic rock that displays bedding. Quartz and tremolite are always present in small quantities. Diopside, muscovite, K-feldspar and sphene are accessory minerals present in variable proportions. Typical mineral parageneses are calcite+quartz+tremolite+diopside and calcite+quartz (Ahtola 1998). Calcite content in most drill cores is 80-95 % (Fig. 4a). There is no dolomite in the calcite marble and the MgO content is 0.2-0.8 % and (Fig. 4b).

The indicated mineral resource estimate of the

Genböle deposit is 3.9 Mt of calcite marble with 87 % calcite to the depth of 75 m (Seppänen et al. 1998). The calcite resource estimate is based on 46 drill holes, a total length of 3781 m. The chemical composition of calcite concentrate after flotation fulfils the quality requirements of GCC (Table 1).

Norrlammala deposit

The Norrlammala calcite marble deposit is 2 km long and 10-55 m wide (Figs. 5 and 6). The strike of the deposit is E-W and the dip 70-80°S (Reinikainen 1997). The deposit is composed of a continuous calcite marble layer, which in the eastern part is divided into two layers by a mafic dike. In the eastern part of the deposit there are also thin layers of dolomite marble within calcite marble (Reinikainen et al. 1998). The deposit is also oriented along the F2 fold axis to 50-60°W. The country rocks are felsic and mafic metavolcanic rocks, originally tuffs, tuffites and lavas, which under high-grade metamorphism have altered to quartz-feldspar gneisses, biotite gneisses and amphibolites. Pyrrhotite-bearing schist follows the carbonate marble along the foot wall causing a strong magnetic anomaly.

Calcite marble is light grey, coarse-grained (2-5 mm), granoblastic rock and is divided into three types according to calcite content: 1) >85 % calcite, 2) 70-85 % calcite, 3) 60-70 % calcite. In all types calcite is chemically pure and contains >54 % CaO, <0.01-0.03 % MgO, 0.05-0.50 % Fe₂O_{3TOT} and

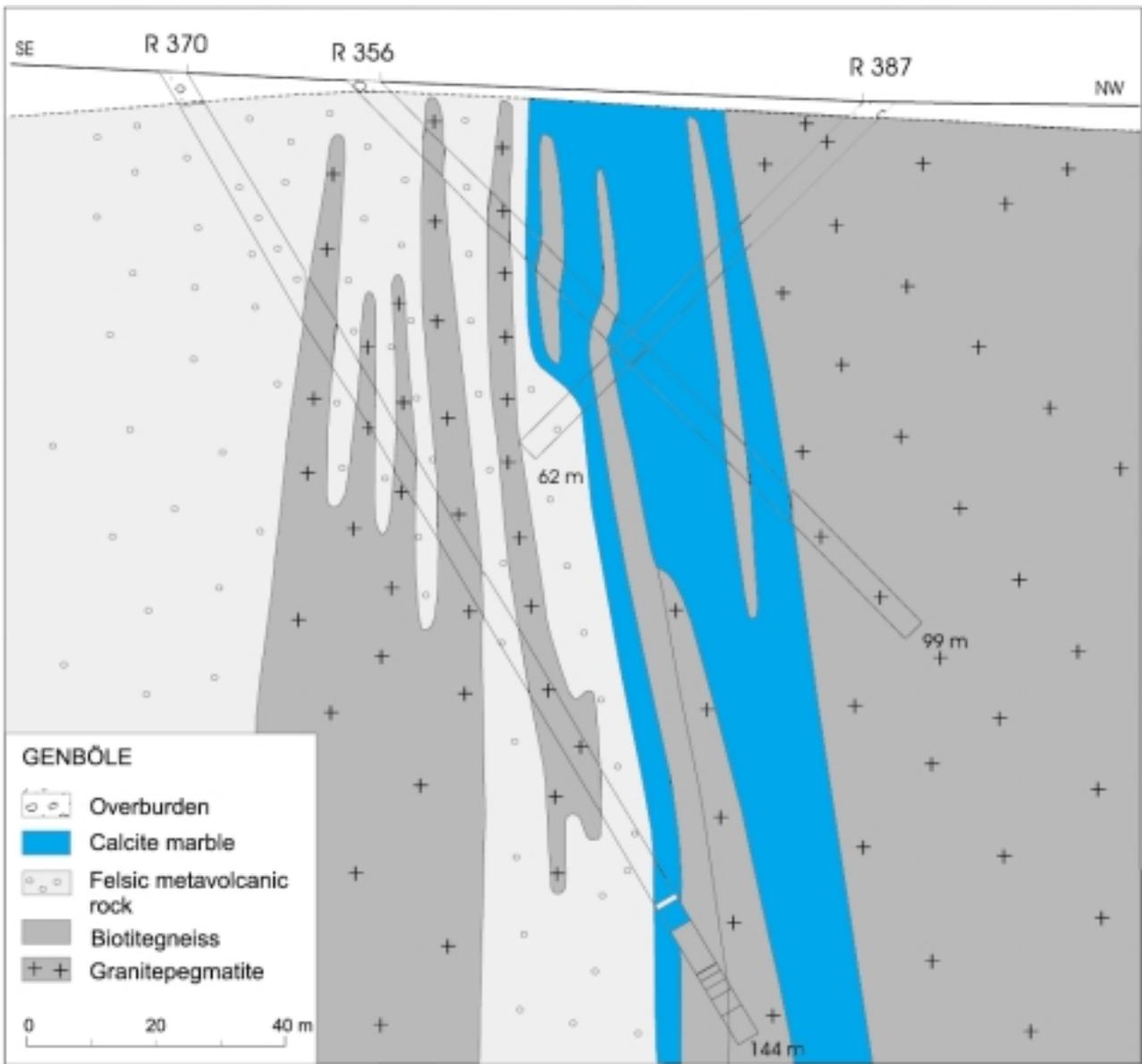


Fig. 3. A cross section of the Genböle deposit.

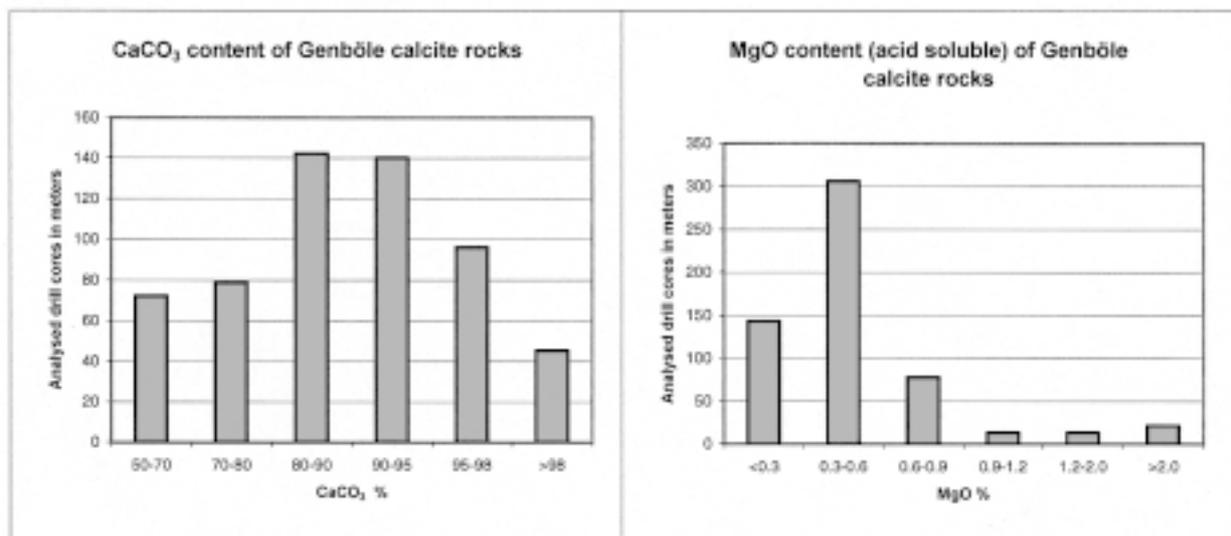


Fig. 4. Calcite and magnesium content in drill cores at Genböle.

0.02-0.05 % MnO according to microprobe-analyses. Calcite-dolomite marbles are rare and their composition is 0.7-2.5 % MgO, 0.5-1.0 FeO_{TOT} and 0.25-0.5 % MnO. Quartz, K-feldspar and plagioclase are the main silicate minerals in calcite marble. Tremolite, phlogopite, wollastonite and forsterite occur as secondary metamorphic minerals.

An indicated mineral resource estimate has been made from the central part of the Norrslammala deposit. It is 880 m long and there are seven drilling profiles with 14 drill holes, a total length of 1260 m. The indicated resources to the depth of 75 m are 7.5 Mt calcite rock, with the average calcite content of 76 %. The total resources are 41 Mt with 75% calcite estimated to the depth of 300 m.

In laboratory scale processing tests the calcite content of concentrate after flotation is more than 99% (Table 1). The brightness measured as ISO-value from the concentrate is 91-93 % (Chernet 1998b), in grain size under 45 microns. This indicates that Norrslammala calcite could be used as raw material for paper coating pigment.

Other carbonate deposits

Four other promising marble deposits Illo, Järvenkylä, Iso-Sorro and Kalkkimäki are under exploration by the GTK in southern Finland (Fig. 1). **Illo** is an old mine on Kemiö Island. The deposit

is at least 500 m long comprising two 20-40 metres thick vertical calcite marble layers (>80% calcite). The surrounding rock is silicate-rich calcite marble with 60% calcite. The high-metamorphic country rocks are garnet-sillimanite gneiss, amphibolite and granite pegmatite. Flotated calcite concentrate is chemically pure (>99% calcite) and has the brightness value acceptable to GCC. The **Järvenkylä** calcite marble deposit is partially covered by flat lying granite. The minimum length of the deposit is 500 m and the vertical calcite layer is 20-40 metres thick. The calcite concentrate has a high brightness and is chemically pure (Table 1). The **Iso-Sorro** carbonate marble deposit is located in a medium-grade metamorphic area at Kisko. There a 60-m-thick, fine-grained, granoblastic dolomite marble, occurs side by side with a 20-m-thick, pure medium-grained calcite marble. The marble deposit are surrounded by mafic and felsic metavolcanic rocks (Fig. 7). The dolomite marble is obviously suitable for agricultural use and maybe also as dimension stone. The calcite marble contains 70-95 % calcite and after processing tests the concentrate indicates GCC-quality. The **Kalkkimäki** deposit at Nummi-Pusula consists calcite, calcite-wollastonite and dolomite layers. The drilling program in 1999 will be directed into the wollastonite-bearing part of the deposit.

Table 1. The properties of calcite concentrations from different deposits of SW-Finland.

Deposit Drill hole sample	Illo		Järvenkylä		Genböle		Norrslammala	
	R 393 67.10-89.30 m		R 312 97.60-117.60 m		R 375 26.25-41.35 m		R 440 68.40-85.45 m	
	Feed	Concentrate	Feed	Concentrate	Feed	Concentrate	Feed	Concentrate
CO ₂	41.77	43.97	41.77	43.60	38.47	43.97	36.16	43.97
CaO	54.20	56.90	55.00	56.90	49.90	56.40	46.10	55.70
MgO	.26	.14	.36	.15	1.06	.37	2.45	.98
SiO ₂	3.09	.05	2.52	.05	10.30	.32	10.40	.16
Al ₂ O ₃	.70	.00	.51	.00	.25	.03	2.02	.03
Fe ₂ O ₃	.20	.08	.16	.05	.22	.10	1.48	.17
Na ₂ O	.01	.00	.00	.00	.00	.00	.29	.00
K ₂ O	.14	.00	.12	.00	.04	.00	.23	.00
P ₂ O ₅	.00	.00	.00	.00	.00	.00	.00	.00
TiO ₂	.01	.00	.02	.00	.01	.00	.15	.00
MnO	.01	.01	.01	.01	.04	.04	.06	.05
Total	100.39	101.15	100.47	100.76	100.29	101.23	99.34	101.06
Calcite %	94.9	99.9	94.9	99.1	87.4	99.9	82.2	99.9
ISO-Brightness	-	93.0	-	93.7	-	91.6	-	92.1
Yellowness % -45 µm	-	1.0	-	1.8	-	0.7	-	1.8

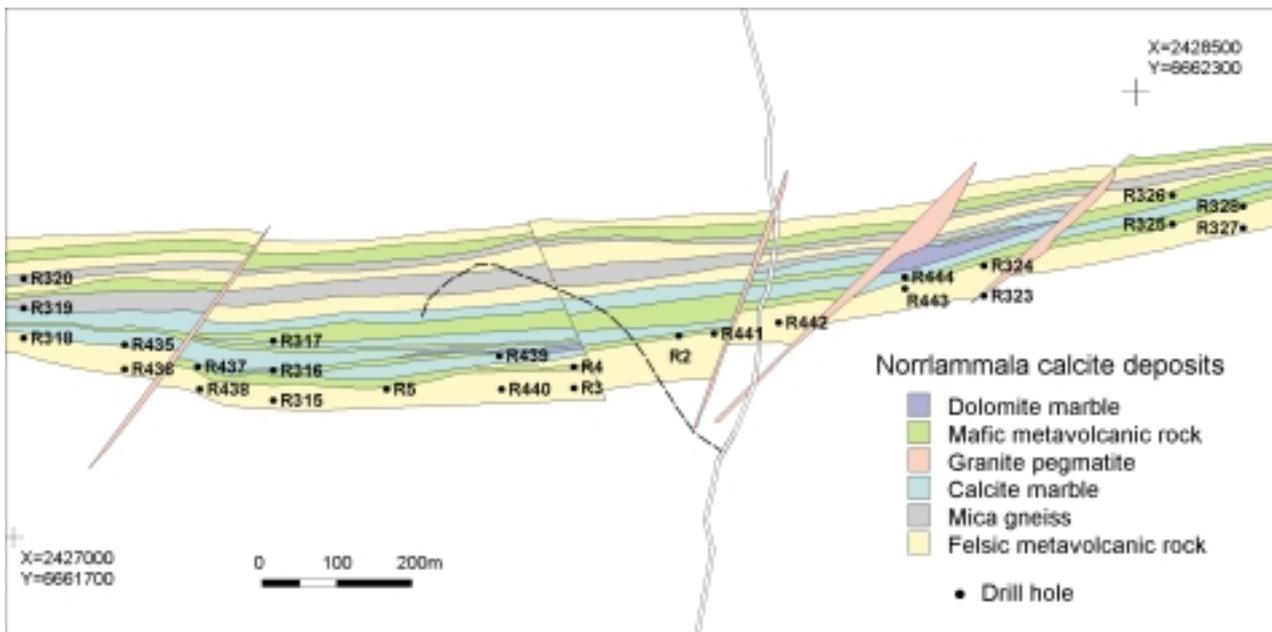


Fig. 5. The calcite marble deposit at Norrliammala.

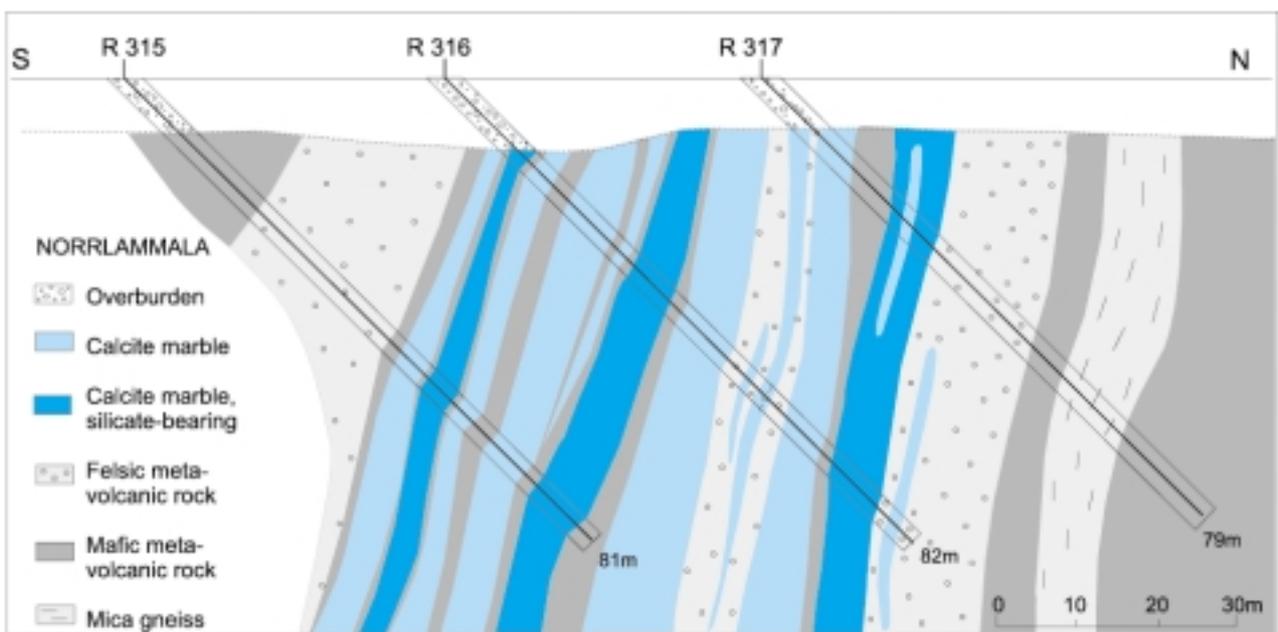


Fig. 6. A cross section of the Norrliammala deposit.

Peräneva ilmenite deposit

The Peräneva mafic intrusion is located 3 km southwest of the Koivusaarenneva gabbro and is partly located in the Halsua and partly in Kälviä communes in an important Kairineva peat production area (Fig. 8). The Peräneva intrusion was found by regional gravity mapping (6 points per km²) as an anomaly analogous to the Lylyneva and Koivusaarenneva intrusions (Kärkkäinen et al. 1997).

Detailed ground geophysical measurements of

Peräneva revealed a 3 km long and 0.5 - 1.5 km wide gravity and magnetic anomaly field consisting of two to three parallel maximum zones (Fig. 9). There are no outcrops within the anomaly area. The nearest outcrops are deformed tonalites. The southernmost maximum zone is as far checked by drilling. The drill holes revealed Fe-Ti mineralization in a gabbro, but in some localities it penetrated only peridotite. As a whole the gravity field outlines a mafic intrusion composed mainly of gabbro. Only the eastern part of the gravity field has been drilled in detail.

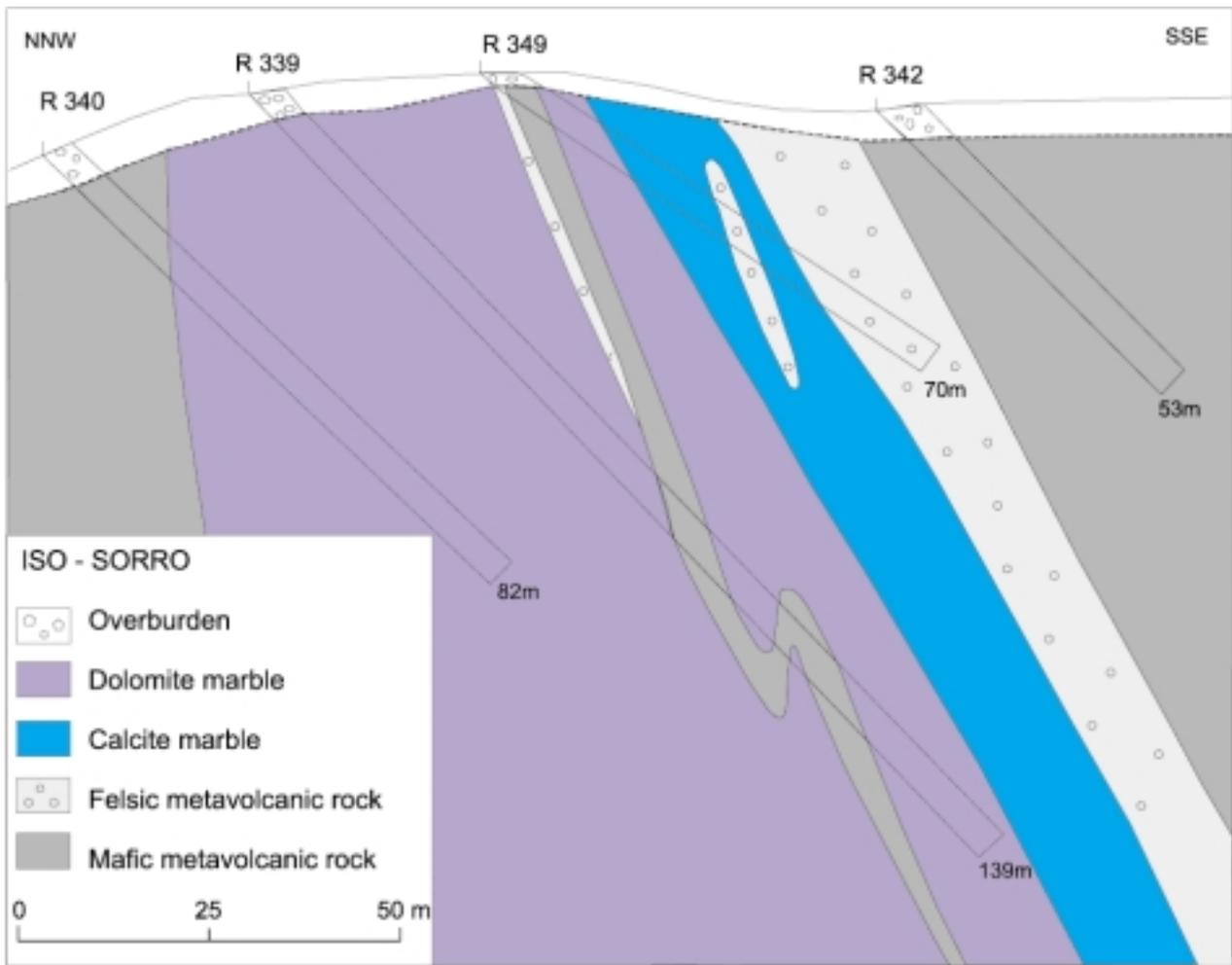


Fig. 7. A cross section of the Iso-Sorro carbonate marble deposit.

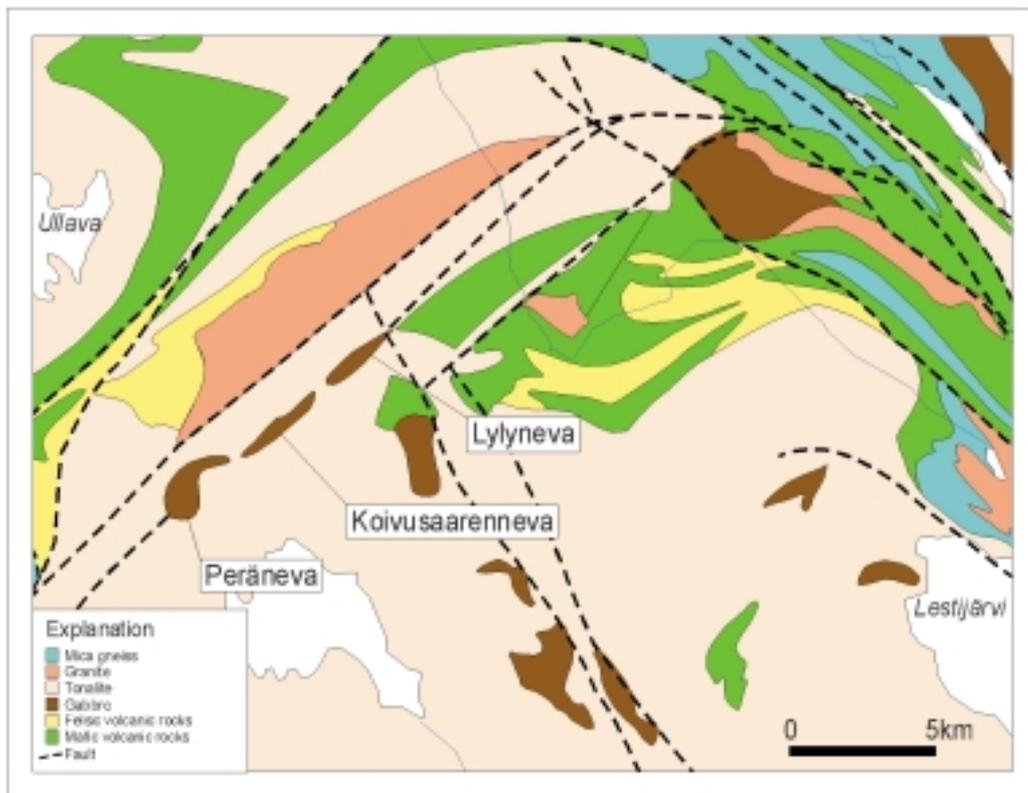


Fig. 8. Geological map of the Peräneva area.

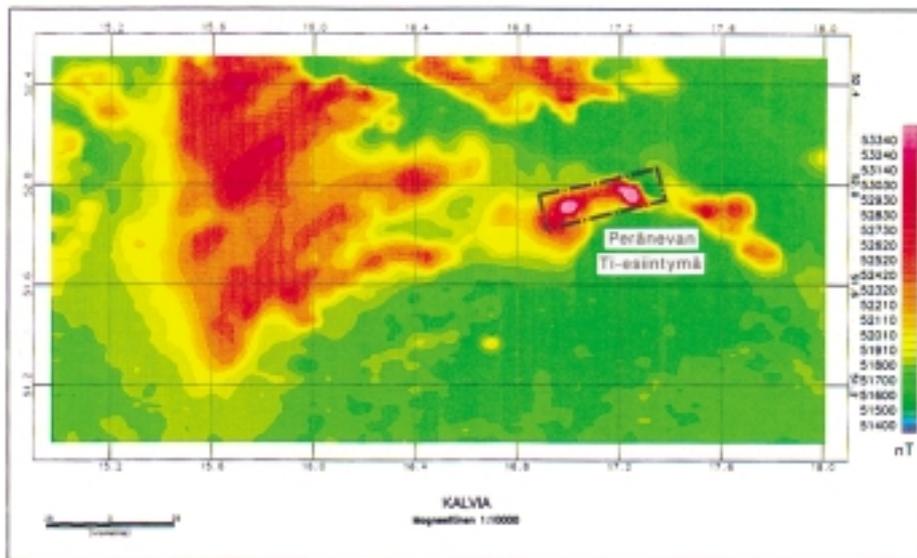


Fig. 9. Magnetic map of the Peräneva intrusion.

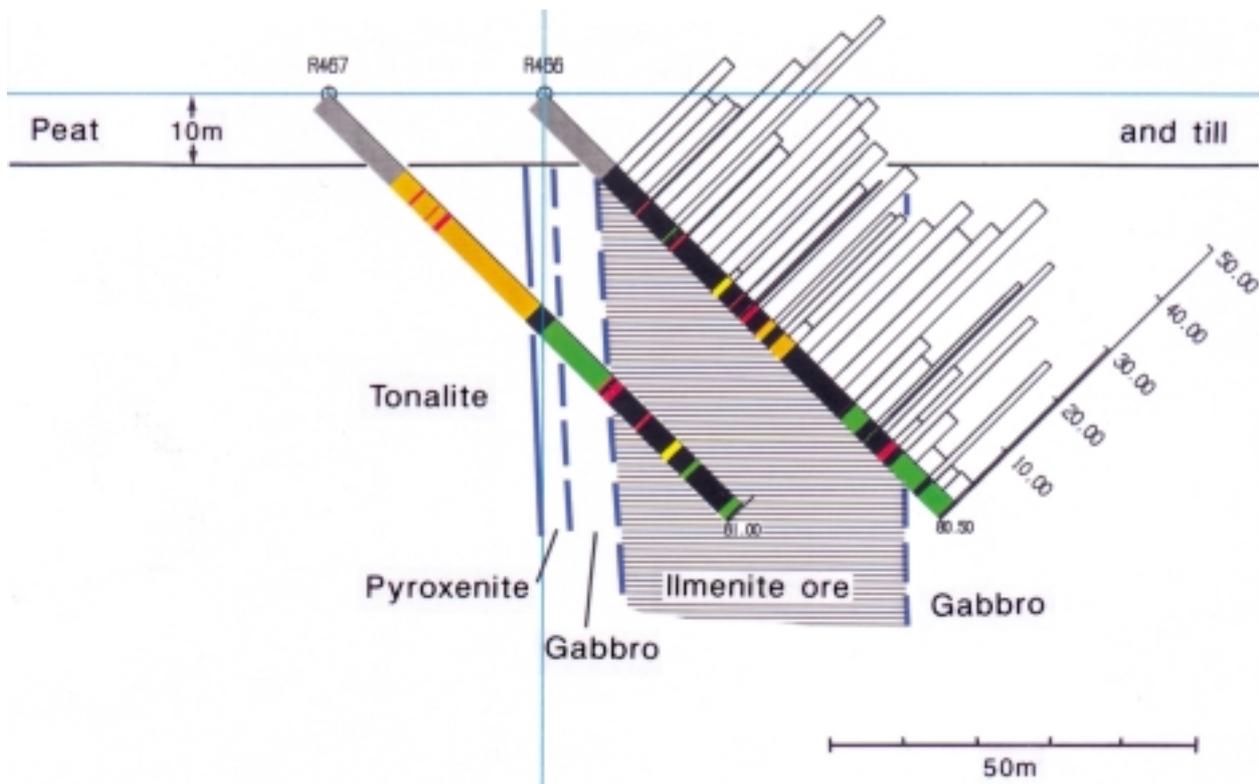


Fig. 10. A cross section of the Peräneva deposit, scale wt-% ilmenite.

This part includes the Peräneva ilmenite deposit.

The Peräneva deposit is a subvertical, about 600 m long and 15 - 40 m thick zone. It is composed of disseminated and massive ilmenite layers in gabbro. The average grade is about 20% ilmenite (range 10 - 50 wt %) (Fig. 10). The host rock is a homogenous, medium-grained gabbro or gabbro norite, where pyroxene has been totally amphibolitized. Pyroxenite

occurs as a few metres thick layers near the contact to tonalite. At western end of the ilmenite deposit, the mineralized zone is ruptured by a pyroxenite dominated block.

The low content of magnetite and the high ratio of titanium to iron ($TiO_2/Fe_2O_3 = 0.3$ to 0.4 , total iron as Fe_2O_3) are typical features of the Peräneva ilmenite deposit. The distributions of the rocks

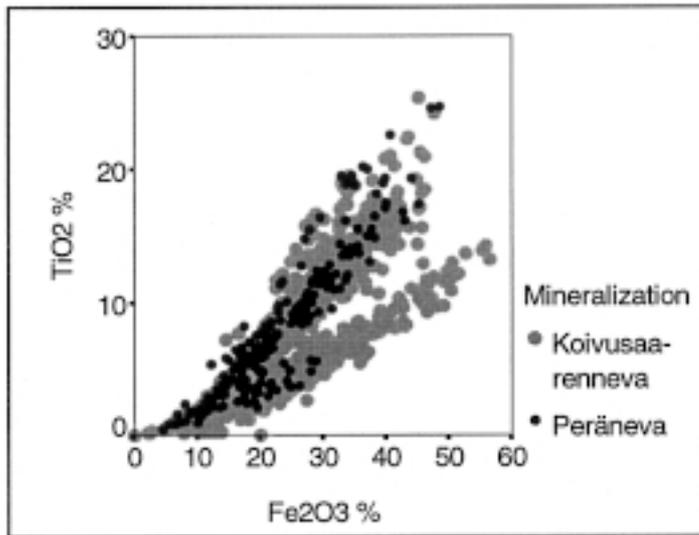


Fig.11. TiO₂-Fe₂O_{3TOT}-scatterplot of Peräneva (black) and Koivusaarenneva analyses (gray).

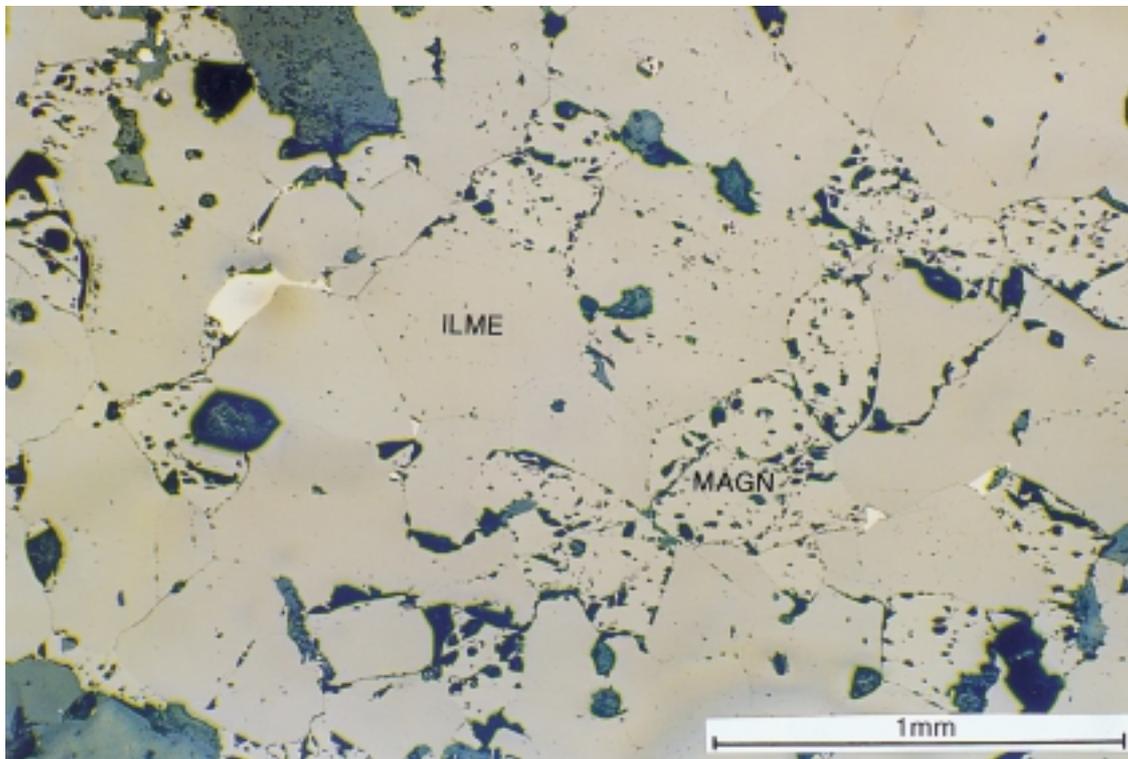


Fig. 12. A microphotograph of Peräneva ilmenite ore, part of a large ilmenite-magnetite aggregate. Crystal faces are visible both in ilmenite and magnetite grains. Small white grains are pyrite. Sample DH 467/65.35. Reflected light, one polarizer.

follow in the diagram of TiO₂ vs Fe₂O₃ (Fig. 11) the same trend as the middle zone of the Koivusaarenneva gabbro (Kärkkäinen 1997).

Ilmenite occurs as separate, 0.1 to 1.0 mm grains, containing locally few silicate inclusions (Fig. 12). Magnetite occurs as smaller grains around ilmenite. Magnetite contains only few, very thin ilmenite lamella, and ilmenomagnetite (as metamorphosed

Ti-bearing magnetite) does not occur. The surface of the mafic intrusion is slightly weathered. There is a small amount of pyrite, and a few grains of chalcopyrite in the ilmenite mineralization. The ratio of ilmenite to magnetite is 5:1 (range 3:2 - 9:1). Apatite is rare, usually less than 0.2%. Bench scale mineral processing tests from Peräneva ilmenite ore made at the GTK have yielded industrial grade

ilmenite (45-46% TiO₂, Chernet 1998b). The mineralization is identical to the highest grade ilmenite mineralization in the Koivusaarenneva gabbro. The Peräneva ilmenite deposit belongs to a suite of small gabbro intrusions (Kärkkäinen 1999); typically Ti critical for the bedrock in this part of Finland. Future studies will be directed towards discovering the richest part of the Peräneva ilmenite deposit.

Conclusions

The Genböle and Norrslammala deposits hosts economically interesting calcite resources in terms of quantity and quality. Apart from these, there are four other promising carbonate marble deposits under exploration, all of which have good potential for paper quality GCC-production. The Peräneva ilmenite ore nearby the Koivusaarenneva deposit represents the richest part of ilmenite concentration in the ilmenite province of western Finland so far located by the exploration program of GTK.

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THE AGE OF THE KOIVUSAARENNEVA ILMENITE GABBRO, WESTERN FINLAND

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Key words (GeoRef Thesaurus, AGI): gabbros, ilmenite, absolute age, U/Pb, zircon, Paleoproterozoic, Koivusaarenneva, Finland

Introduction

The Koivusaarenneva gabbro in the Kälviä commune, mid Pohjanmaa (Fig. 1), is characterized by ilmenite as the dominant Fe-Ti oxide. It hosts an economically interesting ilmenite deposit that consists of ilmenite (8 to 48%) and vanadiniferous magnetite (0.7% V) (Chernet & Kärkkäinen 1995, Kärkkäinen et al. 1997, Kärkkäinen 1999). The sill like intrusion is emplaced into tonalitic bedrock of the mid Finland Granitoid Complex (MFGC), near the boundary between the granitoid area and the Pohjanmaa schist belt. The closest dated mafic intrusion is the Kumiseva gabbro, at 1879 Ma (Ekdahl 1993), and Hitura Ni-ore bearing mafic complex, dated at 1875 Ma (minimum age) (Isohanni

et al. 1985). The Kumiseva gabbro is situated within the CFGC and is a central intrusion of several small satellites (Ekdahl 1993), 30 km east from the Koivusaarenneva gabbro.

Two drill core samples of coarse grained gabbro from the lower zone of the Koivusaarenneva intrusion were taken to determine the radiometric age of zircon. The coarse grained gabbro occurs as discontinuous layers (5 to 40 m) in the lower zone. Stratigraphically it is situated just below lowest Fe-Ti oxide-rich layers, and locally also coarse grained gabbro contains much oxides. The composition of the coarse grained gabbro is tholeiitic, and similar to the most common, fine to medium grained gabbro in the intrusion. The main minerals are recrystallized plagioclase and uralitized pyroxene. The most common minor minerals are ilmenite, biotite, ilmenomagnetite, and in pegmatoid variations sometimes quartz, and apatite. Zircon is a common accessory mineral, and generally the Zr-content in XRF-analysis is 0.02 to 0.04% Zr, locally up to 0.08% Zr. The gabbro is recrystallized under mid-amphibolite facies metamorphism and later hydrothermal events.

The analyses were made in GTK's laboratory for isotope geology by O. Kouvo using conventional methods (e.g. Huhma 1986). The analyzed samples are composed of 14 to 31 m long split drill cores from two drill holes in the northern part of the intrusion, map sheet 2341 05, x= 7053.68, y=2512.10:



Fig. 1. Location of the Koivusaarenneva gabbro.

Sample number (Table 1)	Drill hole	Depth	Symbol in the concordia diagram (Fig. 2)
A926a	R374	55.40 - 86.46 m	a = cross
A926b	R377	45.00 - 59.00 m	b = circle

Zircon is of normal color, and the grains are absolutely euhedral. The surfaces of the crystals are clear and the edges are sharp. Growth structures are visible on the surfaces. The ratio of length to cross section (L/B) of the crystals are between 2 and 7. The crystals are dominantly prismatic, seen as (100) planes, but also weak crystal faces of (110) are visible.

Characteristic of the Koivusaarenneva zircon is the variation of color; a common feature for zircon in mafic rocks. The dark brown and light colored crystals were picked into separate fractions for

analyses, but there is no appreciable difference in the isotope composition of these fractions (Table 1). The concentration of uranium is 251 to 1925 ppm. Based on the $^{206}\text{Pb}/^{204}\text{Pb}$ -ratio, the abundance of common lead is low. A peculiarity of the Koivusaarenneva zircon is that the purest fractions are found in samples with the highest concentrations of uranium.

Because drill holes R374 and R377 are situated close to each other, the results are presented in the same concordia diagram (Fig. 1). The regression line cuts the concordia curve in the point 1881 ± 6 Ma. The lower intercept is 191 ± 96 Ma. If the age is calculated separately for each sample the ages are

A926A	1881 ± 8 Ma	178 ± 128 Ma
A926B	1880 ± 8 Ma	217 ± 135 Ma.

Table 1. Isotopic composition and radiometric ages. All fractions were air abraded. Sample size 5 - 10 mg; d = density; r = size (μm); *) corrected for fractionation, blank (0.5 ng Pb) and age related common lead. Errors are 2σ in last significant digits. Decay constants: Jaffey et al. (1971).

Sample	Fraction	Concentration		Measured	Isotopic composition			Atomic ratios and radiometric ages, Ma (*)		
		^{238}U ppm	^{206}Pb ppm		^{206}Pb ^{204}Pb	$^{206}\text{Pb} = 100$ 204	207	208	^{206}Pb ^{238}U	^{207}Pb ^{235}U
A926aA	d>4.3 r>160 light	251.4	69.41	8679 ± 146	.01078	11.629	9.284	.3191 ± 20 1785	5.052 ± 32 1828	.11484 ± 21 1877
A926aB	4.2<d<4.3 r>110 light	783.3	202.81	8473 ± 269	.01094	11.596	10.790	.2992 ± 19 1687	4.723 ± 30 1771	.11448 ± 8 1871
A926aC	4.2<d<4.3 r>110 dark	947.9	252.98	8776 ± 129	.01076	11.586	10.583	.3085 ± 20 1733	4.866 ± 32 1796	.11441 ± 10 1870
A926aD	4.0<d<4.2 r>160 light	1009	255.36	5539 ± 76	.01751	11.653	12.184	.2925 ± 18 1654	4.604 ± 30 1750	.11416 ± 18 1866
A926aE	4.0<d<4.2 r>110 dark	1075	289.86	11911 ± 452	.008035	11.555	10.989	.3117 ± 20 1748	4.919 ± 32 1805	.11446 ± 17 1871
A926bA	d>4.3 r>110 light	479.7	131.25	9304 ± 99	.01010	11.615	9.330	.3162 ± 19 1771	5.004 ± 31 1820	.11478 ± 10 1876
A926bB	4.2<d<4.3 r>110 light	757.7	200.23	3277 ± 37	.02986	11.823	10.191	.3054 ± 21 1718	4.808 ± 34 1786	.11419 ± 20 1867
A926bC	4.0<d<4.2 r>110 light	1171	297.01	5840 ± 99	.01630	11.611	10.940	.2932 ± 18 1657	4.605 ± 29 1750	.11391 ± 16 1862
A926bD	4.0<d<4.2 r>110 dark	1259	349.16	10556 ± 188	.008705	11.561	9.878	.3206 ± 20 1792	5.059 ± 33 1829	.11443 ± 17 1871
A926bE	3.6<d<4.0 r>110 dark	1925	503.44	13966 ± 453	.007005	11.515	9.522	.3023 ± 23 1702	4.760 ± 37 1777	.11420 ± 15 1867

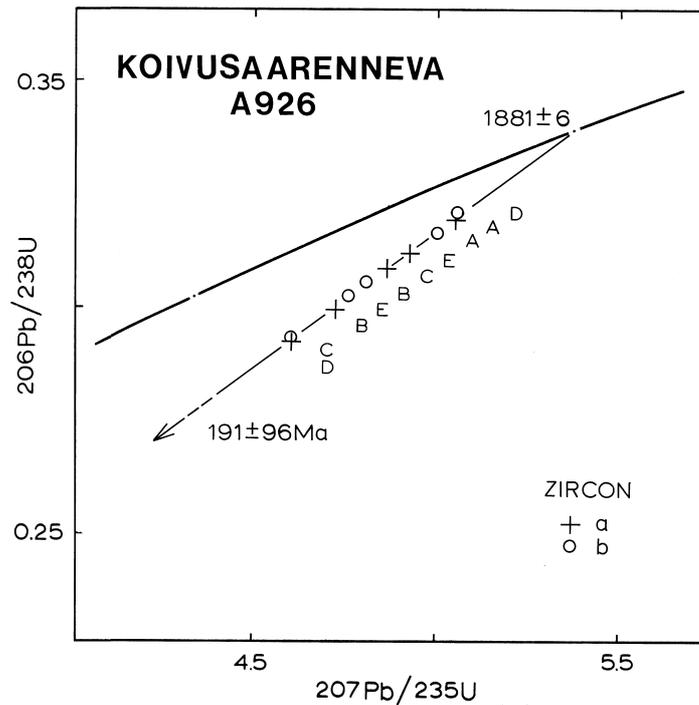


Fig. 2. Uranium - lead concordia plot of zircons from the Koivusaarenneva gabbro.

Based on the radiometric age, the Koivusaarenneva gabbro belongs to the same age group as the main part of the Svecokarelian mafic intrusions. The age (1881 ± 6) is practically the same as the age of the Ni-ore bearing Svecofennian intrusions (Huhma 1986). Instead, the age of the Koivusaarenneva gabbro is clearly younger than the Otanmäki Fe-Ti-V deposit of the age of 2060 Ma (Talvitie & Paarma 1980).

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HALPANEN CALCITE CARBONATITE DIKE, SOUTHEASTERN FINLAND

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Key words (GeoRef Thesaurus, AGI): limestone deposits, carbonatites, dikes, calcite, alvikite, chemical composition, Proterozoic, Paleoproterozoic, Halpanen, Kalkkiniemi, Mikkeli, Finland

Introduction

The small calcite rock deposit of Halpanen was first mentioned in the catalogue of limestones of Finland (Eskola et al. 1919), and described later as

a calcitic carbonatite (Puustinen 1986). It is located on the narrow Kalkkiniemi cape at Lake Halpanen, 12 km to the northeast of the city of Mikkeli, southeastern Finland (Fig. 1). At the site there is an old quarry, measuring 8 x 30 m, with a depth of 3 m,

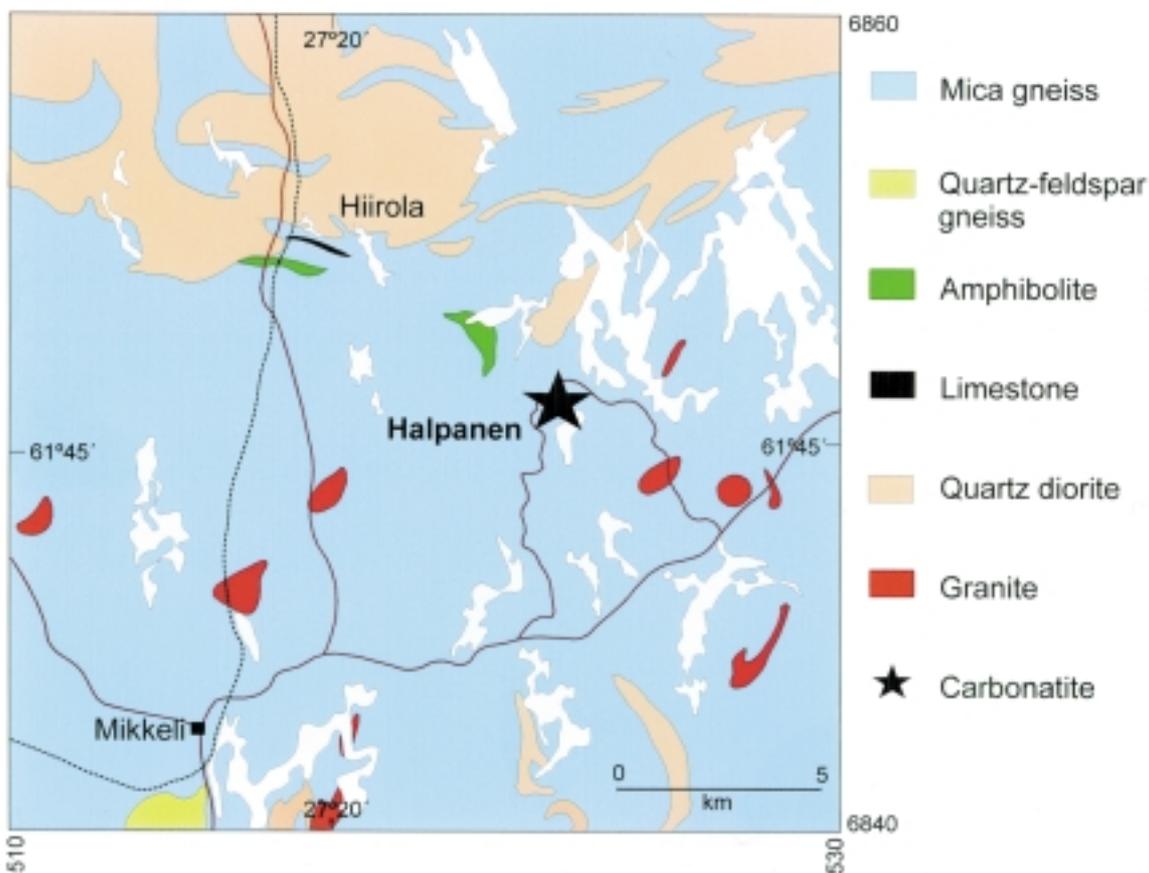


Fig. 1. Location of the Halpanen alvikite dike. General geological map modified after Simonen (1982).

from where calcite rock has been quarried and burnt for local use, probably before the year 1916. The critical area of 0.5 x 1.5 km has been covered with geophysical measurements by the Geological Survey of Finland using magnetic and electromagnetic (slingram) methods with a 20 x 50 m grid (Puustinen 1993).

General geology

The Halpanen carbonatite dike is located close to a major north-south trending deep fracture zone. This feature includes for example the Siilinjärvi carbonatite complex (Puustinen & Kauppinen 1985) some 150 km to the north, and gneiss domes to the south of the city of Kuopio. To the south of the city of Mikkeli the zone continues to the Gulf of Finland.

The surrounding bedrock is a part of an extensive complex of originally pelitic sediments (Fig. 1). The most common types are migmatitic mica gneisses, with only narrow zones of quartz-feldspar gneiss, amphibolite, and diopside amphibolite. Plutonic rocks are composed of quartz diorite and granodiorite with additional bodies of gabbro or granite. Small limestone and skarn deposits occur as interbeds among mica gneisses. The largest limestone deposit (Marmo & Metzger 1953) occurs in a 2 km long and 20 m wide east-west trending zone at Hiirola, some 6 km to the northwest of Halpanen.

The Halpanen carbonatite dike has been exposed only in the main quarry and in a couple of small pits, some 80 m to the north. Geophysical and topographic indications with locally more abundant vegetation suggest that the dike could extend some 1100 m to the north, and some 400 m to the southwest from the main quarry (Puustinen 1993). Thus, the very narrow carbonatite could have a total length of up to 1500 m. The depth is unknown because no drillings have been done at the site. The carbonatite dike cuts the schistosity of the surrounding rocks, the difference in strike being 20 - 30° and in dip 30 - 35°. This feature is representative the intrusive nature of the dike.

Carbonatites

The calcite carbonatite is massive or weakly banded, fine-grained, and white or slightly pink in color. Accordingly, the rock type could also be called alvikite. Its texture is granoblastic to hypidiomorphic. The mineral composition is calcite 97 - 99 %, with apatite, magnetite, pyrite, baryte, monazite and fluorite as accessory minerals. The

calcite has no dolomite exsolution textures, which is also shown by the general low magnesium content. Apatite and magnetite occur in the groundmass and as phenocrysts up to 1 cm in size. The contact zone between the alvikite dike and the surrounding alteration halo is mylonitic and it is also associated with a small granitic fragment.

Apatite-calcite rock has been found at the Kalkkiniemi quarry as not more than 0.1 m bands or segregations at the eastern contact of the dike. It is a hypidiomorphic, banded medium-grained rock, in which the apatite content varies from traces to an almost pure apatite rock. The mineral composition is calcite 20 - 80 %, apatite 20-80 %, with accessory magnetite, pyrite, baryte, monazite.

The chemical composition (XRF analyses) of the main rock types and the weighted average calculated from a profile of 6 samples across the dike are given in Table 1. SrO contents vary from 1.1 to 4.2 % and BaO contents from 0.2 to 0.6 %. The contents of Y range from 0.010 to 0.013 %, La from 0.09 to 0.11 % and Ce from 0.19 to 0.22 %. Below detection limits are K₂O < 0.01 %, Na₂O < 0.05 %, Nb < 0.001 %, U < 0.001 % and Th < 0.001 %. The δ¹³C values of calcite range from -12.2 to -12.4 ‰.

Preliminary age determinations made from monazite by the U-Pb method indicate a Paleopro-

Table 1. Chemical composition of carbonatite rocks at Halpanen.

	1	2	3
SiO ₂	0.56	0.62	0.52
TiO ₂	0.01	<0.01	<0.01
Al ₂ O ₃	0.18	0.01	0.02
Fe ₂ O ₃ [*]	0.55	0.39	0.44
MnO	0.10	0.15	0.15
MgO	0.32	0.34	0.34
CaO	52.41	53.48	54.58
SrO	3.63	1.07	1.57
BaO	0.22	0.63	0.38
Na ₂ O	<0.05	<0.05	<0.05
K ₂ O	0.01	<0.01	<0.01
P ₂ O ₅	21.41	0.54	0.77
CO ₂	20.41	42.51	42.08
SO ₃	0.11	0.48	0.39
Cl	0.05	0.04	0.04
Total	99.97	100.26	101.27
Rb	10	<10	-
Y	130	100	104
Zr	180	<100	-
Pb	90	250	249
REE	6450	4920	4720
δ ¹³ C (PDB)	-12.29	-12.39	-12.30
δ ¹⁸ O (SMOW)	13.34	16.71	15.50

^{*}) Total Fe as Fe₂O₃

1 - apatite-calcite rock; 2 - alvikite from the middle of the dike; 3 - weighted average of 6 analyses from a cross section.

terozoic age of 1700 - 1800 Ma.

A possible fenitic alteration halo exists around the calcite carbonatite, but is limited to a meter or less. The contents of barium and strontium are higher in this quartz-feldspar rock compared with the adjacent mica gneisses.

Discussion

High REE, Y, Sr and Ba contents are typical for carbonatites. However, the average $\delta^{13}\text{C}$ value of -12.3 ‰ is outside the range of primary mantle melts, which could indicate either crustal source areas, or extensive crustal differentiation of mantle derived material.

It can be concluded that the Halpanen carbonate rock occurrence represents an intrusion of a hydrous melt into a fracture. The calcite-apatite rock represents primary segregation at the walls of the conduit. Calcite carbonatite (alvikite) crystallized from a hydrous carbonatite melt. Fenitization of the country rock has been insignificant, which is a characteristic feature of alvikite dikes in general (Le Bas 1987). In the Halpanen alvikite dike this is compatible with the alkali-poor character of the carbonatite body.

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DISTRIBUTION AND PRODUCTION OF FINNISH LIMESTONE MINES

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Key words (GeoRef Thesaurus, AGI): economic geology, limestone deposits, mines, spatial distribution, carbonates, production, Proterozoic, Archean, Finland

Introduction

Limestone mining has a long tradition in Finland. The first written references date back to the year 1329, when the Föryby limestone deposit was donated to the Cathedral of Turku. During old times the use of limestone was limited mainly to the production of burnt lime, which was used in the production of plaster. In compilations of works dealing with old mineral deposits and mines (Holmberg 1858, Furuhjelm 1884a, 1884b, 1886, 1887) limestone was always mentioned together with the metallic ore deposits. The industrial revolution in the late 19th century raised limestone to the important position in all construction. For this reason an inventory was started of limestone deposits and former mines in the whole of Finland (Eskola et al. 1919) and their list of 652 limestone deposits is the main source for this paper. The prospectors in the past were extremely sharp-eyed. This is obvious from the fact that nearly all limestone outcrops of southern Finland show evidence of some degree of mining activity, which of course contributes to the great number of old and small mines. In the present-day official statistics (Kauppa- ja teollisuusministeriö 1950-1998, Teollisuustilasto 1921-1998) limestone production for major mines is given as from 1944. However from 1965 did the renewed Finnish Mining Law include all limestone production with other mining operations. In recent years limestone production and related products have been reported by e.g., Forstén (1998), Puustinen (1997) and Boström (1966).

Regional distribution of limestone mines

In Finland a large number of limestone mines or actually small quarries have been in operation at various times, supplying limestone at scales ranging from domestic use to large-scale industrial production. Figure 1 shows the regional distribution of the 283 limestone mines included in this study. The location of each mine is shown by a circle, the size of which represents the value of its production using a consistent unit value. A rough classification of limestones is based on the dominant carbonate mineral; 178 are dominated by calcite, 39 by dolomite and 66 are mixed. Already Eskola et al. (1919) found that the calcite-dominated deposits are located in southern Finland whereas the completely dolomitic ones are north of a line crossing Finland from Pitkäranta (on the eastern shore of Lake Ladoga) via Savonlinna and Kuopio to Oulu. This is largely true even today, although a closer study reveals that numerous exceptions exist on both sides of the line (Lundén 1988).

The majority of Finnish limestone mines is situated in southwestern and southern Finland, in an area extending from west of Parainen to east of Sipoo. This area is also known as the Svionian leptite zone, the rocks of which are metasedimentary, originally laid down in a shallow sea (Kinnunen & Saltikoff 1989). On the map in Figure 1 the circles showing production volumes of mines overlap and are difficult to distinguish. From a detailed inspection it is possible to distinguish a belt of limestone mines extending from Korppoo (Åvensör, also

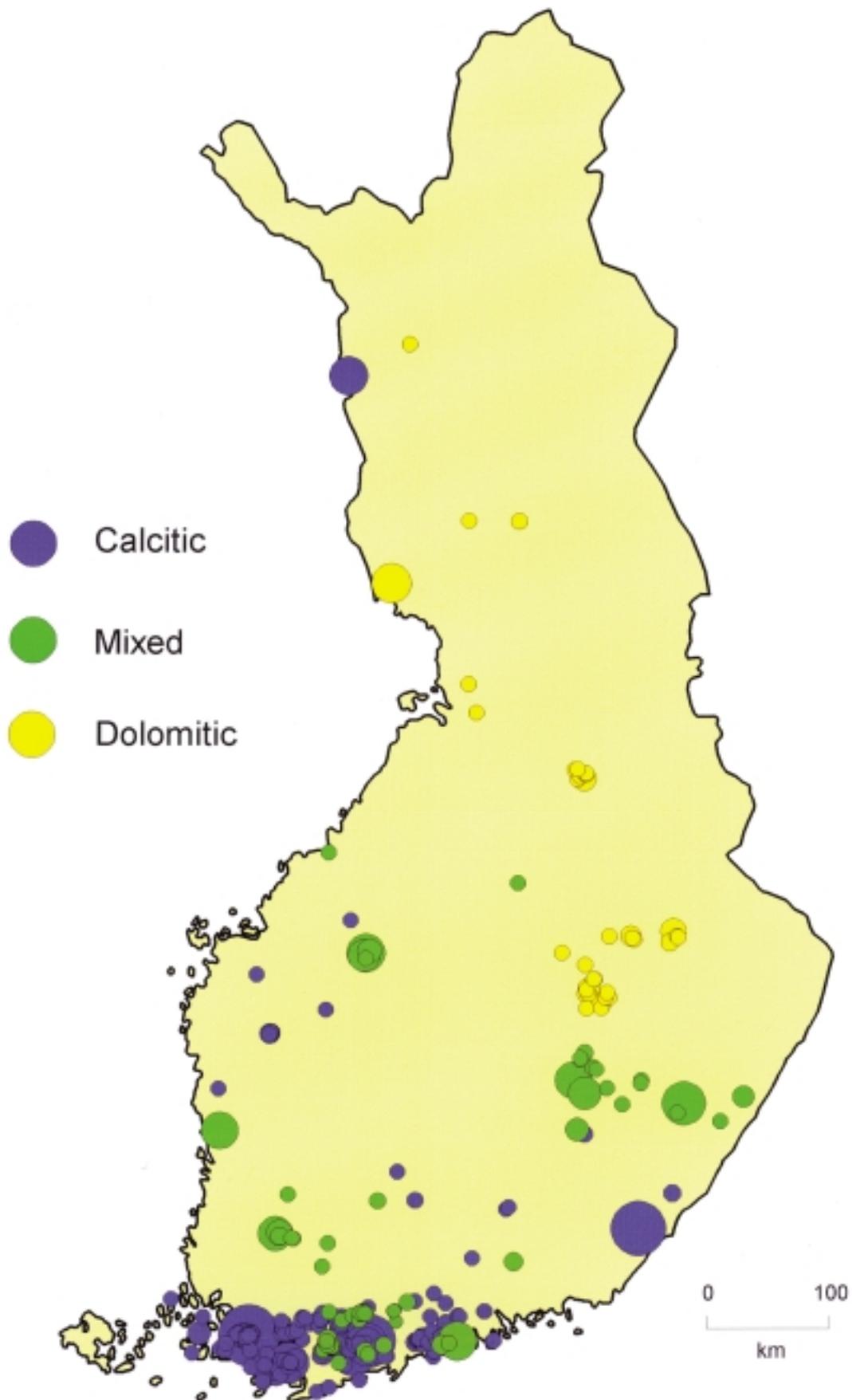


Fig. 1. Location of limestone mines in Finland. The sizes of the circles represent the gross value of extracted limestone on the basis of the 1998 unit price.

known as Runudden or Kirmonniemi) via Parainen (Skräbböle-Limberg, Ersby, Pettiby, Piukala and Tennby), Sauvo (Järvenkylä and Marike) and Suomusjärvi to Hyvinkää (Kalkkivuori in Kytäjä and Ridajärvi).

Another belt starts in the southern part of the island of Kemiö (Illo, Lammala and Vestlax, also known as Stenholmen) and continues via Särkisalo (Förby and Kaukosalo), Kisko (Viiri), Karjaa (Mustio), Lohja (Ojamo limestone, Pitkäniemi and Tytyri), Nummi-Pusula (Lähteenoja) and Vantaa (Sillböle limestone) to Sipoo (Mårtensby). A line running in a northeast - southwest direction through Kisko divides the limestones into two groups. The western one is dominated by calcite, but east of the line the deposits may be either calcitic or have alternating calcitic and dolomitic layers. Some nearly pure dolomites have recently been found in the Orijärvi area at Kisko.

The sequence of skarn iron ore deposits on the outer islands of the Gulf of Finland (Hermansö in Tammissaari) may also be traced along the locations of limestone mines. This southernmost limestone mine belt includes among other Kalkkiranta, also known as Nevas, in Sipoo. Although the Ihalainen deposit in Lappeenranta seems to be a single occurrence, it may be considered as part of the mixed carbonate rock sequence of southern Finland. It consists mainly of very pure calcitic limestone, but also contains dolomitic zones.

An example of regional clusters of mixed limestone mines in southwestern Finland is Vampula (Punola and Siivikkala) and the small quarries in its vicinity. In western Finland mixed deposits occur in the Vimpeli area (Ryytimaa and Vesterbacka). Otamo in Siikainen is a fairly pure dolomitic deposit, although it is classified as mixed. The Kurikka deposits, although classified as calcitic, might also in practice be of mixed type.

Finland is geologically divided by a line running roughly from Parikkala to Oulu into the Paleoproterozoic Svecofennian Domain to the southwest and the Archaean Kola-Karelian Domain to the northeast. This geotectonic line also represents the margin of an ancient continent. South of this line the mixed carbonate deposits occur in clusters, e.g., in Jäppilä (Rummukajärvi), Virtasalmi (Ankele and Montola), Kerimäki (Ruokojärvi, also known as Louhi) and Kesälahti (Varmo).

The carbonate deposits of the Archaean Domain are mainly dominated by dolomite. Some examples are the mines in Kuopio (Jynkkä and Korsumäki), Vehmersalmi (Juonionlahti), Juankoski (Huosiaisniemi), Juuka (Matara and Petrovaara) and Paltamo

(Reetiniemi). The Kalkkimaa deposit in Tornio fits neatly into the dolomitic Perä-Pohja schist zone. On the other hand the calcite-dominated deposit of Äkäsjöensuu in Muonio is an exception to the otherwise dolomitic region of northern Finland.

Outside the present national borders of Finland there have been at least 14 more limestone mines in operation besides those mentioned above. Production was the largest in the so-called Ruskeala marble quarry, of mixed type, which started operations in 1767 and possibly earlier. Other mines were the calcitic Kuparsaari in Antrea and the dolomitic Hopunsaari in Impilahti (within the mining district of the Pitkäranta sulphide ore deposits), and Kintsinniemi in Soanlahti.

Production of limestone mines

The production of the largest mines and quarries operational in Finland at various times is shown in Table 1. Where actual production tonnages were not available, an attempt was made to estimate them on the basis of size of quarry. In many cases where it was not possible to specify the year when a deposit was found, it is assigned to the oldest reference found in the literature.

The total output of limestone mining (including both limestone and wall rock) is estimated at a minimum of 252.2 Mt, of which at least 217.0 Mt was used. According to this estimate the amount of accumulated waste rock is 35.2 Mt, or 14% of the total rock extracted. The gross value of limestone extracted during historical time calculated on the basis of the year 1998 prices is at least 35.4 billion FIM. The biggest producers, according to the amount of limestone extracted, have been the main quarry of Parainen, i.e. Skräbböle-Limberg (74.3 Mt), Ihalainen in Lappeenranta (35.6 Mt), Tytyri in Lohja (33.3 Mt), Mustio in Karjaa (11.2 Mt) and Ruokojärvi in Kerimäki (10.7 Mt). It may further be mentioned that the apatite mine of Siilinjärvi has so far produced about 1.4 Mt of calcite concentrate as a by-product.

Figure 2 shows the extraction of limestone based on its use during the years 1944 - 1997 according to Kauppa- ja teollisuusministeriö (1950-1998) and Teollisuustilasto (1921-1998). The statistics on limestone extraction are interesting in that they also serve as indicators of economic activity. After World War II the total extraction of various materials grew steadily, reaching a peak of about 5.8 Mt in 1983. Soon after this, the global recession that began in 1990 is reflected as a crash in the amount

Table 1. Largest limestone mines in Finland

Mine	Area	Year of discovery	Years of operation	Total output (tonnes)	Limestone output (tonnes)
Parainen	Parainen	1100b	1100e, 1898-	88 283 559	74 255 473
Ihalainen	Lappeenranta	1792b	1792-, 1910-	45 536 933	35 621 452
Tytyri	Lohja	1824b	1911-	33 687 443	33 325 282
Mustio	Karjaa	1700c	1700c-1800c, 1954-	14 410 587	11 201 860
Ruokojärvi ¹⁾	Kerimäki	1906b	1906-1908, 1937-	11 406 256	10 725 256
Ojamo-kalkki	Lohja	1925	1925-1965	9 570 000	8 700 000
Förby ¹⁾	Särkisalo	1329b	1329b-, 1882-	7 082 721	6 577 776
Kalkkimaa ¹⁾	Tornio	1838b	1838b-, 1903, 1917-	5 841 242	5 810 234
Ryytima	Vimpeli	1916b	1916b, 1962-	5 554 390	4 833 391
Punola	Vampula	1982	1983-	4 808 045	2 504 928
Kalkkiranta ¹⁾	Sipoo	1600c	1600c-, 1938-	4 670 721	4 567 230
Äkäsjoen suu	Kolari	1861b	1968-1989, 1995-	4 642 468	4 401 821
Otamo	Siikainen	1971	1978-	4 461 267	3 583 928
Montola	Virtasalmi	1906	1909-1976	3 869 360	3 684 489
Ankele	Virtasalmi	1902b	1966-	2 252 088	1 840 840
Kotakangas ²⁾	Vimpeli	1800c	1800c, 1934-1962	1 400 000	1 400 000
Pitkäniemi ¹⁾	Lohja	1800c	1914-1924, 1937-1963	918 577	838 746
Ersby ²⁾	Parainen	1740b	1740b-1800e	490 000	400 000
Siivikkala	Vampula	1600c	1600c-1700c, 1989-1996	489 285	250 439
Pettiby ²⁾	Parainen	1740b	1740b-1900e	250 000	225 000
Illo	Västanfjärd	1825b	1882-1952	232 820	139 561
Matara	Juuka	1919b	1979-	241 257	230 907
Hiirola ²⁾	Mikkelin mlk	1800c	1800c, 1938-1939	200 000	180 000
Piukala ²⁾	Parainen	1828b	1792b-1800c	200 000	180 000
Others				1 684 563	1 514 095
Total				252 183 582	216 992 708

Notes: Production amounts: 1) Data only from 1944 on; 2) Estimated on the basis of size of quarry. Years of discovery: b = before year mentioned; c = during century mentioned; e = early in century or decade mentioned.

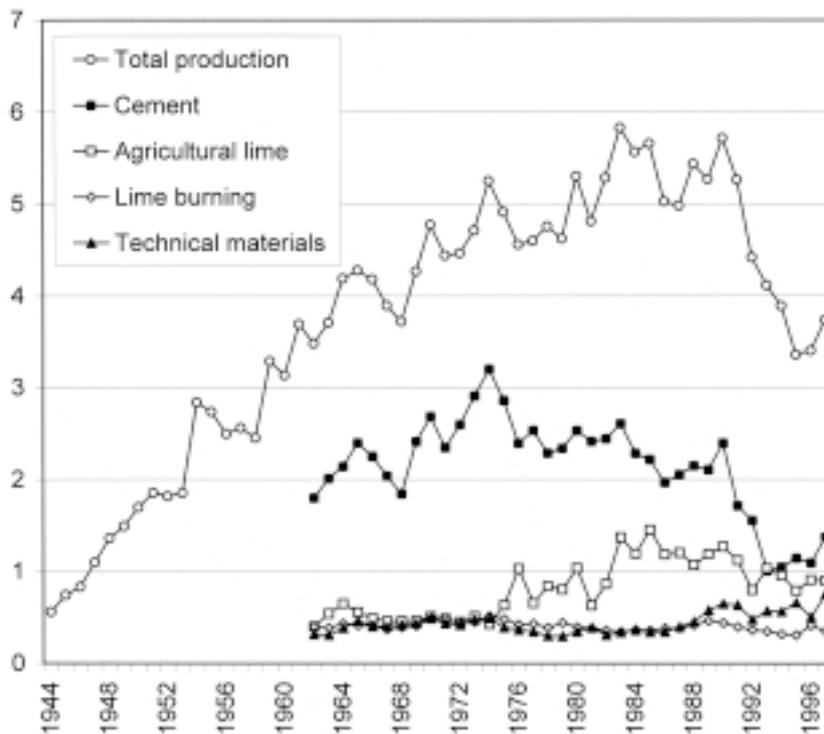


Fig. 2. Extraction of limestone in Finland and the use of various materials (for cement production, agricultural lime, lime burning and technical materials) during the years 1944 - 1997 according to Kauppa- ja teollisuusministeriö (1950-1998) and Teollisuustilasto (1921-1998), given in metric tons.

of limestone extracted, especially that used for production of cement. Actually the amount of rock used for cement production had been decreasing slowly after the 3.2 Mt peak year of 1974, reaching a minimum of only 1.0 Mt in 1993. The economic recovery and the simultaneous rise of the building industry are seen as an increase in extraction during the past few years. The amounts used for lime burning, and e.g. for crushed aggregates, industrial powders and animal feed have been nearly equal and showed only slight fluctuations. An increase in amounts of limestone used as agricultural lime, mainly dolomite, is seen after 1975, and at its maximum it was almost 1.5 Mt a year.

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SUBFOSSIL SHELLS IN SOUTHWESTERN LAPLAND, IN FINLAND

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Introduction

Several localities with shell fragments were discovered during the mapping of Quaternary deposits in scale 1:400 000 in the Kemi area, SW-Lapland. The northernmost subfossil shells were found from Ulko-Salonaho and Tornionkumpu in Tervola about 30 kilometres northeast of the present shoreline. Fossil shells in the area of the northernmost Gulf of Bothnia have earlier been described by Helle and Ylinen (1965), Donner (1976), Eronen et al. (1979), Hokkanen (1988), Eronen et al. 1995 and Donner et al. (in press). In adjacent areas in Sweden subfossil shells have been described by Fromm (1965) and Åhman and Königsson (1976).

Both in SW-Lapland in Finland and in Norrbotten, in Sweden subfossil shells are generally situated in littoral deposits. Some of them are also situated in fine sand, which have been deposited in shallow water probably quite near the shoreline. According to Fromm (1965), subfossil shell fragments have also been found in the Litorina clay (sulphide clay) near Torneälven.

The most common among the shell fragments are *Mytilus edulis* (common mussel) and *Macoma baltica* (Baltic tellin). *Mytilus* have been found from each locality where the shell species were determined. Shell fragments have been described from 40 locations in the area of the northernmost Gulf of Bothnia (Fig. 1). *Macoma* have been found in thirteen localities. From the Swedish side one locality with fragments of *Cardium edule* (common cockle) and two localities with brackishwater gastropods

(*Litorina rudis* var. *tenebrosa* and *Hydrobia ulvae*) have been found (Fromm 1965, Åhman & Königsson 1976).

Subfossil shells in SW-Lapland

The most abundant subfossil shell deposits in SW-Lapland are about 30 kilometres northeast of the present day shoreline. The localities are situated at an elevation of 45-50 metres (a.s.l.). Only a few shell fragments have been found in the localities at an elevation of 18-20 metres. The most representative *Mytilus* deposits have been found in the littoral deposits at Ulko-Salonaho and Tornionkumpu in Tervola. In both of these localities shell fragments have been deposited on the northeast sides of former islands.

The shell layers in the littoral deposits are normally only 2-5 mm thick. In places the layers can have been in the restricted areas even from 5 to 10 centimetres thick. The structure of *Mytilus* shells are very fragile and they have been crushed by the masses of overlying sand and gravel deposits. It is nearly impossible to find a whole shell and they are all broken when they are loosened from the deposit. The size of the shells are between 5 and 10 millimetres. No other shells have been found in the littoral deposits in SW-Lapland.

Shells of both *Macoma baltica* and *Mytilus edulis* were found from the Elijärvi open mine (Kalevi Puijola, Outokumpu company) near Kemi at an elevation of 18 metres. The shells are situated in fine sand overlying sulphide clay (Litorina clay) (Fig. 2).

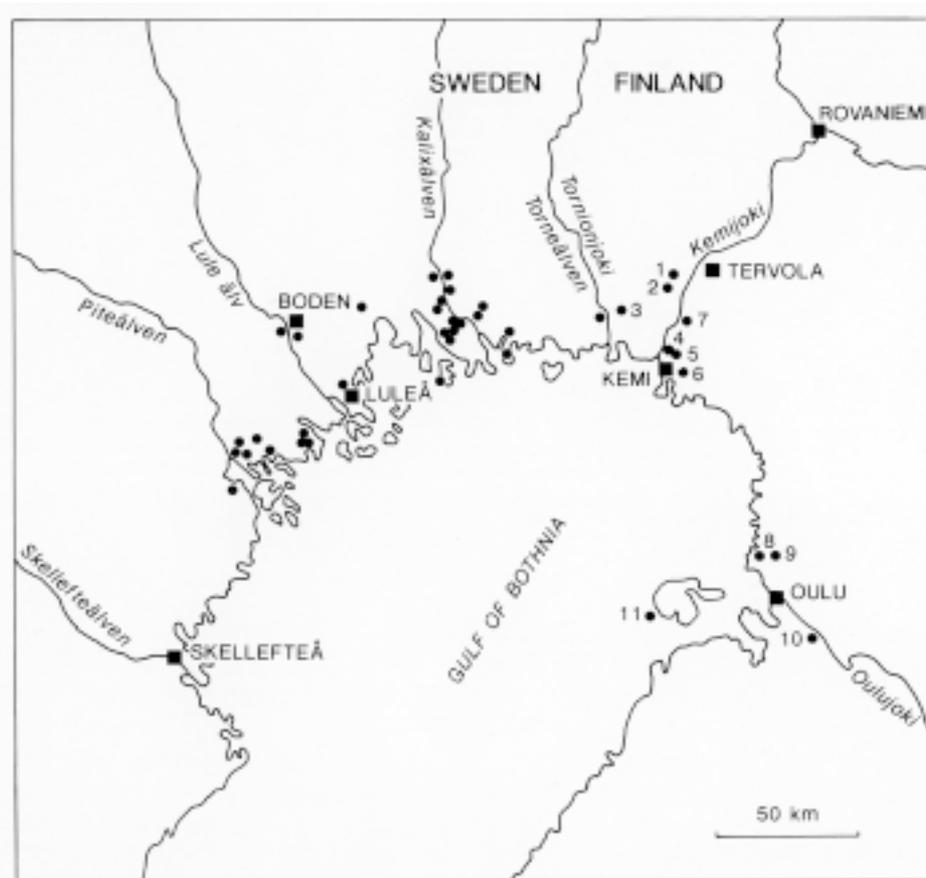


Fig. 1. Subfossil shell localities in SW-Lapland and in the adjacent areas. Number 1 = Ulko-Salonaho, 2 = Tornionkumpu, 3 = Rantamaa, 4 = Sivakkavaara, 5 = Elijärvi, 6 = Kaijansuo, 7 = Maula (Hokkanen 1988), 8-9 = Haukipudas (Eronen et al. 1995), 10 = Hangaskangas (Helle & Ylinen 1965) and 11 = Hailuoto (Segerstråle 1960). Localities in Sweden according to Fromm 1965 and Åhman and Königsson 1976.

Lenslike deposits of shells were found in various places which are situated at the same level. Only very few *Mytilus* shells have been found in these deposit as also in other localities at the same altitude. The amount of *Macoma* is high. Most of the shells have been loosened from their hinge joints. According to the measurement of 500 valves the mean size of *Macoma* shells is 17.7 x 14.7 x 8.2 millimetres.

In nature the colour of *Macoma* is light or pinkish. The colour of *Macoma* shells found at Elijärvi are mostly white because the coating of shells have peeled off (Fig. 3) and the calcareous inner layers have become visible.

As earlier mentioned the shell fragments have been found in SW-Lapland from the northeast slopes of the hills. In Sweden in the Kalixälven area they have been found mostly from the north slopes and areas west of Kalixälven from northwest, west and even from the southwest slopes of the hills. According to the fact that the localities are facing towards

the land and not towards the sea does not mean that shells have been living on the sheltered sides of the islands but that the empty shells have been transported and deposited on the lee-sides of the islands.

The age of the shells

Four shell samples have been dated by the radiocarbon method, three of them from Ulko-Salonaho and one from Elijärvi. The samples from the littoral deposits at Ulko-Salonaho were taken from the depths of 4, 6 and 8 metres. The radiocarbon dating of *Mytilus* shells gave the apparent ages 4 760 ± 90 (Su 1139), 4 810 ± 100 BP (SU-1138) and 5 320 ± 80 BP (Su-1140) (Donner et al. in press). The uppermost sample gave the youngest age and the lowermost sample gave the oldest age. The age of the *Macoma* shell sample gave an apparent age of 4 180 ± 90 BP (Su-1162) (Donner et al. in press). The ¹⁴C dates given as years BP used in the present work were normalized to ¹³C = -25 ‰ (Stuiver & Polach



Fig. 2. Subfossil shells in fine sand in the Elijärvi open mine near Kemi. At the bottom of the section there is basal till, then sulphide clay followed by fine sand and peat. The shells are at the same level as the small spade.



Fig. 3. Valves of *Macoma baltica* in the Elijärvi open mine near Kemi (scale 5 cm).

1977) and then the reservoir effect of the sea water, the “apparent age” of 320 years used for the southern part of the present Baltic Sea (Mangerud & Gulliksen 1975) was subtracted from the dates as described by Donner et al. (in press). *Mytilus* shells have been found also at Hangaskangas east of Oulu. The radiocarbon dating of the *Mytilus* shells gave the apparent age 4130 ± 90 (Hel-3543) BP (Eronen et al. 1995). The ages at Ulko-Salonaho are more than 500 years older than at Hangaskangas. Hangaskangas lies about 20 metres lower than Ulko-Salonaho, which could be the explanation for the age difference. All the given ages represent the Litorina stage. The ages of the *Mytilus* shells seems to be a little older than the ages of the *Macoma* shells.

The environment of the shells

The most important factor which has regulated the occurrence of molluscs in the Gulf of Bothnia has been the salinity of the sea water. The salinity increased in the Gulf of Bothnia at the beginning of the Litorina Sea stage about 7000 BP. The salinity began to decrease gradually already during the Litorina stage (Eronen 1979). In the valley of Kalixälven have been found fragments of *Littorina rudis*, which requires a salinity of at least 7,9 ‰ to live. Also *Littorina litorea*, which was found in Kruunupyy near Kokkola and lives nowadays in the southern Baltic Sea, requires a salinity of 8,1 ‰. So the salinity has been during “the optimum phase” of the Litorina Sea stage in the northernmost areas of the Gulf of Bothnia at least 8 ‰ (Eronen et al. 1979).

Mytilus edulis requires a mean salinity of at least 4,0-4,5 ‰ (Lassig 1965). Nowadays *Mytilus* is quite common in the south part of the Gulf of Bothnia and the northern limit of the present occurrence is in the archipelago of Vaasa. *Mytilus* is totally absent in the northern part of the Gulf of Bothnia, because the salinity is in the area between Vaasa and Kokkola only from 3 to 4 ‰ and in the areas north of Oulu only about 2 ‰ or even lower (Lassig 1965, Eronen et al. 1995).

Living *Macoma baltica* molluscs occur at least in the coastal areas round Kokkola (Nordqvist 1890). *Macoma* has also been found in Hailuoto but the shells have been empty (Segerstråle 1960, Valtonen 1964, Haahtela 1964). Segerstråle (1960) explains that *Macoma* seems only to occur there sporadically. The size of the Hailuoto shells are nearly the same as in Elijärvi. The length of the largest shell in Hailuoto was 18 mm and in Elijärvi 23 mm.

According to the land/sea level curve (Saarnisto 1981) and the radiocarbon ages it can be estimated that SW-Lapland was covered by sea up to an elevation of about 60-70 metres when the *Mytilus* shells were deposited. The tops of the Ulko-Salonaho and Tornionkumpu hills are now at an elevation of 60 metres. So during the time when these shells were deposited the tops of the hills were probably less than ten metres beneath the water level. It is not known if *Mytilus* were living on the tops of these hills or on the slopes or on both but it seems to be so that the depth of the water was from 1 to 25 metres. This is in good agreement with the present occurrence of *Mytilus*, because it lives normally at the depth of 1-15 metres (Lassig 1965).

If we compare similarly the land/sea level curve and the radiocarbon ages in Elijärvi, so we find that *Macoma* shells were deposited when the water level was approximately at an altitude of 47 metres (a.s.l.). *Macoma* shells were deposited in a lagoon which situated to the southwest of the present Sivakkavaara hill. The top of this hill is at an elevation of 65 metres. The maximum depth during the sedimentation was less than 30 metres. This is in good agreement with the present occurrence of *Macoma*, which lives nowadays normally in the depth of from 3-4 to 40 metres, in places up to 62 metres in the Gulf of Bothnia (Segerstråle 1962).

Conclusions

Shells of *Mytilus edulis* and *Macoma baltica* have been found from the northernmost parts of the present Gulf of Bothnia area. The radiocarbon ages represent the Litorina Sea stage. These molluscs were living in SW-Lapland not in the early development of the Litorina Sea but slightly after that when the brackishwater had reached the northernmost parts of the Gulf of Bothnia. According to the *Littorina rudis* fragments in the Kalix area it could be possible that the salinity was during the “optimum phase” of the Litorina Sea 6 ‰ higher than at present. The shells were deposited 1-30 metres below the sea level.

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MAP OF GLACIAL FLOW INDICATORS IN FINLAND

by

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Introduction

Exploration in glaciated terrain like that of Finland must deal with the fact that most of the area is covered by glacial and postglacial sediments. Till is composed of fragments derived from nearby or underlying bedrock units. The relationship between till material and bedrock can often be determined with great accuracy, which makes till an important prospecting medium (Kujansuu & Saarnisto 1990). During the past centuries the tracing of glacial transport of clasts and minerals within till has been successfully applied to exploration of iron, base metals, gold and diamonds. This fruitful method is sure to be important in future as well.

Glacial transport can be described in terms of ice flow direction and transport distance. Glacial transport distance is a statistical measure, which is related to many factors such as glacial dynamics, distance from the ice divide, durability and size of studied clasts, and postglacial weathering rate (Salonen 1986). Despite some regional consistency in transport distance (Salonen 1985), in prospecting it must be determined separately for the area of interest.

Flow direction is a more consistent parameter of former glacial activity. Previous studies, in which glacial flow indicators have been collected systematically (e.g. Hirvas et al. 1977, Hirvas 1991, Hirvas & Nenonen 1985, Punkari 1995) show a general picture of Scandinavian ice flow directions from

NW towards SE and displaying a radial flow pattern towards the Salpausselkä end moraines. In certain areas such as Lapland and Ostrobothnia, complex glacial flow configurations are found, originating from different flow regimes.

The total number of glacial flow measurements in Finland is huge. These include observations on striations (Glückert 1974), oriented glacial landforms, till fabric analyses (Hirvas et al. 1977) and boulder trains (Salonen 1985). However in only a few studies were all different kinds of numerical information compiled into a single presentation. Punkari (1995) made such a compilation from southwestern Finland.

Although the amount of geological information increases continually, the accumulated information is not always used as a basis for new investigations. Some of the old information remains unused, regardless of its high quality. In modern publications, reference is usually made only to the geological conclusions of previous work, while the actual data is mostly left unused. This is largely due to the heterogeneity of the data and the great amount of work it would require to compile it (Mäkinen 1990).

The aim of this investigation is to compile as much as possible of the available geographical information on flow directions of inland ice, into uniform data base which can serve ore prospecting as well as Quaternary research, and can be easily updated with data from future investigations. Another aim was to use computer cartography to identify areas in which the glacial history is com-

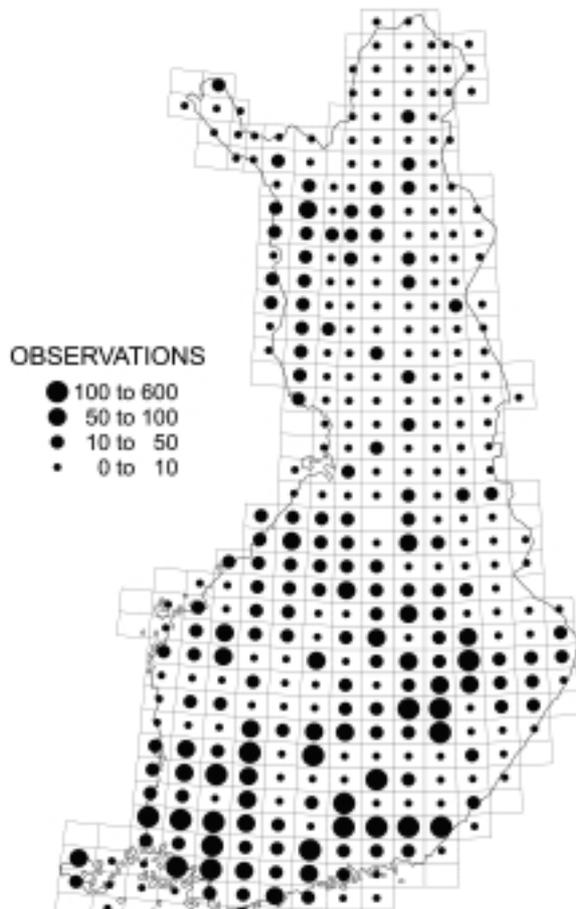


Fig. 1. Numbers of observations on each 1:100 000 map sheet.

plex, so that in ore prospecting special emphasis will have to be placed on detailed observations of glacial transport, stratigraphy and different glacial flow directions.

Material and methods

Observations on glacial transport were collected from several sources, which were selected on the basis of reliability and accuracy, so that the later treatment and analysis of the observations by computer cartography would not suffer from inaccuracies in the source data (Gustavsson 1987, Campbell 1993). In addition special care was taken to avoid multiple records of the same observation reported in different sources.

The primary source was the summary of glacial action of the Scandinavian ice sheet in Finland, by Salonen (1985). The data in this publication, which covers the entire area of Finland in variable detail, were compiled from about 750 reports and publications in the archives of the Geological Survey and various exploration organizations. Nearly all observations on boulder fans, isolated boulders, provenance areas and provenance sectors are from these

sources. Observations of striations and till fabric are also included.

The second most important source was the files compiled by the GTK on Quaternary investigations for ore exploration and on striation observations made during mapping of Quaternary deposits. Over 500 observations on till fabrics and 7000 on striations were obtained from these files. An additional 250 observations on till fabric and striations were collected from several maps of Quaternary deposits and their explanations, and over 400 observations from the 1:1 000 000 map published as a result of the Nordkalott Project (1986), by cooperation of the Finnish, Swedish and Norwegian Geological Surveys. Over 400 geographically well-documented observations were obtained from the summary of striations caused by the Scandinavian ice sheet, compiled by Glückert (1974).

The coordinates of observations obtained from the two latter sources are somewhat less accurate than those from other sources, but they were included in order to supplement the data in areas with few observations. 52 observations of isolated boulder transport and 38 of provenance sectors and provenance areas are included under "Other" in Table 1.

In summary the compiled database comprises over 10 000 separate, geographically located observations reflecting glacial transport distance and direction, which cover the whole of Finland with variable observation density, as shown in Figure 1.

All files and observations from various reports, publications and paper maps were recorded using the MS Excel (version 4.0) spreadsheet program, which is capable of reading and if necessary recording the formats of other spreadsheet and database programs (Seppänen & Skinnari 1992). Separate fields were used for each of the following data for each individual observation: number of 1:20 000 base map sheet, x coordinate, y coordinate, transport direction, transport distance, observation category and reference. The coordinates were recorded as accurately as possible either as given by the source, or measured directly from a map. The coordinates are based on the (Niemelä 1984) rectangular basic coordinate system. In this system,

Table 1. Distribution of observation types

	Striae	Till fabric	Boulder fans	Other	Total
Number	8 262	1 227	524	90	10 103
Percentage	81.8	12.1	5.2	0.9	100

Finland is mapped using four different projections (Heinonen 1986), so that the data is assigned to one four longitude zones, and the MapInfo program is used for projection conversion. In order to achieve compatibility of the observations, they were converted into a single coordinate system, in which the whole of Finland is in one longitude zone. At the same time the structure of the file changed automatically from the format used by the Excel spreadsheet into that used by MapInfo, so that the separate observations could be combined into a single file. From this source file, which contained all observations, the searches, subdivisions and computer-cartographic analyses were then made.

Observations are particularly frequent in six 1 : 100 000 map sheets in SW Finland, six map sheets in SE Finland and Outokumpu map sheet in eastern Finland, each containing over 200 observations. The abundant observations in these areas are mainly from the complete 1 : 20 000 mapping of Quaternary deposits and most of the GTK files containing observations on striae and till fabric were from these areas. In contrast there are no observations from two map sheets in the area of Repokaira in Lapland, due to their remote location, nor from the Kestilä map sheet in Middle-Finland, at least partly due to its extensive peatlands. However Sauramo's (1926) explanation to the 1:400 000 Kajaani Quaternary deposit map sheet states that striae in the Kestilä area are quite regularly oriented towards SE.

Results

The source file covering all of Finland was investigated for each 1:100 000 map sheet, in which the various transport directions of the ice sheet were separated from each other using the different observation types. For these directions the following data were extracted: number of observations, compass readings, minimum and maximum readings in degrees. The following statistical parameters were also calculated: mean direction bearing, variance and standard deviation.

In the interpretation of glacial flow directions there is a danger of mixing observations from different flow directions (Clark 1997). Divergent individual readings were therefore excluded from the predominant sets of readings using standard deviation of the set mean as the criterion for exclusion. The standard deviation of each set of observations was reduced in this way to less than ten degrees, which means variations of about 20 degrees in the ice flow direction. Greater standard

deviations were accepted only if visual inspection showed that divergent observations probably belonged to the same glacial flow. For example, the flow direction of the ice sheet might bend distinctly within the map sheet being studied. In some map sheet areas the standard deviation of the till fabric observations was greater than that of other observations. Figure 2 shows a compilation of the resulting average glacial flow directions for each 1:100 000 map sheet, calculated on the basis of striae, till and boulder fan observations.

The map was made using the Finnish national 1:100 000 base map, which was complemented by picking marginal formations, eskers and the national borders of Finland from the map of Quaternary deposits digitized on the scale of 1:1 000 000.

Discussion and conclusions

A uniquely comprehensive and representative database has been made reflecting glacial transport over the whole area of Finland. The source file contains most of the known reliable data, although some data remains to be recorded. These include the till fabric analysis data of the Kuhmo project at the University of Oulu (Saarnisto et al. 1981) and some of the original observations made during the Quaternary study project for exploration in northern Finland (Hirvas et al. 1977). In addition, the geochemical investigations of the GTK included observations on till stratigraphy and glacial flow directions. Furthermore all the information on Quaternary landforms shaped by the ice sheet are lacking, as are nearly all boulder fan observations made after 1985. Completion of the database would also facilitate analysis by computer cartography, which would make it possible to study the variation in flow directions for example in the vicinity of interlobate eskers.

From the glacial flow directions calculated on the basis of the material now available, map layers have been made, from which those map sheets were identified in which more than three flow directions exist, each based on at least eight observations. Eleven such map sheets on a scale of 1 : 100 000 were found, situated either in the area of the Salpausselkä end moraines or in the ice-divide area in northern Finland. Additions to the database will probably reveal more map sheets with several directions of glacial flow. In such areas the directions of glacial flow should be investigated site in the field. Using the present database it is still not possible to draw conclusions regarding transport distances in the various parts of Finland, so distances must still

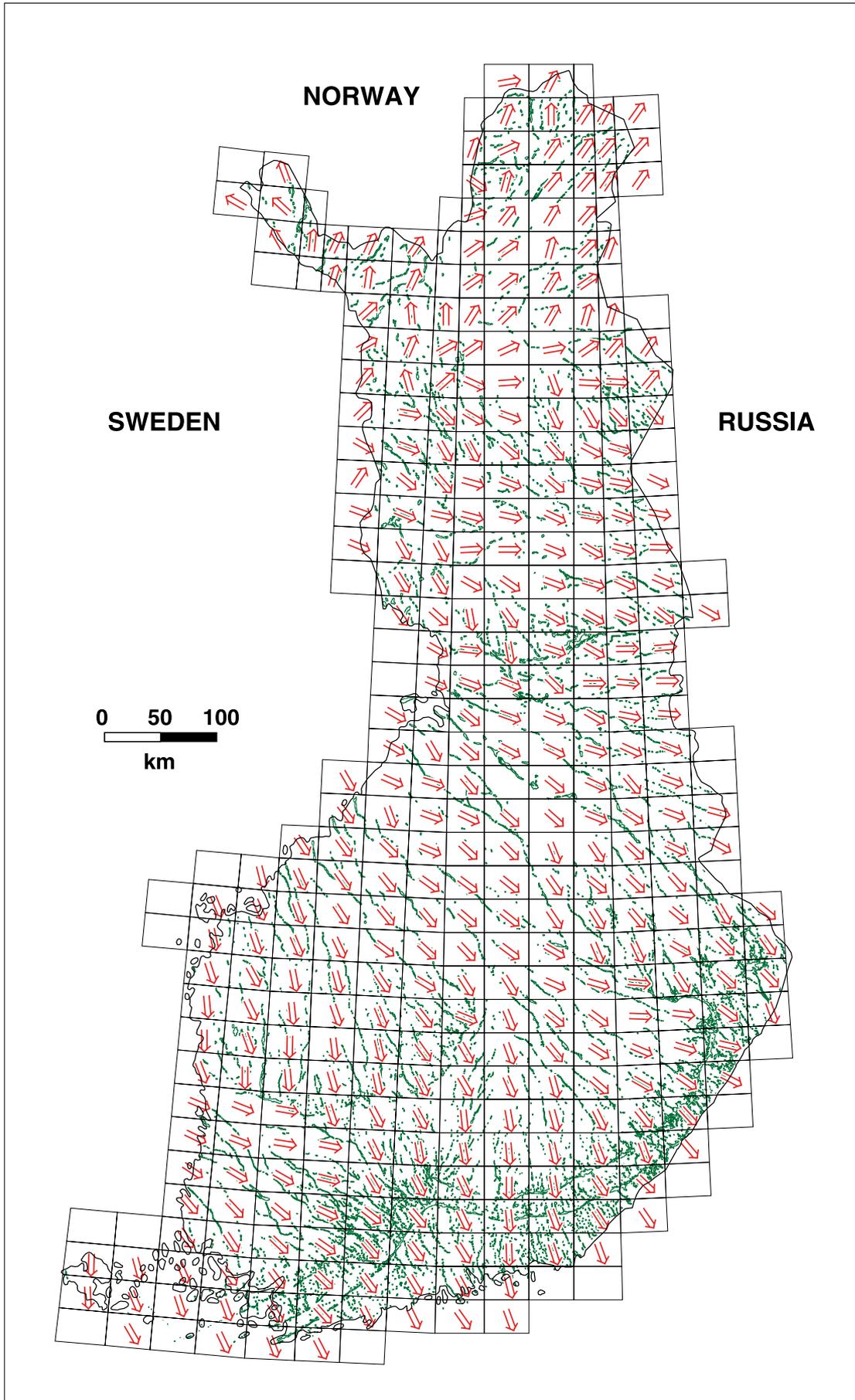


Fig. 2. Average predominant glacial flow direction for each 1:100 000 map sheet, calculated on the basis of striae, till and boulder fan observations.

be determined for each site during prospecting.

Using geographical information system programs the database is easy to treat statistically by map sheet regardless of type of observation, flow directions or chronological order of the observations. In particular the quick and easy calculation of average flow directions may attract users less familiar with the measurement and geological conditions. However such calculations might ignore critical parts of the information, and may not reflect the actual flow directions of the ice sheet. An average result close to the real flow direction will only be arrived at in cases where observations of only one direction and age are recorded, or where one direction is so predominant that statistical treatment is unaffected by a few divergent observations. Completely inaccurate mean directions will obviously result if roughly equal numbers of observations for several flow directions are present. Inaccurate mean directions are also produced by arithmetic mean calculations of bearings straddling true north.

The database is now part of the geographical information archive of the Geological Survey of Finland. It is intended to supplement the data in future and to produce 1 : 20 000 maps (10 km x 10 km) over the whole area of Finland, each with an arrow showing the predominant transport directions of the ice sheet.

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GEOCHEMISTRY OF AFFORESTED AND ARABLE SOILS IN FINLAND

by
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Key words (GeoRef Thesaurus, AGI): soils, arable lands, forest soils, humus, horizons, geochemistry, nutrients, heavy metals, Finland

Introduction

Around 8.5 million hectares of agricultural land is set aside today in Europe and is subjected to alternative land use, such as afforestation. In Finland around 200 000 hectares of fields have been afforested since 1969. The changing land use, however, results in changes in soil properties and processes. These changes are due to and modified by different management practices, geochemistry, mineralogy, texture, trees, organic matter production, initial properties such as acidity and heavy metal content at the time of afforestation, hydrology, climate and the time elapsed since afforestation.

Acidity is the main factor regulating the mobility of elements, especially heavy metals. In a neutral pH range the solubility of most metals is limited by strong sorption conditions (McBride 1989). Both field data and model predictions indicate that afforestation may result in changes in soil pH from neutral values to a ca 3 to 4 within 40–60 years (Römkenes & de Vries 1994). The greatest changes seem to take place during the first 20 to 30 years after afforestation (Alriksson & Olsson 1995). Apart from acidity, the organic matter chemistry will also change through afforestation. With an increase of organic matter the cation exchange capacity and complexing ability of the soil will increase and metals, especially Pb and Hg can bound strongly to organic matter (Frielands & Johanson 1985, Turner et al. 1985, Aastrup et al. 1991).

The concept “chemical time bombs” was defined

by Stigliani (1991) as a chain of events resulting in the delayed and sudden occurrence of harmful effects due to the mobilization of chemicals, stored in soils and sediments in response to slow alteration of the environment. This concept is adequate for afforested systems in which a sudden release of elements might be induced by changes in acidity (Salomons & Stigliani 1995).

This research is one part of the large-scale research program called “Effects of Afforestation of Agricultural Land on Heavy Metal Mobility in Soil” (MEMO) carried out jointly by the Swedish Agricultural University (the project coordinator), the Agricultural Research Centre of Finland, the Royal Veterinary & Agricultural University in Denmark, the Danish Forest & Landscape Institute, the Macauley Land Use Research Institute in Scotland, the DLO-Winand Staring Centre for Soil and Water Research in the Netherlands and the Institute of Terrestrial Ecology in England. The overall objectives of the MEMO-project are to quantify the impacts of soil properties on heavy metal behaviour and the integrated effects of stand and site properties in influencing factors such as dissolved organic carbon and acidity.

The MEMO-project consists of 12 different tasks, which are divided between different partners. The GSF takes part in tasks 1, 2, 3, 5 and 6 and will evaluate the results from Finnish sites and evaluate mainly the aqua regia leachable elements from all sites. The modelling and especially the elaboration and the guidelines are the cooperative tasks between all partners. The main tasks of the MEMO-project are:

- 1) Selection of sampling sites
- 2) Soil sampling and site and stand description
- 3) General soil analysis: pH, exchangeable cations and acidity, ammoniumoxalate soluble Al and Fe, total C and N and texture
- 4) Heavy metal analysis
- 5) Basic mineralogical properties: aqua regia soluble elements and XRD-analysis
- 6) Soil water analysis
- 7) Heavy metal association
- 8) DOC and pH induced mobilization
- 9) Field acidification manipulation
- 10) Heavy metals and SOM/DOC turnover
- 11) Modelling and scenario analysis
- 12) Elaboration and guidelines for afforestation.

In this study is the preliminary results of the geochemical variation of afforested and arable soils in Finland by using the hot aqua regia method (ISO/DIS 11466) are presented. The general soil analyses are under evaluation and soil water and XRD samples are under the analyses.

Materials and methods

The sites in the MEMO-project were selected so that each country focuses on a specific site properties. These are the species composition, age, different soil types, climate and atmospheric pollution. In Finland the selection of sites was done with respect that focus was put on climate and atmospheric deposition. Within each site 2 subplots were selected, forest versus arable soil, giving a total of 24 plots (Table 1). In Finland the three different tree species were selected, Norway spruce, pine and birch.

The soil types were till, silt, clay and peat soils. The ages of the trees in afforested sites varied from

23 to 31 years. The altitude of the sampling sites ranged from 14 to 153 m.a.s.l. and the annual precipitation from 600 mm to 650 mm. Additional climatic data will be achieved through other investigations and consist of deposition, temperature, precipitation and it's distribution over the year and length of growing season. Attention is also paid to historical land use and previous management measures.

The soil samples were taken from pits with a spade sampler during the summer of 1997. The profiles were visually podzols, histosols and gleysols. The soil sampling was volumetric to enable determination of bulk density and of elements per unit area. The sampling was carried out according to pedogenetic horizons. At afforested sites the samples were taken at humus, the uppermost and lower part of the A-horizon, at the upper part of the B-horizon and the C-horizon. At arable soils the soil samples were taken from A-, B- and C-horizons. From each depth a minimum of 20 subsamples were taken and put together in composite sample.

The soil samples were air dried at < 40 ° C and sieved to < 2 mm fraction (ISO/DIS 11464). The samples were analysed at the Chemical Laboratory of GSF in Rovaniemi. A microwave-assisted nitric acid digestion was applied to dissolve the humus samples (Niskavaara 1995). The method is based on a standard release by the U.S. Environment Protection Agency (US EPA 3050). This method will give total element contents in humus samples, but humus can contain mineral particles (silicates which are not dissolved by this method. The abundance and solubility of the main elements (Al, Ca, Fe, K, Mg, Na, P, S) and heavy metals (Cd, Co, Cr, Cu, Hg, Ni, Pb and Zn) were determined by using the hot (90 ° C) aqua regia (1HNO₃: 3HCl) digestion method from the mineral soil samples. The portion of the fraction soluble in aqua regia is a measure of the general solubility of the elements and their potential availability as nutrients. Most of the silicates dissolve only slightly in mineral acids. Therefore the aqua regia leach resulted in only a partial dissolution for the majority of the mineral soil samples.

Results

The median values and range of main the elements soluble in aqua regia and nitric acid of each pedogenetic horizon are given in Tables 2, 3, 4 and 5. Element concentrations indicate the potential solubility of elements and availability as nutrients and as well toxides. Calcium and magnesium were

Table 1. Site description of the Finnish soil.

Site	Location	Land use	Parent material	Tree age	m.a.s.l. m
1	Orivesi	birch/arable	till	27	93
2	Koivu	spruce/arable	silt	31	43
3	Ylivojakkala	spruce/arable	till	23	14
4	Kiikka	spruce/arable	clay	27	70
5	Karkku	pine/arable	till	27	110
6	Hämeenkyrö	birch/arable	clay	27	103
7	Töysä	pine/arable	silt	27	116
8	Töysä	pine/arable	peat/silt	27	116
9	Töysä	pine/arable	peat/till	27	120
10	Kuortane	pine/arable	till	27	153
11	Urjala	spruce/arable	till	27	122
12	Urjala	pine/arable	clay	27	100

the main base cations in all horizons. Potassium and especially sodium concentrations were distinctly lower. Calcium concentrations were highest in the humus horizon (median 0.48 %) in the afforested sites and in the A-horizon, i.e. in ploughed horizon (median 0.36 %) of the arable soils. The magnesium, potassium and sodium concentrations increased as a function of depth. The aluminium concentration was highest in the illuvial horizon in the afforested sites, but in the arable soils Al was highest in the A-horizon. Iron concentrations increased as a function of depth both in the afforested and arable soils.

The calcium concentrations (median 0.39 % in the afforested and 0.33 % in arable soils) in the C-horizon were higher than in general in Finnish tills (median 0.27 %, Salminen 1995). In the clays the Ca concentrations is approximately 0.59 % (Salminen et al. 1997). The relatively high solubility in soils indicates that calcium is incorporated in carbonates, pyroxenes, amphiboles and Ca-rich plagioclases in the studied sites. The magnesium concentrations (median 0.69 % in the afforested and 0.67 % in the arable soils) were clearly higher than in tills (median 0.46 %, Salminen 1995) in Finland. This is due to mafic and clay minerals in the parent material. Magnesium minerals weather easily, with the dissolved magnesium being removed from solution mostly into clay minerals and carbonates (Koljonen 1992). In the clay soils the magnesium concentrations are, in general, much higher (median 1.56 %) (Salminen et al. 1997). Potassium minerals are normally resistant to weathering. In the studied sites the median values (median 0.30 % in the afforested and 0.28 % in the arable soils) were, however, somewhat higher than in tills (median 0.19 %, Salminen 1995) in general, but clearly lower than in clays (median 1.0 %, Salminen et al. 1997).

The phosphorous concentrations were considerably higher in the uppermost horizons, i.e. in the humus horizon in the afforested soils and in the ploughed horizon in the arable soils. On average, the afforested (median 1220 mg/kg) soils clearly contained higher amounts of phosphorous than the arable soils (median 858 mg/kg). The sulphur concentrations were highest in the humus horizon and in the arable soils in the A-horizon and the concentrations decreased distinctly as a function of depth. In the humus horizon of the afforested sites the concentrations were considerably higher (median 1495 mg/kg) than in the ploughing horizon (median 302 mg/kg) in the agricultural soils. This indicates that sulphur is an essential component and macro-nutrient but S is both leached from the soil and taken

up by plants. In addition, the sulphur deposition and the specification of sulphur processes in soils have not been studied adequately; thus its accumulation in the soil is difficult to evaluate.

The Ca+Mg+K+Na and P concentrations by sampling horizons (O, A1-, A2-, B- and C-horizons) both in afforested and arable soils were studied in northern, central and southern Finland (Fig. 1 and 2). In the humus horizons the P concentrations were clearly higher due to phosphorus-rich fertilizers especially in the Koivu site in northern Finland. In general, the concentrations decreased as a function of depth. In the central Finland site till was the parent material and was found to contain the lowest P concentrations in the C-horizon. The concentrations were somewhat higher in the arable soils than in the afforested soils of this area. In the southern Finland site in Hämeenkyrö consisting of the clay soil the Ca+Mg+K+Na concentrations were distinctly higher in all the horizons, increasing as a function of depth than in till and silt soil. The concentrations were lower in the arable soil horizons than in afforested soils except the C-horizon when compared to other two sites. It seems that the base cation concentrations are higher in southern Finland than in northern Finland, probably due to higher clay content and climate.

Aluminium goes into solution most easily when in clay minerals, chlorite, biotite and, to a degree, in amphiboles and pyroxenes. The aluminium concentrations (median 1.2 % in afforested and 1.4 % in arable soils) were quite similar to tills (median 1.15 %, Salminen 1995), but in some places higher indicating the high clay content (median in clays 3.56 %, Salminen et al. 1997). The median iron concentrations (2.7 % in afforested and 2.9 % in arable soils) were also higher than in tills (1.8 %, Salminen 1995) but lower than in clays (median 4.99 %, Salminen et al. 1997) in general.

The Co, Cr and Cu concentrations were somewhat higher in the A-horizons of arable soils than in the humus and A-horizons in afforested soils (Tables 4 and 5). However, the concentrations were quite similar as a function of depth. The median concentrations of Cr (36.3 mg/kg) and Cu (18.4 mg/kg) were considerably lower than the average values for Cr (74.4 mg/kg) and for Cu (46.5 mg/kg) for the arable soils (Mäkelä-Kurtto et al. 1992). The Cu concentrations are expected to increase remarkably in agricultural soils due to fact that these elements used as fertilizers have become more and more common. Cu deficiency recorded in peat soils as well as mineral soils has led to the increased use of Cu as fertilizes (Erviö et al. 1990). The concen-

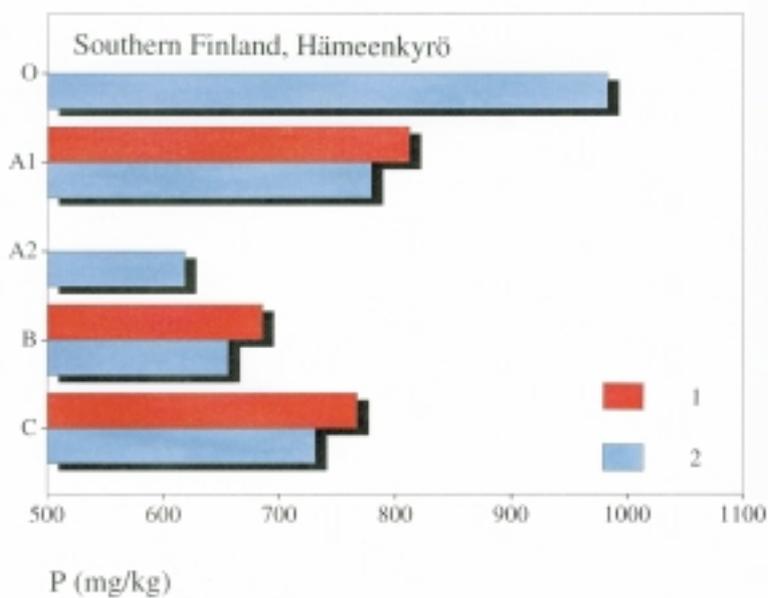
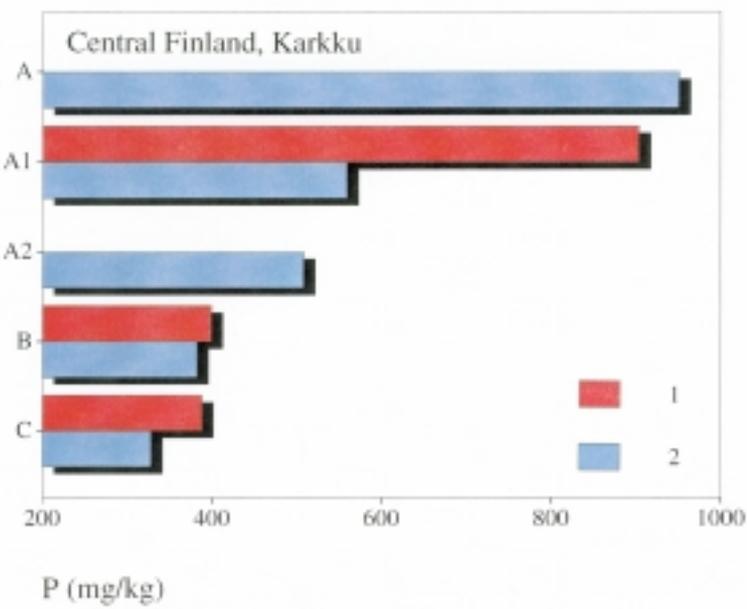
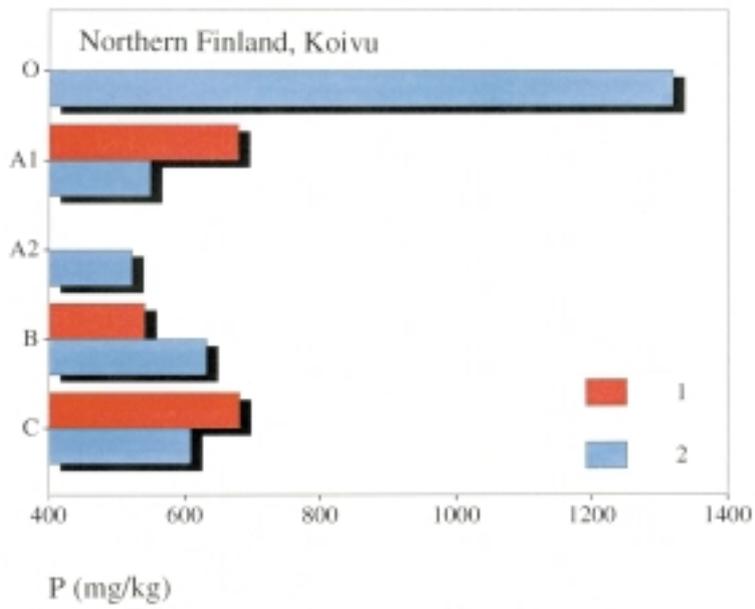


Fig. 1. The concentrations of Ca+Mg+K+Na by sampling horizons in the sites of northern, central and southern Finland. The parent material in the Koivu site silt, in the Karkku site till and in the Hämeenkyrö site clay. 1 = arable and 2 = afforested soil.

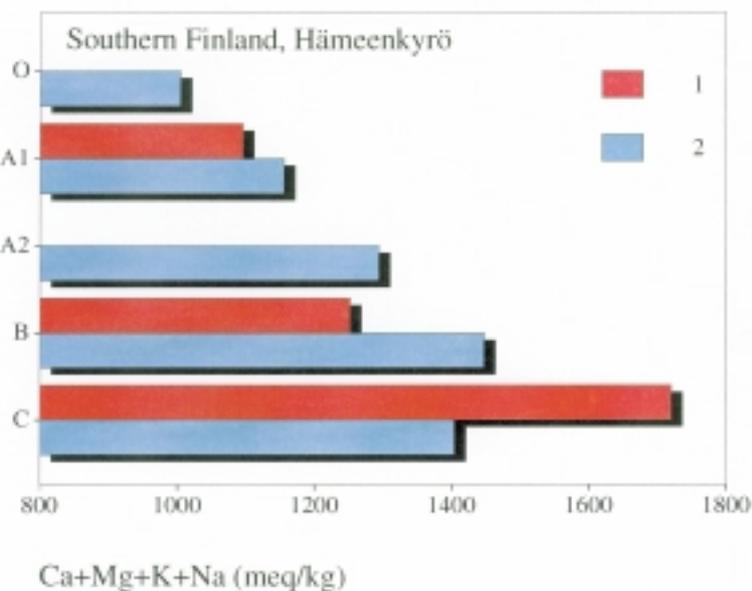
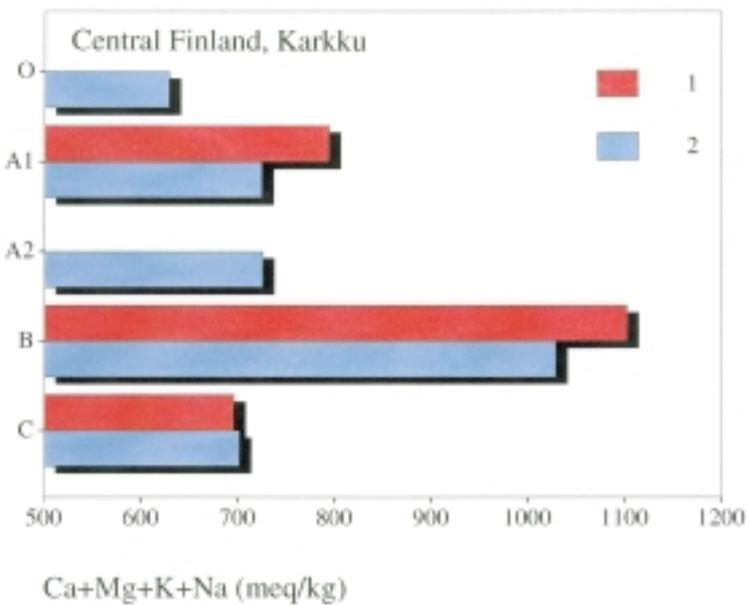
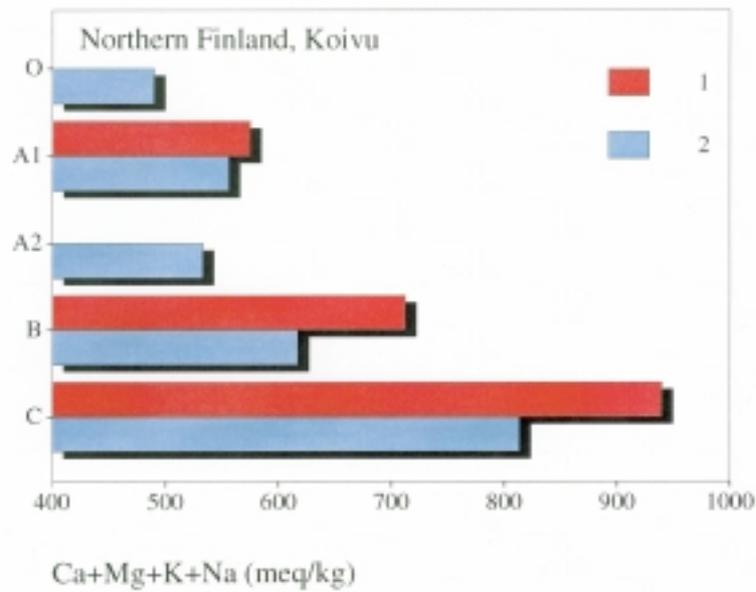


Fig. 2. The concentrations of P by sampling horizons in the sites of northern, central and southern Finland. The parent material in the Koivu site silt, in the Karkku site till and in the Hämeenkyrö site clay. 1 = arable and 2 = afforested soil.

trations of Co, Cr and Cu in the parent material are quite similar to those in tills in Finland (Salminen 1995). In the clays these concentrations are two or three times higher (Salminen et al. 1997) than in the studied afforested sites.

The lead and zinc concentrations were similar both in afforested and arable soils. Slightly higher values were found in the humus horizon. The median concentrations for Pb was 10.5 mg/kg and for Zn 43.4 mg/kg in the A-horizons of the arable soils which were clearly lower than the average values for Pb (21 mg/kg) and for Zn (114 mg/kg) in Finnish agricultural soils (Mäkelä-Kurtto et al. 1992). Zinc has been added no earlier than since 1986 to the soils through fertilizers (Erviö et al. 1990). The Zn concentrations in the parent material of studied soils were at the same level as in tills (Salminen 1995) but much lower than in clay soils (Salminen et al. 1997).

There has been found clear increase in cadmium and mercury concentrations in the uppermost horizons i.e. in the humus and A-horizons in afforested and arable soils (Sippola & Mäkelä-Kurtto 1986). According to Mäkelä-Kurtto et al. (1990) the average value for Cd in Finnish arable soils is 0.23 mg/kg. In this study in the A-horizon of the arable soils the median was (0.1 mg/kg) but in the humus horizon in the afforested soils the median value was

higher (0.28 mg/kg). There was, however, quite a large variation in the Cd concentrations in the studied humus horizons (Fig 3). The guide value for Cd in contaminated land is 0.5 mg/kg (Manninen & Willamo 1993). In one site this value was exceeded (0.54 mg/kg).

The concentrations of Cd decreased as a function of depth. The values were six times higher in the humus horizon than in the parent material (median 0.05 mg/kg) in the afforested soils and 2.5 times higher in the A-horizon than in the parent material (median 0.04 mg/kg) in the arable soils in general. Cadmium contents in the soil and water have increased from their natural background levels due to industrial and agricultural practices (Sippola & Mäkelä-Kurtto 1986). Cadmium is transferred from soil to plants via food chains and finally to humans. Cadmium is therefore considered to be one of most toxic substances in environment. Phosphorus fertilizers, atmospheric deposition and sewage sludge are the main sources of cadmium in cultivated soils. Phosphorous fertilizers, containing cadmium as an impurity consists of about one half of total cadmium input to soil and one third of atmospheric fallout (Sippola & Mäkelä-Kurtto 1986).

The cadmium contents in Finnish cultivated soils have been recorded and are approximately similar to soils in Sweden (0.22 mg/kg) and Denmark (0.25

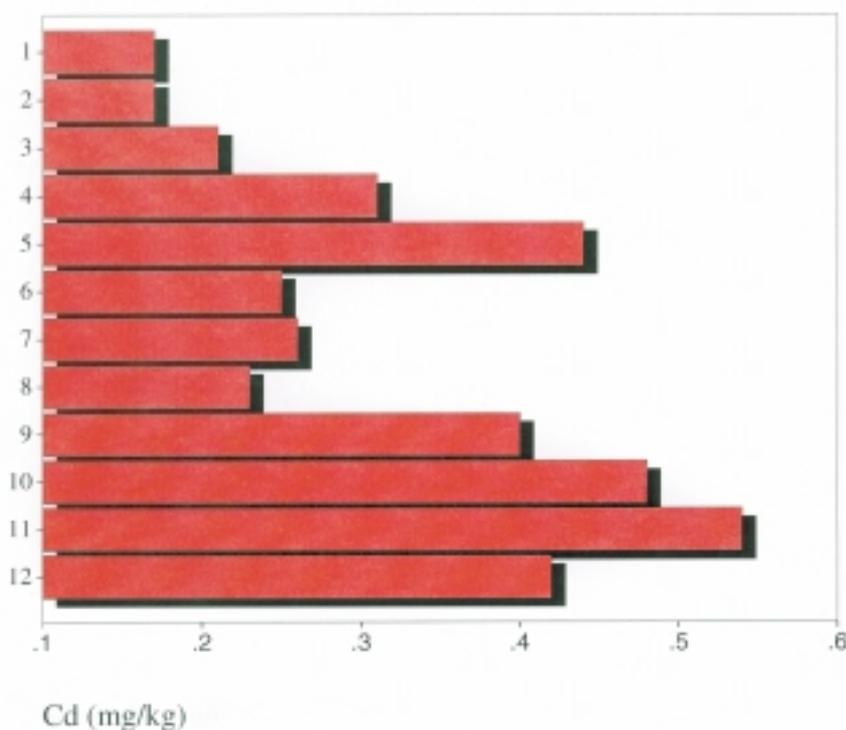


Fig. 3. The concentrations of Cd in the humus horizons in the studied sites. 1= Urjala, 2=Urjala, 3=Kiikka, 4=Karkku, 5=Hämeenkyrö, 6=Orivesi, 7=Töysä, 8=Töysä, 9=Töysä, 10=Housunkylä, 11=Ylivojakkala and 12=Koivu.

mg/kg) but lower than in other European countries, for instance in Germany (0.8 mg/kg) and the Netherlands (0.4 mg/kg) (Andersson 1977, Tjell & Hovmand 1978, Kick et al. 1980, van Driel et al. 1983). However, since 1986 P fertilizers in use in Finland have been made mainly of the domestic, nearly Cd-free raw phosphate and consequently, the annual Cd load from fertilizers has been 0.5 g/ha, on average. Thus it is expected that the rate of increase in soluble Cd in Finnish cultivated soils will be lower (Erviö et al. 1990). The highest Cd values are found in organic and clay soils in Finland and other countries (Sippola & Mäkelä-Kurtto 1986, van Driel & Smilde 1981, Mclean 1976). Organic soils and clays have, in general, higher adsorption capacities than do coarse mineral soils. Obviously, this is true for cadmium as well.

Mercury concentrations were around 1.5 times greater in the humus horizon (median 0.12 mg/kg) than in the lower horizons (median 0.08 mg/kg) in the afforested soils. In the arable soils only in the ploughing horizon were the Hg concentrations (median 0.09 mg/kg) over the detection limit. The Hg values on average were 0.062 mg/kg in Finnish arable soils (Mäkelä-Kurtto et al. 1992). The main source of mercury in afforested and arable soils are Hg-rich fertilizers. In the bedrock the Hg concentrations are low, an average 9 µg/kg and in general 99 % is < 50 µg/kg (Sippola & Mäkelä-Kurtto 1986). The shales and schists contain by far the highest natural Hg concentrations (0.18 mg/kg) (Reiman et al. 1997).

Conclusions

This study indicates that the main nutrients (Ca, Mg, K and P) are highest in the humus and uppermost A-horizon and decrease as a function of depth. This is connected with application of these nutrients as fertilizers. The heavy metal (Pb, Cd, Cr, Cu and Zn) concentrations are lower than in general in Finnish arable soils. However, in some places the Cd concentrations are clearly higher than the average values in Finnish arable soils. The cadmium concentrations are approximately similar than in soils in Sweden and Denmark but lower than in other parts of Europe. Hg concentrations are somewhat higher than in Finnish soils, on average. The main source for Cd and Hg concentrations are the fertilizers used in cultivated soils. The elements are in more soluble form in clay soils than in tills. This explains the higher values in the southern and western parts of Finland as well the high utilization rates of fertilizers in agriculture and industry.

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BALTIC SOIL SURVEY: FINNISH RESULTS

by

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Introduction

The aqua regia extractable concentrations of 27 elements in Finnish arable soils were studied as part of the Baltic Soil Survey, a regional geochemical mapping being carried out by the geological surveys of the Baltic Rim countries and Norway 1996-2000. The Baltic Soil Survey includes most countries around the Baltic drainage basin: Belarus, Estonia, Finland, Germany, Latvia, Lithuania, Norway, Poland, Sweden and Russia. Topsoils and subsoils have been sampled using a density of 1 profile per 2500 km². Three analytical methods will be applied: total analysis using X-ray fluorescence; inductively coupled plasma atomic emission spectroscopy (ICP AES) and ICP mass spectroscopy (ICP MS) after hot aqua regia extraction; and ICP AES and ICP MS after weaker acid ammonium acetate extraction.

Sampling has been carried out using standardised methods by national geological surveys in each country. In Estonia, the samples were taken by the Geological Institute. The samples will be sieved and homogenized at the Geological Survey of Norway. The analyses will be carried out by the Chemical laboratories of the Federal Institute for Geosciences and Natural Resources, Germany, and the Geological Survey of Finland.

The preliminary results of Finnish samples are summarized in this article. Only one set of analyses (hot aqua regia extraction) were available.

Materials and methods

The sampling density was 1 profile per 2500 km², and two samples were taken for each profile: topsoil 0-25 cm (plough layer) and subsoil 50-75 cm. Each of the samples was 8 litres in volume and was a composite of five subsamples collected from an area measuring 100 m x 100 m. Direct point sources of contamination and big roads were avoided when selecting the sampling sites.

Filed observations included sample identifier (e.g. FIN087TOP and FIN087BOT), coordinates, elevation above sea level, province, municipality, nearest village, size of the sampled field, number of subsamples, soil type, texture, cultivated plant, topography and depth of the groundwater table if observed. The total number of sampling plots was 135.

The samples were homogenized and a 100 g subsample was taken for chemical analysis. The samples for analysis were freeze-dried and a <2 mm fraction was sieved. Abundances of 27 elements were determined by ICP-AES and GAAS methods after hot (90°C) aqua regia extraction in the laboratory of the Geological Survey of Finland.

Results

Soil type

In this study the analysis results have also been

classified into four classes according to the soil type:

Fine grained soil (silt, clay)	42 sampling plots
Coarse, sorted soil (sand)	27 sampling plots
Till	11 sampling plots
Biogenic material	55 sampling plots

The large number of biogenic sampling plots is due to the great amount of peat in the arable land in Lapland and Kainuu.

Macro nutrients

Minimum, maximum and median values of macro nutrients (Ca, K, Mg, P and S) are given in Tables 1-3.

The distribution of calcium is much the same as that in till (Koljonen 1992, Salminen 1995). The highest values are in the regions where arable soil is rich in fine-grained and in biogenic material (Figs. 1a and 1b). The Ca values in the topsoils and subsoils are nearly the same; only the Ca concentrations in biogenic material are higher in topsoil due to Ca fertilizing. The poorest in Ca are the areas where the arable soil consists of till.

The distribution of potassium (Figs. 1c and 1d) is much similar to that in regional till sampling

(Salminen, 1995). The highest values are in the fine-grained clay areas in southwestern Finland. The median value of K in clay and silt samples is 3-4 times as high as in sand and till samples. Biogenic samples have the lowest K concentrations. That explains the low values in eastern Finland and in Kainuu because the portion of biogenic material (peat) in the arable soil is high in those regions (Urvas 1995). Also some regions in the Ostrobothnian coastal area are poor in potassium. The median values are somewhat higher in subsoil samples than in topsoils with the exception of the values in biogenic material.

The highest magnesium contents are found in clay and silt subsoil samples (Figs. 2a and 2b). So the clayey fields in the southwestern Finland are rich in Mg. Coarse-grained and biogenic samples have the lowest Mg values; this is seen in the samples from Lapland and Kainuu and also from central parts of Finland. The high median value in biogenic topsoil samples compared with subsoil samples may be explained with fertilizing.

The median values of phosphorus in all soil types are clearly higher in topsoils than in subsoils (Figs. 2c and 2d). This is because most of the phosphorus supplied to the soil as fertilizers is not soluble but is tightly fixed to the surface of soil particles (Urvas

Table 1. The median values (mg/kg) of subsoil samples (50 - 75 cm) in different soil types.

	Clay and silt		Sand		Till		Biogenic	
	Count	Median	Count	Median	Count	Median	Count	Median
Al	42	14800	27	6700	11	6260	55	4450
As	42	2.33	27	0.6	11	1.58	55	0.789
Be	42	<0.50	27	<0.50	11	<0.50	55	<0.50
Bi	42	<0.02	27	<0.02	11	<0.02	55	<0.02
Ca	42	3420	27	1590	11	1570	55	3560
Cd	42	0.044	27	0.019	11	0.020	55	0.059
Co	42	9.49	27	4.95	11	4.7	55	1.97
Cr	42	39.8	27	21.6	11	23.6	55	13.7
Cu	42	16.1	27	6.58	11	11.4	55	8.30
Fe	42	20900	27	11400	11	11250	55	6700
K	42	1800	27	650	11	464	55	95.0
Mg	42	5600	27	2960	11	2570	55	929
Mn	42	212	27	84.0	11	86.5	55	68.0
Mo	42	<0.2	27	<0.2	11	<0.2	55	0.458
Ni	42	17.3	27	10.5	11	11.6	55	6.77
P	42	551	27	397	11	347	55	538
Pb	42	7.2	27	<5.0	11	<5.0	55	<5.0
S	42	<50.0	27	<50.0	11	<50.0	55	1490
Sb	42	0.064	27	<0.04	11	<0.04	55	<0.04
Se	42	<0.1	27	<0.1	11	<0.1	55	0.176
Sr	42	16.0	27	5.46	11	6.42	55	19.8
Ti	42	1470	27	721	11	700	55	133
V	42	44.6	27	22.8	11	24.6	55	13.7
Zn	42	38.8	27	12.9	11	12.5	55	4.66

Table 2. Median values (mg/kg) of topsoil samples (0 - 25 cm) in different soil types.

	Clay and silt		Sand		Till		Biogenic	
	Count	Median	Count	Median	Count	Median	Count	Median
Al	42	13200	27	6400	11	9250	55	4200
As	42	2.39	27	0.505	11	2.04	55	0.80
Be	42	<0.50	27	<0.50	11	<0.50	55	<0.50
Bi	42	<0.02	27	<0.02	11	<0.02	55	0.03
Ca	42	3110	27	1370	11	2130	55	6590
Cd	42	0.139	27	0.038	11	0.071	55	0.148
Co	42	6.31	27	3.36	11	4.31	55	3.50
Cr	42	31.4	27	15.5	11	18.0	55	13.1
Cu	42	15.9	27	7.90	11	9.59	55	18.9
Fe	42	16900	27	9300	11	11900	55	9410
K	42	889	27	231	11	223	55	200
Mg	42	3970	27	1270	11	2120	55	1980
Mn	42	183	27	80.7	11	89.5	55	94.3
Mo	42	0.205	27	<0.2	11	<0.2	55	0.466
Ni	42	13.4	27	6.54	11	6.81	55	6.47
P	42	805	27	456	11	672	55	1080
Pb	42	10.0	27	5.07	11	<5.0	55	7.60
S	42	259	27	156	11	218	55	1660
Sb	27	0.068	27	<0.04	11	0.051	55	0.055
Se	27	0.158	27	<0.1	11	<0.1	55	0.269
Sr	27	21.7	27	10.7	11	14.5	55	47.8
Ti	27	976	27	362	11	568	55	123
V	27	36.2	27	21.5	11	24.5	55	18.2
Zn	27	37.1	27	11.6	11	20.6	55	19.7

Table 3. Minimum, median and maximum values (mg/kg) in Finnish topsoil (0 - 25 cm) and subsoil (50 - 75 cm) samples.

	Subsoil samples			Topsoil samples		
	Minimum	Median	Maximum	Minimum	Median	Maximum
Al	370	7420	46900	314	7495	32900
As	<0.2	1.30	12.0	<0.2	1.24	13.4
Be	<0.5	<0.5	2.08	<0.5	<0.5	1.5
Bi	<0.02	<0.02	0.22	<0.02	<0.02	0.136
Ca	410	2560	18600	<50.0	3355	22700
Cd	<0.01	0.034	0.318	<0.01	0.115	0.49
Co	<1.0	4.40	33.8	<1.0	4.25	19.5
Cr	<4.0	22.3	104	<4.0	19.0	86.0
Cu	<1.0	11.0	78.2	<1.0	13.45	60.2
Fe	560	11400	63800	1140	11550	51000
K	<50.0	447	9440	<50.0	304	6030
Mg	120	2700	18800	149	2165	11000
Mn	<1.0	101	850	4.5	123	1690
Mo	<0.2	<0.2	7.97	<0.2	0.214	12.0
Ni	<2.0	10.6	65.1	<2.0	8.08	60.1
P	103	507	2600	<50.0	805	4310
Pb	<5.0	<5.0	25.5	<5.0	7.60	43.2
S	<50.0	92.0	10800	<50.0	401	5420
Sb	<0.04	<0.04	0.192	<0.04	0.052	0.908
Se	<0.1	<0.1	5.88	<0.1	0.158	8.3
Sr	<2.0	13.3	110	<2.0	23.9	153
Ti	<5.0	696	3010	6.78	391	2190
V	<1.0	24.2	122	<1.0	24.7	176
Zn	<1.0	16.0	140	<1.0	21.9	121

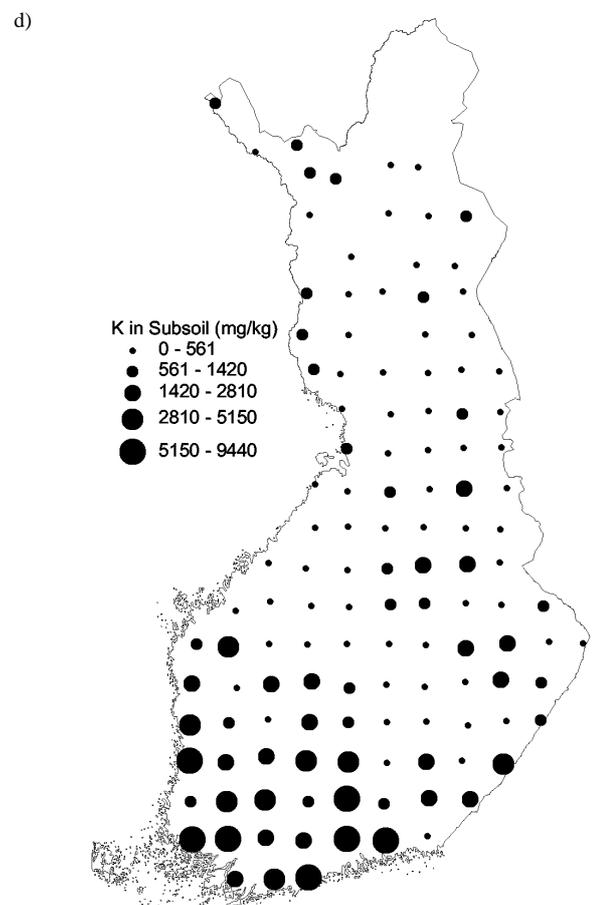
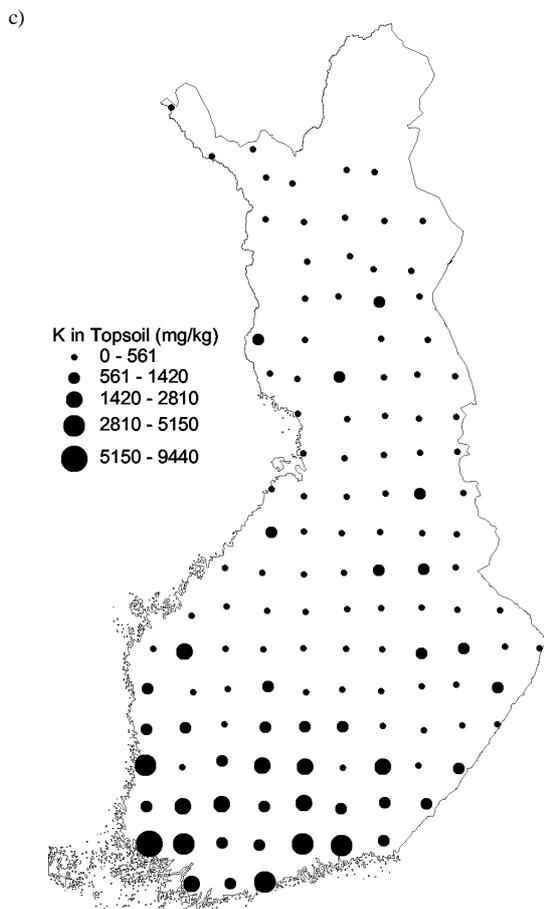
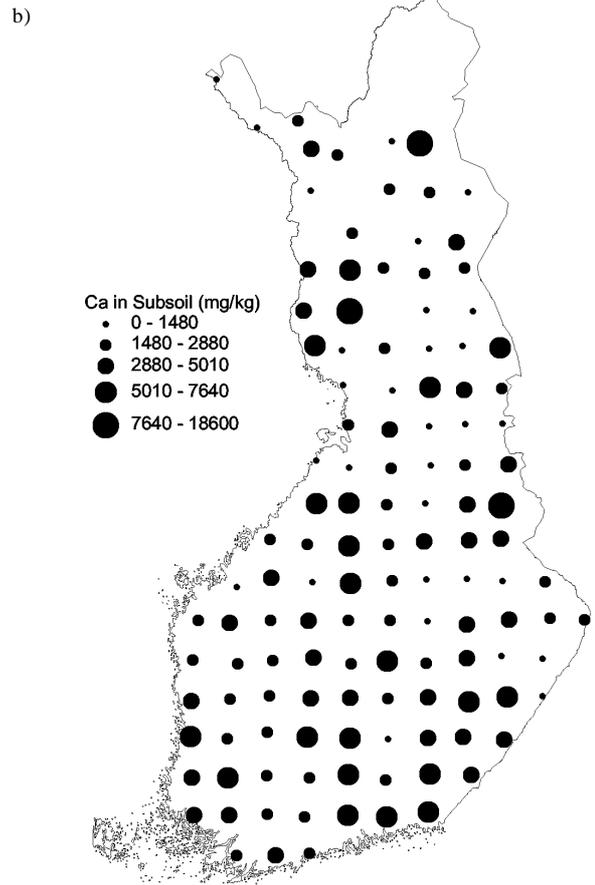
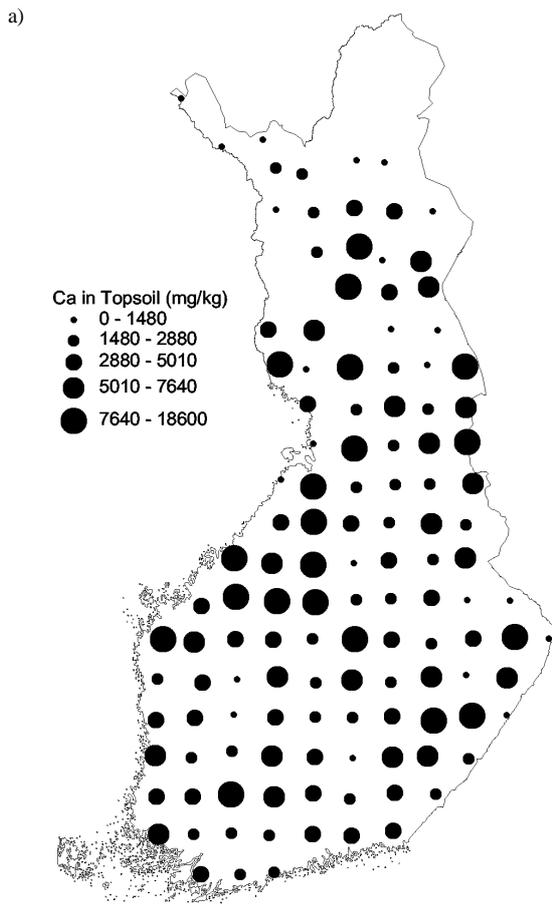


Fig. 1a. Distribution of Ca in topsoil samples.
Fig. 1b. Distribution of Ca in subsoil samples.

Fig. 1c. Distribution of K in topsoil samples.
Fig. 1d. Distribution of K in subsoil samples.

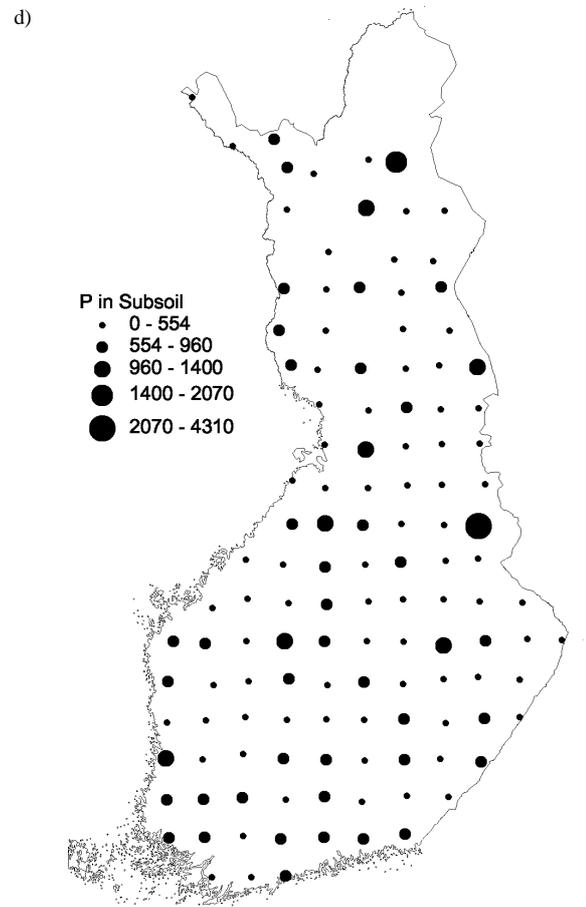
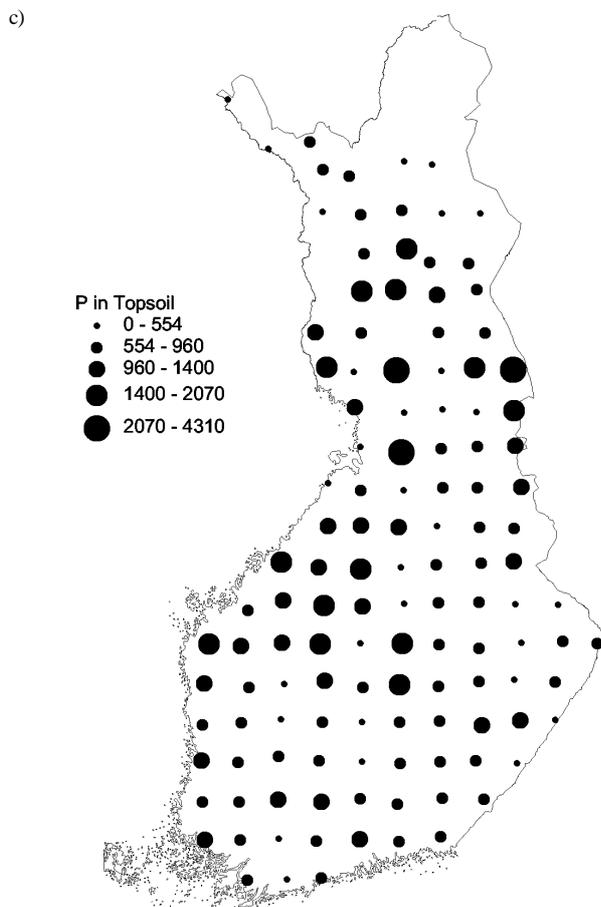
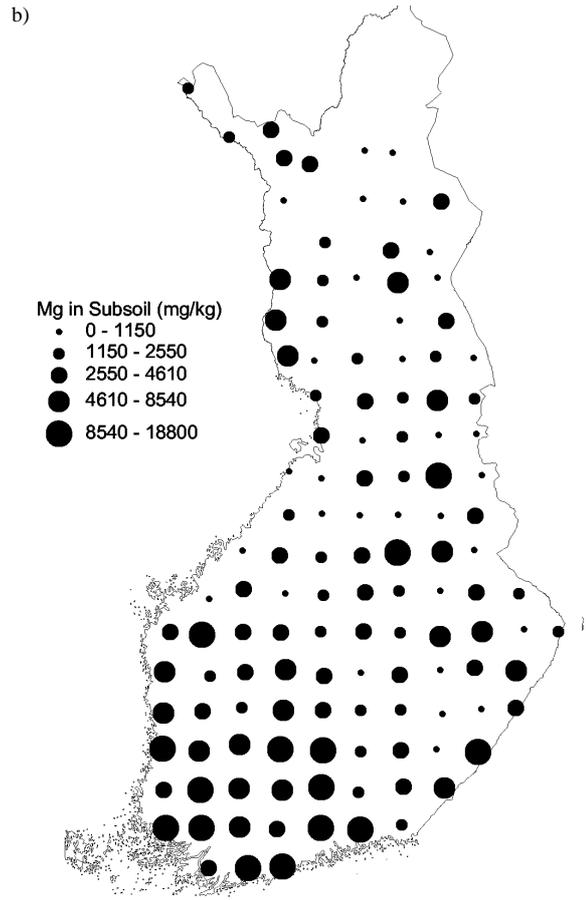
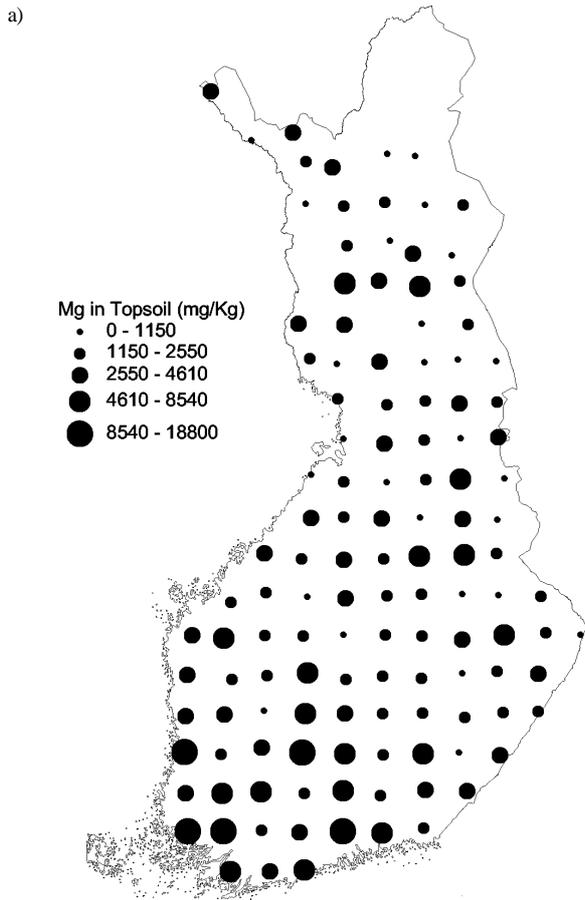


Fig. 2a. Distribution of Mg in topsoil samples.
Fig. 2b. Distribution of Mg in subsoil samples.

Fig. 2c. Distribution of P in topsoil samples.
Fig. 2d. Distribution of P in subsoil samples.

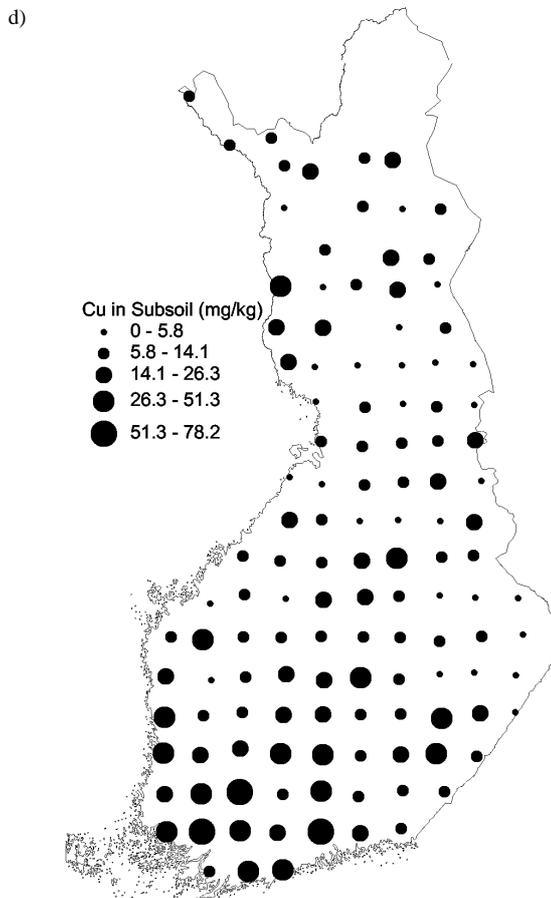
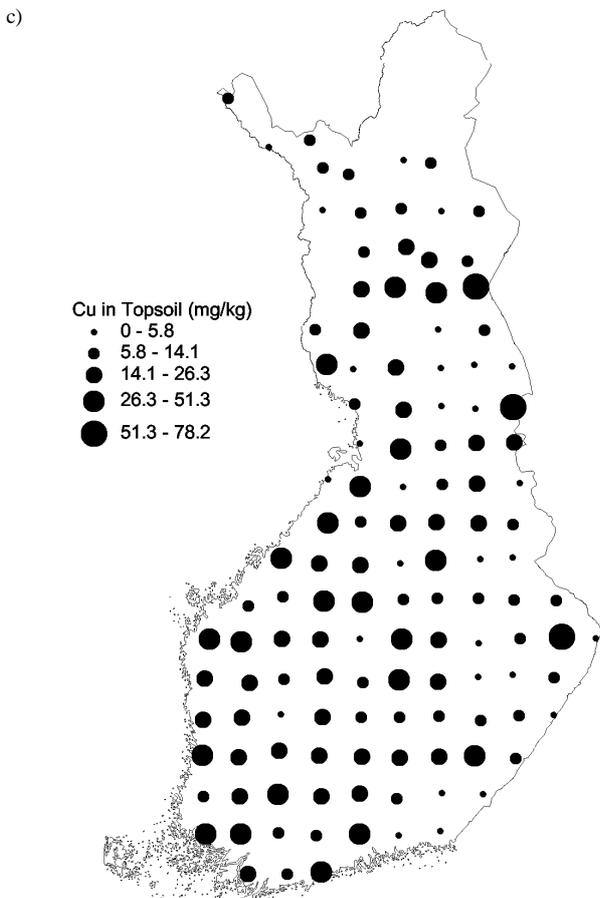
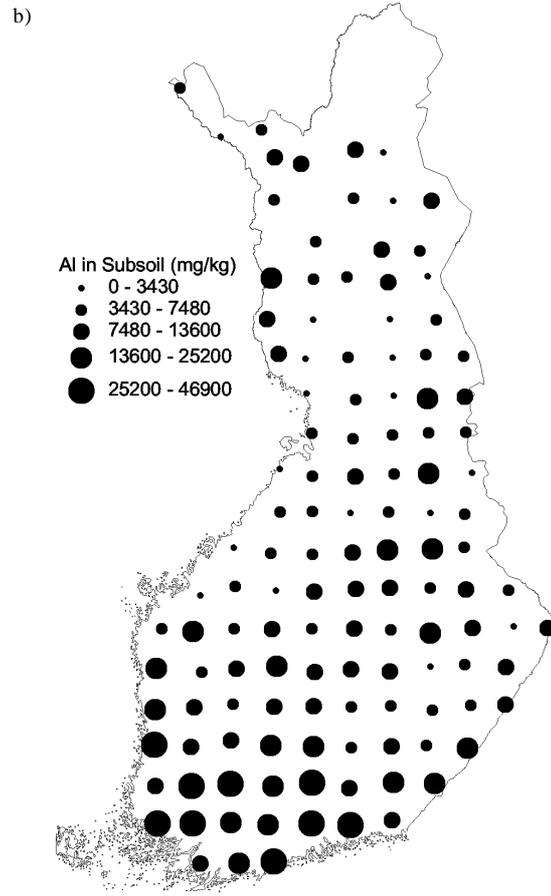
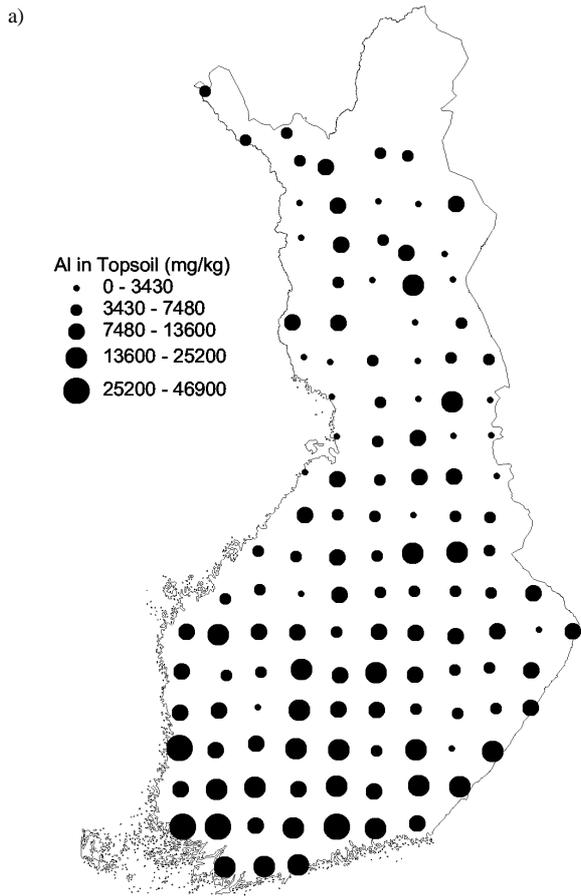


Fig. 3a. Distribution of Al in topsoil samples.
Fig. 3b. Distribution of Al in subsoil samples.

Fig. 3c. Distribution of Cu in topsoil samples.
Fig. 3d. Distribution of Cu in subsoil samples.

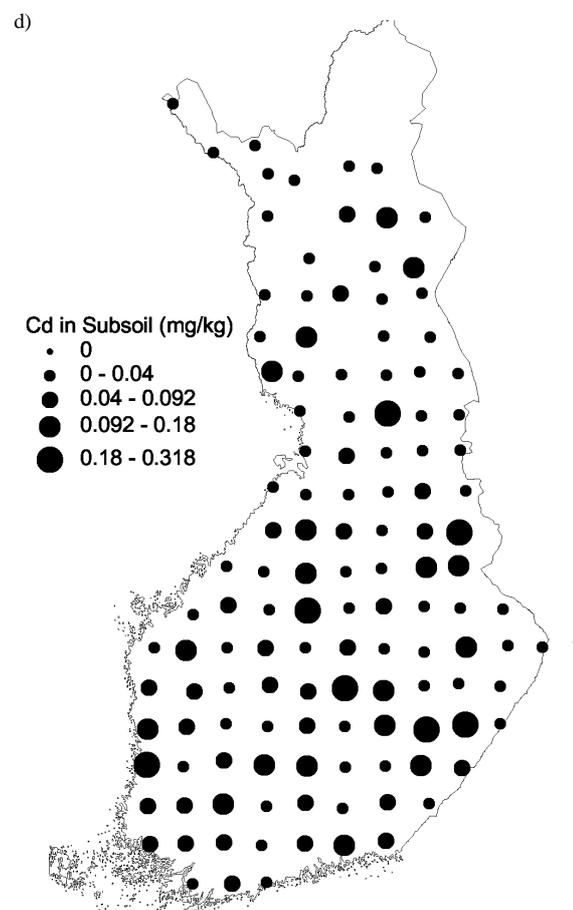
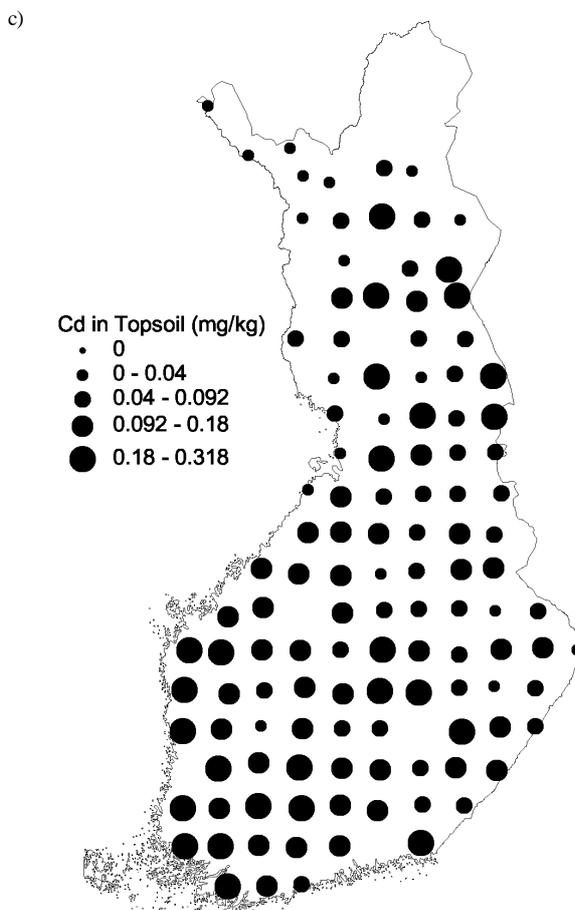
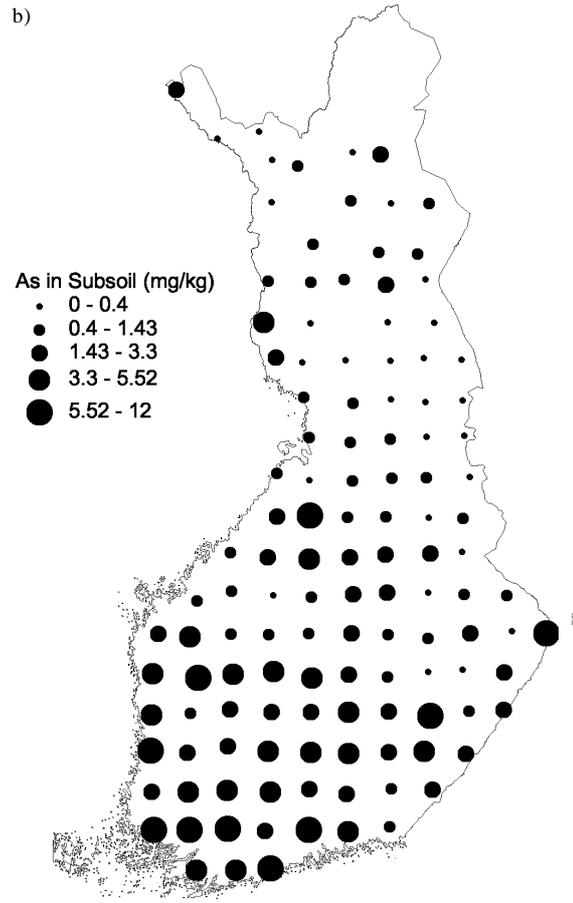
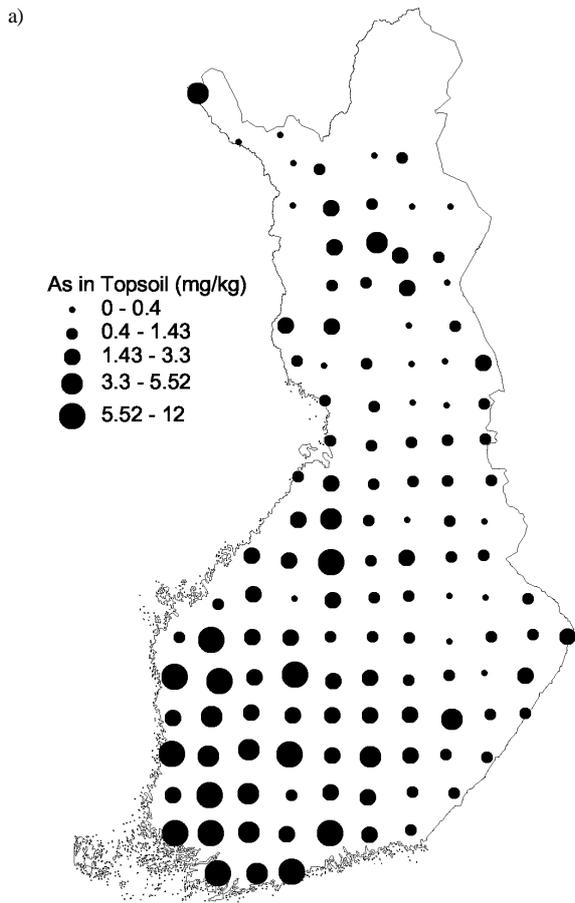


Fig. 4a. Distribution of As in topsoil samples.
Fig. 4b. Distribution of As in subsoil samples.

Fig. 4c. Distribution of Cd in topsoil samples.
Fig. 4d. Distribution of Cd in subsoil samples.

1995). Phosphorus forms organic complexes and colloids and can be fixed to humus and clay particles (Lahermo et al. 1996). This explains the high P values of biogenic topsoil samples. Phosphorus is rather evenly distributed in the samples of this study; only few exceptionally high contents are met.

Sulphur is an essential nutrient and an important constituent of organic matter. So the sulphur values are high in biogenic samples. This is well seen in the results from Lapland and Kainuu where the portion of biogenic material in samples is bigger than in other parts of Finland. In this study topsoil samples are clearly richer in sulphur than subsoil samples. The influence of the sulphide- and sulphate-bearing clay area on the coast of central Ostrobothnia is discovered. Some high S values are also found in the Eastern Finland, Kainuu and Kuusamo - Kittilä greenstone belt.

Micronutrients and potentially harmful elements

The distribution of many trace metals in subsoil samples was rather similar to the distribution in regional till sampling (Salminen 1995). The highest concentrations of Al, Co, Cr, Cu, Fe, Mn, Ni, Ti, V and Zn were usually found in southwestern Finland, in the eastern part of the Lake Ladoga - Bothnian Bay zone and in the schist belts of Kuusamo and central Lapland (Figs. 3a, 3b, 3c and 3d). Median values are given in Tables 1-3. The median values of the metal concentrations were higher in till than in arable soils. However, those concentrations in clay-silt-rich arable soils exceeded the concentrations in the nearby till samples. The distribution of the above mentioned metals was almost similar in the topsoil samples except for Cu, which has been added in fertilizers, and V with two anomalous values in central Finland.

The highest concentrations of As (Figs. 4a and 4b) were measured in southwestern Finland, in Ostrobothnia, in Ilomantsi and in Kittilä. The anomalies are similar to those in till (Koljonen 1992), organic stream sediments and stream waters (Lahermo et al. 1996). The concentration of Be seldom exceeded the analytical limit 1.0 mg/kg. The few exceptions were located in Lapland both in topsoil and subsoil samples. The concentrations of Bi were always very low (max 0.22 mg/kg), the highest values were analysed from Ostrobothnia between Vaasa and Kokkola and from the southeast. The distribution of Cd was sparse, the concentrations were higher in topsoils due to the impact of Cd

rich fertilizers in use during the period 1975-1981 (Erviö et al. 1990) (Figs. 4c and 4d).

Molybdenum exhibited very low concentration throughout the country, most of the results were lower than the analytical limit 0.2 mg/kg. The highest concentrations were measured in biogenic soils in central Lapland and in southeastern Finland. Concentrations of lead were generally higher in topsoils than in subsoils. In subsoils, the highest concentration were located in the fine-grained sediments in southern Finland. In topsoils, slightly elevated concentrations (max. 43.2 mg/kg) were found in many samples in southern and central Finland.

The median value of Sb concentrations was higher in topsoils than in subsoils. Highest concentration were found from fine-grained soils of southern and central Finland. Selenium concentrations are generally low in Finnish soils (Koljonen 1975). Selenium has been added to the soils with fertilizers, and the concentrations are bit higher in topsoils. The highest concentrations were observed in the topsoils of central Lapland. In subsoils, the highest concentrations of Se were located in southeastern Finland and in Lapland.

The distribution of Sr was best explained by the soil type: biogenic soils exhibited the highest concentrations.

Conclusions

The distribution of many trace metals and nutrients in this study was similar to that of regional till sampling and of organic stream sediment and stream water sampling. Metal content was clearly dependent on soil type, so that the highest contents of most elements were in fine-grained clay and silt and in organic soils. There were not very big differences between the contents of topsoil and subsoil samples, only a few elements were poor in subsoil organic material. Fertilizing raised the contents of some elements in topsoil samples. This was true especially for Ca, Cu, Mg, P, Se, Sr, Mo and Cd.

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THE COMPARISON OF HYDROGEOCHEMICAL DATA FROM THE FOREGS PROGRAMME AND REGIONAL MAPPING IN FINLAND

by
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Key words (GeoRef Thesaurus, AGI): stream water, hydrochemistry, electrical conductivity, pH, alkalinity, FOREGS, baseline studies, geochemical surveys, Finland

Introduction

Stream water samples from 66 small drainage basins (< 100 km²) were collected in Finland during June - August 1998 as part of the FOREGS Geochemical Baseline Programme. In this pilot study, only the field measurements (pH, conductivity and alkalinity) were available. The FOREGS data were compared with the regional mapping data based on 1165 stream water samples (Lahermo *et al.* 1996).

The FOREGS programme (Salminen *et al.* 1998) has been initiated to provide high quality environmental baseline data for Europe. This programme forms the European contribution to the International Union of Geological Sciences/International Association of Geochemistry and Cosmochemistry Working Group on Global Geochemical Baselines.

Research conducted since 1988 as part of the International Geochemical Mapping project (IGCP 259) has indicated that although there are several national and regional data sets describing the geochemistry of the Earth's surface they are incomplete and inconsistent between different national surveys (Darnley *et al.* 1995). According to the inventory made by the FOREGS Geochemistry working group 1994-1995, 120 separate geochemical databases existed in European countries, but the variety of sample materials and analytical techniques used varied widely so that the Global Reference Network (Darnley *et al.* 1995) was needed urgently to extend across Europe (Plant *et al.* 1996).

It has become apparent that the need for a consistent and internationally comparable geochemical data set is urgent, not only for scientists but also for policy makers, especially in the area of contaminated land. It is vital to have as detailed an understanding as possible of background variation in the natural system before defining limits for contamination.

The International Geological Correlation Programme (IGCP) projects 259 and 360 recommended the collection of a global reference set of materials which should be collected following predefined, systematic methods, and which should also be consistently analysed in designated laboratories (Darnley *et al.* 1995). In this way a global geochemical database based on a global reference network (GRN) could be created, to provide a reference against which existing national and regional data sets could be compared. The recommendations were endorsed by the UN Committee on Natural Resources which issued Resolution 3/5 in 1996 recognising the urgent need for a global land monitoring programme. The Resolution endorsed the need to establish a global geochemical data set and that the Global Geochemical Baselines project forms the core of the programme.

The FOREGS Geochemical Baseline Programme will be based on six different sample types (stream sediment, stream water, flood plain sediment, topsoil, subsoil and humus) collected from all over Europe. High quality and consistency of the obtained data are ensured by using standardised sampling methods (Salminen *et al.* 1998) and by treat-

ing and analysing all samples in the same laboratories.

The choice of sampling media has been done in accordance with the recommendations of the IUGS working group on Global Geochemical Baselines (Darnley *et al.* 1995). The selected sampling media are considered to be the most representative of the surface environment, and they are the most commonly used media in previous and present environmental geochemical investigations. Sampling sites are chosen at random, so that the data for each of the chosen media will document the actual situation within Europe.

Stream sediment (<0.15 mm fraction) and floodplain sediment (<2 mm fraction) samples are collected because they reflect the average geogenic composition of a catchment basin. Most Geological Surveys have undertaken national stream sediment studies. The new data are necessary to link these surveys to a baseline level.

Stream water reflects the interplay between geosphere/hydrosphere and pollution. At the same time it is the main source of drinking water. Many surveys have completed local studies, so the GTN data can be used to link results across Europe.

Soil samples (topsoil 0-25 cm) and subsoil (a 25 cm layer within a depth range of 50-200 cm) are taken to reflect variations in geogenic composition of the uppermost layers of the Earth's crust. For this purpose it is important to avoid soil sampling at locations that have visible or known contamination. Priority for site selection should be given to

1. Forested and unused lands
2. Green land and pastures, and
3. Agricultural land.

Comparison of topsoil with subsoil samples will give information about enrichment or depletion processes between the layers. One such process is anthropogenic contamination of the top layer. The <2 mm fraction will be taken according to environmental standards. The <0.18 mm and finer fractions have been widely used in mineral exploration programmes and the GTN data will be used to create a link between environmental and mineral exploration databases.

Humus samples can be used to determine the atmospheric (anthropogenic) input of elements to the ecosystem. To reach this aim samples should be collected in forested areas as near as possible to the other sampling sites. To reflect the atmospheric input, the uppermost few centimetres of the organic layer should be collected immediately under the green vegetation and under the litter (max 3 cm).

Methods

In the FOREGS programme, the entire land surface of Europe has been divided into 160 km x 160 km Global Terrestrial Network cells (Darnley *et al.* 1995). Five small drainage basins of <100 km² in area were randomly selected for sampling from each GTN cell. Samples were collected from these small drainage basins except the flood plain sediment sample (upper 25 cm) which was collected from the lowermost point of the larger drainage basin (area 500 - 6000 km²) to which the small catchment is connected. The sampling procedures are described by Salminen *et al.* (1998). During June - August 1998, 66 stream water samples were collected in Finland. Field measurements of pH, electrical conductivity (EC) and alkalinity are now available and were used in this study.

The regional geochemical mapping of stream waters and organic stream sediments was carried out by the Geological Survey of Finland during August - September 1990. The mean sampling density in the regional mapping was 1 sample per 300 km², the total number of sample was 1165. The sampling points were determined to include a drainage area of ca 30 km². Electrical conductivity, pH and alkalinity were determined in the laboratory immediately after receiving the samples. The methods and results have been reported by Lahermo *et al.* (1996).

The distribution of EC, pH and alkalinity are presented as combination maps with regional mapping data shown as background with a color scale and the FOREGS data as superimposed dots. The regional data were first interpolated and smoothed into a regular 1 km x 1 km grid. The grid values were calculated using a moving weighted median in a circular window (radius 160 km). Then a nine-grade colour scale was selected to present the distribution. Finally, the results of the FOREGS mapping were presented as variable dot size. The interpolation method is described by Gustavsson *et al.* (1997).

Another interpolation method called bootstrap estimation (Efron & Tibshirani 1991) was applied to the FOREGS alkalinity data. In the bootstrap estimation the calculation of weighted median is repeated 30 times in each 1 km x 1 km grid cell. Random samples of n points are drawn with replacement from the samples within the circle (radius 160 km). The weighted median M_i is computed for each sample. The Bootstrap estimate of the grid point is the mean of all 30 M_i values.

Results and discussion

Due to fair or scant rainfall in August - September 1990, the surface water bodies were in comparatively steady state and mainly composed of base flow. Hence, the chemistry of streams was well controlled by the interaction between water, geochemical environment of the catchment, and anthropogenic deposition. In contrast to 1990, the sampling period of 1998 was very rainy. This has affected the composition of the stream waters: the median value of pH was 5.91 in 1990 and 6.60 in 1998. The conductivity values were higher in 1990 than in 1998 (median values 4.4 and 4.0 mS/m, respectively). The median value of alkalinity was 10 mg/l CaCO_3 in 1990 and 7 mg/l in 1998.

The declining sulphate deposition has been reflected at least in central and southern Finland in a lowering of sulphate concentrations in ground waters (Backman *et al.* 1998, Lahermo & Backman 1998) and in small headwater lakes (Mannio and Vuorenmaa 1995). The declining sulphate concentration is connected with increasing pH values and alkalinity in the groundwater monitoring. The pH of

surface waters is partly controlled by the amount of dissolved organic matter. The high amount of rain in 1998 could have increased the proportion of dissolved organic matter and thus lowered the pH. On the other hand, the FOREGS samples represent larger drainage basins than the regional mapping streams in 1990, which will partly explain the generally higher pH values in 1998.

Despite the differences in the levels of the measurements, the anomaly areas were similar in both datasets. Highest conductivity was found in the coastal areas in southern and western Finland and along the Kuusamo - Kittilä greenstone belt in the north (Fig. 1). The lowest pH values occurred in central Finland in areas which are characterized by granitic bedrock overlain by coarse grained basal till and peat bogs (Fig. 2). High alkalinity was found in the Åland archipelago, in the southern and southwestern Finland, in the Kuusamo area and in central Lapland (Fig. 3). In coastal areas the high buffer capacity in stream waters is mainly due to fine-textured clay and silt deposits occupying lowland areas and in Åland to carbonate rocks included in the bedrock. As expected, the pH values correlated with

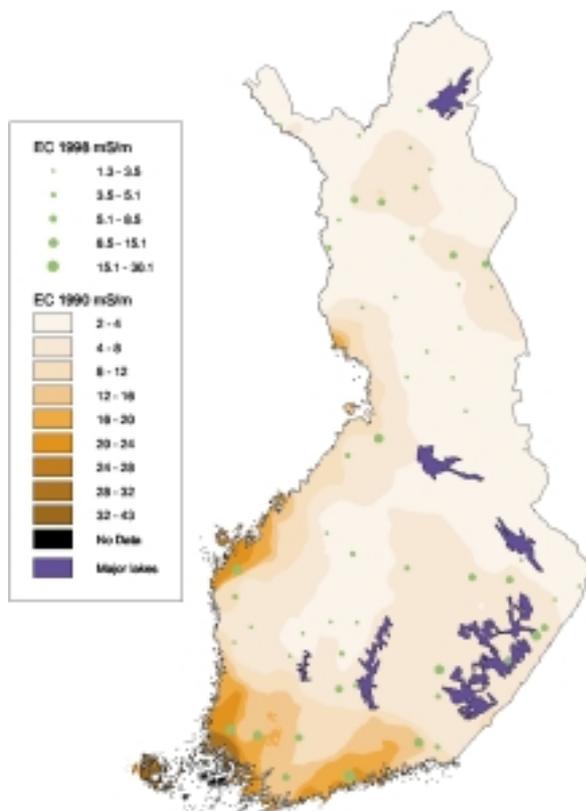


Fig. 1. Areal distribution of electrical conductivity (EC) in Finnish stream waters in 1990 (colour scale) and in 1998 (dots). Unit mS/m, 25°C.

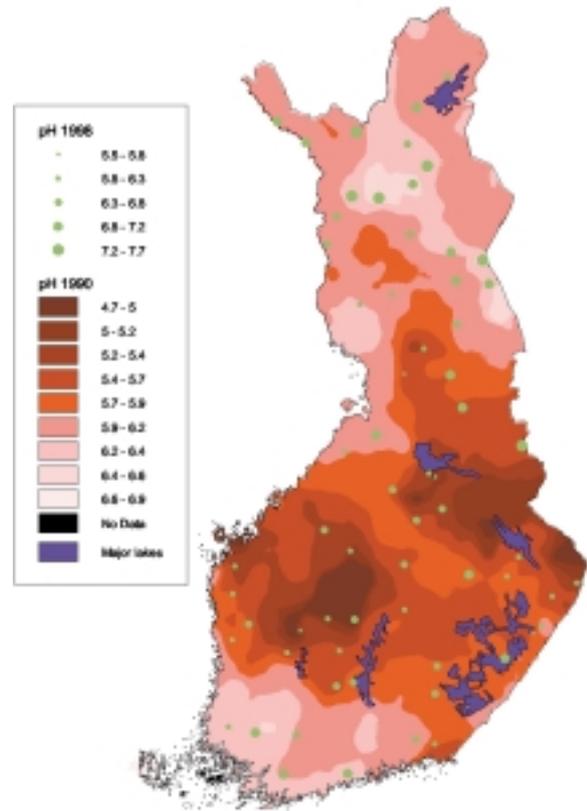


Fig. 2. Areal distribution of pH values in Finnish stream waters in 1990 (colour scale) and in 1998 (dots).

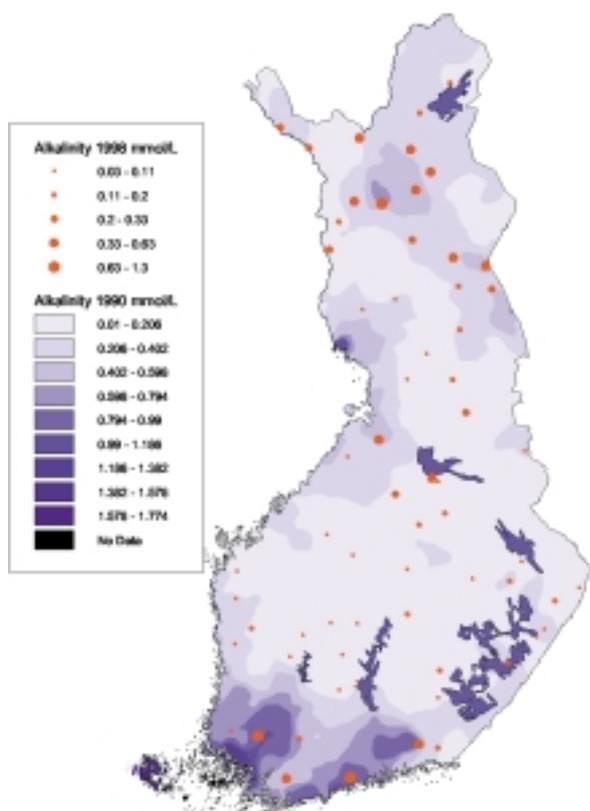


Fig. 3. Areal distribution of alkalinity (mmol/l) in Finnish stream waters in 1990 (colour scale) and in 1998 (dots).

the alkalinity values (Fig. 4). The most acid waters ($\text{pH} < 6.0$) were characterized by low alkalinity ($< 4 \text{ mg/l CaCO}_3$).

The FOREGS geochemical mapping is based on extremely low density sampling. Nils Gustavsson (see Darnley *et al.* 1995) used the bootstrap method for interpolating the data of similar continental wide low density mapping of topsoils of the United States. The interpolated grid was presented with a 20-class colour scale on small scale maps. These maps revealed surprisingly well the main geological and geochemical features of the mapping area. We used the same interpolation method for the alkalinity data of the Finnish FOREGS samples. The bootstrap interpolated map (Fig. 5) shows the same anomaly areas that can be seen in the regional survey (Fig. 3), although the delineation of anomalies cannot be as detailed as in regional maps. The weight of individual erroneous measurements will be minimized in the Bootstrap method. Compared to the whole FOREGS mapping area of over 20 European countries, the geology and surface hydrogeochemistry of Finland is quite monotonous. Thus we can expect that the bootstrap interpolation of the FOREGS data set will provide a representative general overview of the surface geochemistry of our continent.

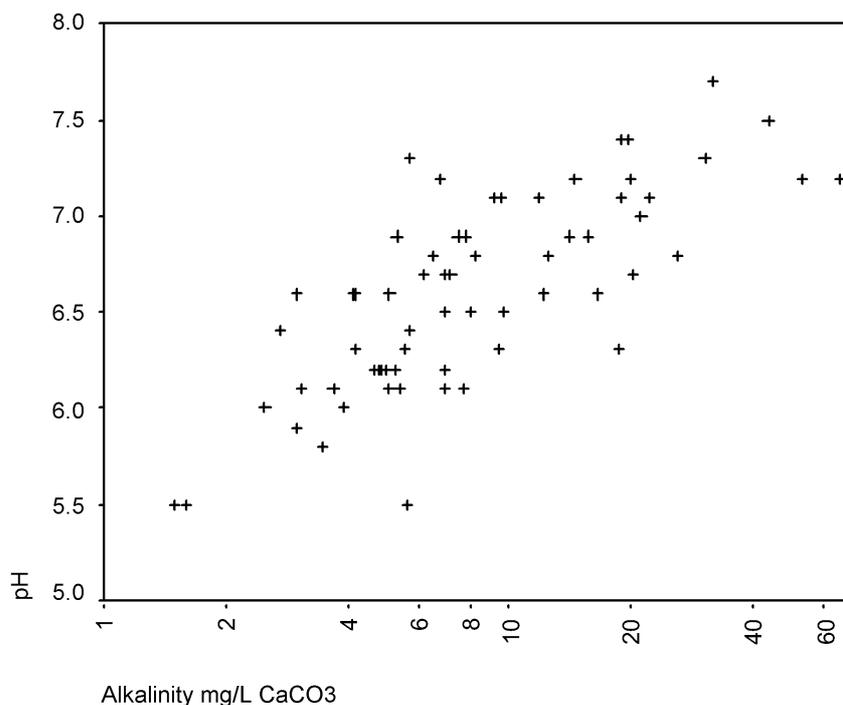


Fig. 4. Scatter diagram of alkalinity (mg/l CaCO_3) on x-axis with logarithmic scale and pH on y-axis. FOREGS geochemical mapping in 1998, 66 samples.

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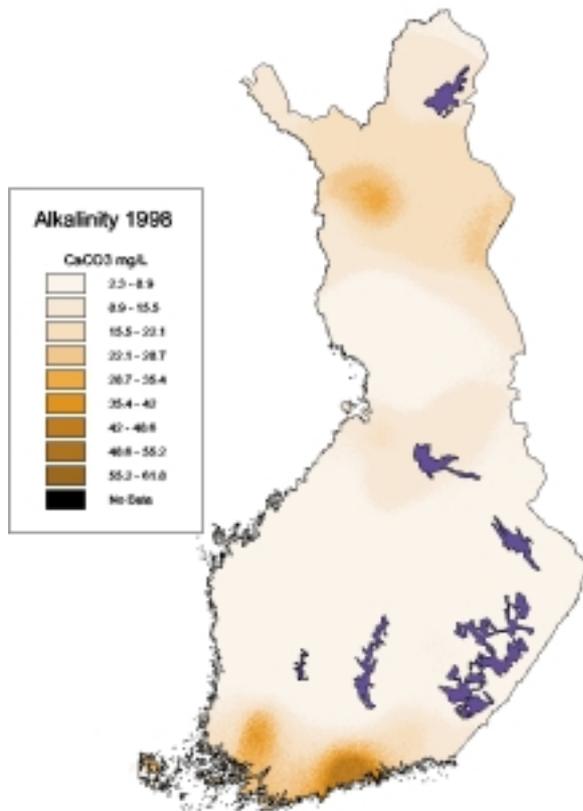


Fig. 5. Areal distribution of alkalinity (mg/l CaCO₃) in Finnish stream waters in 1998 based on the Bootstrap interpolation.

Conclusions

The electrical conductivity and alkalinity values were generally lower and pH values higher in the FOREGS mapping compared to the regional mapping in 1990. However, the regional distributions of anomalies were almost similar. The alkalinity map based on the Bootstrap interpolation of the 66 FOREGS samples revealed the main geochemical features of Finnish streams. A similar interpolation technique applied to the whole FOREGS data set will be an applicable approach to make the geochemical atlas of Europe in reconnaissance scale.

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OCCURRENCE AND CHEMICAL CHARACTERISTICS OF GROUNDWATER IN PRECAMBRIAN BEDROCK IN FINLAND

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Introduction

The fractured upper part of the Finnish Precambrian bedrock, down to 50–200 m, hosts considerable amounts of groundwater. While many communities and towns in Finland rely upon either surface waters or groundwater from surficial glaciofluvial aquifers, generally of limited areal and spatial extent, the groundwater reserves in bedrock are relatively underutilized. The composition of bedrock groundwater is controlled, among other factors, by the texture, structure and lithologic composition of rock material. As well, the geochemical interaction of water with fracture coatings and secondary minerals of various composition modifies the chemical and isotopic quality of groundwater circulating in fractures. The peculiarities of the rock matrix may locally restrict the use of bedrock groundwater as a source of water supply. The elevated concentrations of fluorine, arsenic, uranium and radon in groundwater from drilled wells, for example, have been a source of growing concern in Finland. Values of stable isotopes for fresh and slightly saline groundwaters plot along or near the meteoric water line (GMWL). Some saline bedrock groundwaters and brines, on the other hand, deviate conspicuously about the meteoric waters suggesting a prolonged residence time and consequent water-rock interaction.

Geological and tectonic setting of Finland

The continental crust of the Precambrian Fennoscandian Shield was formed between 3.5 and 1.5 Ga ago during four periods of orogenic activity (Gaal & Gorbachev 1987). The Shield is bordered by the Caledonides in the west and by the Vendian and Phanerozoic sediments to the south. Constituting the central part of the Fennoscandian Shield, the bedrock of Finland is composed of Archaean and Proterozoic igneous and metamorphic rocks (Simonen 1980, Koistinen *et al.* 1996). The Archaean basement complex in eastern and northern Finland comprises felsic and intermediate granitoids, gneisses and migmatites with local greenstone belts composed of metavolcanic and metasedimentary rocks (Fig. 1). Proterozoic mafic layered intrusions and the Central Lapland greenstone belt dominate in northern Finland. The Svecofennian and Karelian schists and gneisses in central and southern Finland are predominantly metasedimentary rocks, ranging from well-preserved schists to high-grade migmatites. Metavolcanic rocks are locally abundant.

The Central Finland and Lapland granitoid complexes are the largest relatively uniform occurrences of Svecofennian granitoids. In addition, there are numerous smaller granitoid plutons within schists. Rapakivi granite batholiths - Viipuri and Ahvenisto in the southeast and Laitila, Vehmaa and Ahvenamaa in the southwest - are characteristic features of the bedrock of southern Finland. The

Bedrock map of Finland

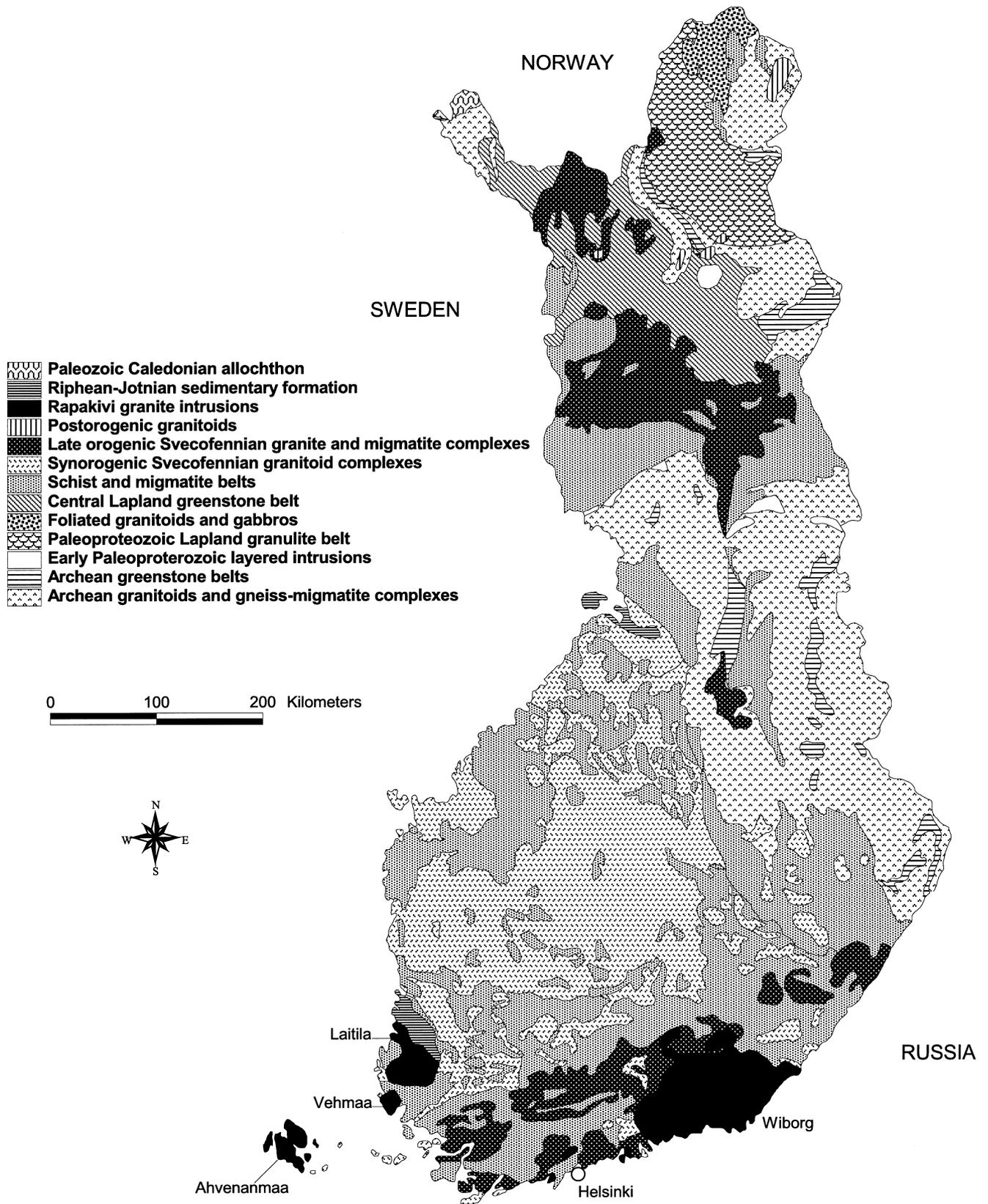


Fig. 1. Precambrian bedrock of Finland 1:5 000 000. Modified after Geological Survey of Finland, 1999.

youngest major rock units found in the country are small occurrences of Jotnian sedimentary rocks (sandstones and shales) in western Finland and Caledonian rocks in the northwestern tip of Lapland. The youngest Precambrian in Finland is represented by 1.27 Ga old diabase dikes cutting the Jotnian sediments (Simonen 1980).

The most widely distributed soil type in Finland is glacial till, while only a few percent of the territory is covered by glaciofluvial sand and gravel deposits (eskers, ice-marginal deltas and sandurs). The average thickness of the overburden is only a couple of metres, and the bedrock crops out in many parts of coastal and northernmost Finland. Till is predominantly of local origin and its mineralogical and geochemical composition reflects the average bedrock in the vicinity. The abundance of fines and the clay fraction in till explain many geochemical dependences and the common areal distribution patterns of elements in till (Räisänen *et al.* 1992, Lintinen 1995), shallow groundwater (Lahermo *et al.* 1990), stream waters and sediments (Lahermo *et al.* 1996). Late-glacial and post-glacial clay and silt deposits are most common in coastal areas, which were submerged by regressive phases of the Baltic Sea. Peat deposits cover the till and bottom sediments most frequently in central, eastern and northern parts of the country.

A prominent feature of crystalline bedrock is its compartmentalization due to the faulting and fracturing. Everywhere in Finland one finds joints, fissures, faults and crushed zones, which divide the bedrock into more or less separate rigid blocks that together form a mosaic-like structure (Niini 1968, Niini 1987). The bedrock blocks vary in size from surficial loose sheets within bedrock outcrops to global shields the size of a continent (Vuorela and Niini 1982). Fracture zones commonly occur in sets of parallel zones oriented in a few major directions, two of them often approximately perpendicular to one another. A typical large fracture zone several tens of kilometres long may easily have a depth dimension measurable in kilometres. Fracture frequency of the bedrock does not necessarily decrease downwards with the exception of the surficial bedrock layer 5-20 metres thick which is more severely jointed and chemically weathered (Niini 1968).

Only a few indications of Archaean fractures has been found in the bedrock topography of Finland. Proterozoic fractures, on the other hand, can be divided into three deformation phases: Early Proterozoic, early Middle Proterozoic and Middle Proterozoic (Talvitie 1979). Owing to their widespread abundance, these fractures lend considerable

plasticity to the whole Precambrian Shield. Later tectonical movements in the bedrock, mainly caused by plate tectonic forces induced by the push at the North Atlantic Ridge and glaciation/deglaciation cycles, have mostly been limited to the existing zones of weakness (Niini 1987, Slunga 1991, Kakkuri & Chen 1992, Saari 1992).

General remarks on the occurrence of groundwater in Finland

Glaciofluvial eskers, related esker deltas and ice marginal formations (e.g. the Salpausselkäs), which are composed of sand and gravel, house the most extensive and economically significant aquifers in Finland. They nevertheless cover only an estimated 3 to 4% of the total area of the country. Furthermore, none of these unevenly distributed eskers and other large glaciofluvial formations lie close to large population centres, e.g. the cities of Helsinki, Turku or Oulu. Hence, at the moment groundwater resources do not supply more than 58% of the water volume distributed by public water works. (The calculation does not include the large volume of surface water used by the pulp and paper industry and the energy sector.) An estimated 20% of the population uses water from private single-household wells, many of them in summer dwellings. If these are included in the estimate, groundwater accounts for a somewhat higher proportion of the total water consumption. Groundwater resources can be enhanced by infiltrating surface water onto eskers and ice-marginal formations. At present almost 10% of the total groundwater volume is produced by direct artificial recharge and this figure is steadily growing.

Most glaciofluvial aquifers are shallow unconfined groundwater systems. Particularly in coastal areas, sand and gravel deposits may extend underneath the late-glacial and post-glacial marine and lacustrine clay and silt deposits, rendering the occurrence of confined groundwater possible. The groundwater table is generally at a depth of only a few metres, but occasionally, in large eskers and ice-marginal formations, at depths of 10-30 metres. Most of the private household wells in rural areas are dug in till deposits and draw from the relatively poor aquifers that cover the bedrock nearly ubiquitously. The thickest till deposits are met at the lee-sides of hills and in valley bottoms. In coastal areas the surficial part of the till cover lying at the foot of bedrock hills is often composed of sorted or redeposited material and hosts small amounts of

perched groundwater. There are also numerous peat bogs which although cannot be used for groundwater exploitation, have a role in restricting and confining groundwater flow.

The fractured upper part of the Precambrian bedrock down to 50-200 metres hosts considerable amounts of groundwater. Wells drilled in the crystalline bedrock generally supply sufficient water to private households but cannot, except in some special cases, support community water supplies. Generally there is enough groundwater in the fractures of Precambrian bedrock composed of igneous and metamorphic "hard rocks" to feed drilled wells intended to supply water for one household only. The drilling of bedrock wells offers a meaningful alternative particularly in coastal areas and the archipelago, where pervious surficial deposits are scanty.

In summary, aquifers can be classified in the following way:

1) Eskers and ice-marginal formations with related deltas and glaciofluvial transverse ridges. In terms of the groundwater regime there are two main types of aquifer: the draining or effluent ("synclinal") type, and the losing or influent ("anticlinal") type, depending on whether the glaciofluvial aquifer gains groundwater from or loses it to the environment. Transitional aquifer types exist between these two main types.

2) Small glaciofluvial lee-side formations at the foot of bedrock hills or littoral deposits overlying glaciofluvial or till deposits or other undefined small sand deposits. These are most frequently encountered in the southwestern part of the country.

3) Partly or wholly clay-covered glaciofluvial or wave-washed till deposits in valleys. The most extensive and productive confined aquifers are the extensions of glaciofluvial eskers or deltas extending underneath clay deposits. These aquifers are met in coastal parts of the country.

4) Glacial till deposits occurring as washed ablation moraine and tighter and fine-rich basal till. The end moraine ridges, hilly hummocky moraines and elongated drumlins may contain comparatively pervious layers, which yield more groundwater than ordinary basal till. In eastern and northern Finland till deposits are often composed of several stratigraphically different layers, sometimes of sand and gravel deposits containing appreciable amounts of groundwater. Till is the most common aquifer material for private wells.

5) Igneous and metamorphic bedrock or "hard rock" aquifers, which in some parts of Finland (in central Lapland) can be divided into upper weath-

ered mantle or saprolite aquifers and lower fissured and fractured hard rock aquifers.

Groundwater in Precambrian bedrock

Shallow groundwater

Unbroken igneous or metamorphic rock is tight and does not contain groundwater. However, large blocks of hard rock are always fissured and fractured in variable degree. The irregular occurrence of fissures and fractures in the crystalline bedrock, their interconnection, and the size of their apertures or abundance of filling material constitute a complex heterogeneous and anisotropic medium for groundwater flow. Groundwater is most mobile in the most broken surficial parts of the bedrock and its movement slows down with increasing depth. The flow regime and circulation of the groundwater in bedrock can be divided into three zones (Salmi 1985). The uppermost or local zone extends to a depth of about 200 m. Below this is the intermediate zone characterized by slow flow and long pathways of circulation. It extends to a depth of 300-400 m. The lowermost zone of regional groundwater flow does not contribute significantly to the hydrological cycle. In this zone of deep groundwater, the prevailing hydraulic conditions are close to stagnation favouring the occurrence of old relict saline waters and brines.

The hydraulic conductivity (K) of open fractures and broken zones of rock may be high. The characteristic feature for the hydraulic conductivity of bedrock is that the K values may vary by several orders of magnitude from 10^{-5} m/s to 10^{-12} m/s depending on the tectonic properties of the rock units, petrographic rock type and the abundance of clayey fracture fillings (Table 1). The hydraulic conductivity of the upper part of fractured bedrock may in the most favourable cases equal the K-values typical for pervious stratified material ($<10^{-5}$ m/s). Generally, however, the K-values in bedrock (aquifers) are of the same order of magnitude as in till rich in fines (10^{-8} - 10^{-9} m/s).

The low productivity of the drilled bedrock wells is due to the rather poor overall permeability and storage ability of the open fracture system. Experimental pumpings have demonstrated strong, directional evolution of the cone of depression along the longitudinal axis of valleys, and an apparent effect on well yield and drawdown due to dewatering of the aquifer (Salmi 1985). The analysis of drawdown data from a highly productive fracture zone aquifer

Table 1. Hydraulic conductivity values (K, m/s) in various rock types.

Rock type, location	K (m/s)	Source
Granite, unfractured, Finland	10^{-10} - 10^{-8}	TVO 1992
Granite, fractured, Finland	10^{-10} - $5 \cdot 10^{-6}$	TVO 1992
Fine-grained granite, Sweden	10^{-11} - 10^{-7}	Wikberg <i>et al.</i> 1991
Småland granite, Sweden	10^{-11} - 10^{-8}	Wikberg <i>et al.</i> 1991
Stripa granite, Sweden	10^{-13} - $5 \cdot 10^{-8}$	Nordstrom <i>et al.</i> 1989b
Gneiss, unfractured, Finland	$5 \cdot 10^{-10}$ - 10^{-8}	TVO 1992
Granite gneiss, Sweden	10^{-9} - 10^{-6}	Ahlbom <i>et al.</i> 1991
Sedimentary gneiss, Sweden	10^{-11} - 10^{-7}	Ahlbom <i>et al.</i> 1991
Gneiss, fractured, Finland	10^{-7} - 10^{-5}	TVO 1992
Mica gneiss, introduced by granitic veins, unfractured, Finland	10^{-11} - 10^{-7}	Lampinen 1996
Mica gneiss, introduced by granitic veins, fractured, Finland	10^{-10} - 10^{-5}	Lampinen 1996
A complex association of serpentinite, black schist, quartzite, dolomite and skarn, Finland	10^{-10} - 10^{-7}	Ahonen 1992
Diorite, Sweden	10^{-10} - 10^{-9}	Wikberg <i>et al.</i> 1991
Mylonite, Sweden	10^{-12} - 10^{-8}	Wikberg <i>et al.</i> 1991
Greenstone, Sweden	10^{-10} - 10^{-9}	Wikberg <i>et al.</i> 1991
Gabbro, Finland	$5 \cdot 10^{-11}$ - $5 \cdot 10^{-8}$	Ahonen 1992
Arkosic sandstone, Finland	$6 \cdot 10^{-11}$ - $4 \cdot 10^{-8}$	Ahonen 1992

indicated that, when the walls of the fracture zone are reached, the initially radial groundwater flow is forced into linear flow (Leveinen 1996). Such hydraulic responses reflect the high lateral anisotropy of the fracture system and no-flow boundaries in the rock mass. Generally the anisotropy results from the higher transmissivity of the upmost part of the rock system and it decreases downward (Salmi 1985). In Norway, transmissive fractures in the upper 12 m of granite induced hydraulic conductivities two orders of magnitude higher (10^{-7} m/s) than the hydraulic conductivity (10^{-9} m/s) of background granite (Banks *et al.* 1992).

The flow of water in bedrock as well as the yields of bedrock wells are controlled by the topographic position of the well site and perviousness and thickness of the Quaternary cover. In contrast to the flat southern part of the country, the greater relative heights in northern and eastern Finland accelerate shallow groundwater circulation. Deposits of low permeability such as till or marine and lacustrine silt and clay in low-lying coastal zones restrict the recharge to underlying fractured bedrock and may partly seal the communication paths between shallow fractures. Flow from soil to rock occurs where the fractures and fracture zones in the bedrock, are hydraulically connected to a groundwater reservoir in permeable soil or to horizons of permeable and conductive material in heterogeneous soil (Olofsson 1994). When the cover is composed of permeable glaciofluvial sand and gravel, the bedrock aquifer becomes more productive because it operates within the multi-aquifer system.

The bulk of the wells drilled into bedrock are 40-

80 m deep and 110 mm in diameter. The typical yield is 500-2000 litres of water per hour. According to Rönkä (1983) the best average yields ($46 \text{ m}^3/\text{d}$) are given by drilled wells in the depth range of 41-50 m. Statistically granitic rocks yield more water than metamorphic schists and basic intrusives (Table 1).

The composition of bedrock groundwater is controlled, among other things, by the type of the bedrock, the density and hydraulic conductivity of fractures, the nature of fracture coatings and fillings (e.g. carbonates, iron sulphides, ferrihydroxides, clay minerals), and the geochemical and hydraulic characteristics of the overlying soil cover. Table 2 shows the chemical composition of shallow bedrock groundwater as compared with groundwater in overburden. Most of the water samples were collected with a hand pump installed at the top of the well or from taps supplied by an electrical pump, often through a pressurized container. This induces a danger of heavy metal contamination. However, since the drilled wells are relatively small in diameter, pumped water, if not conducted through and preserved for some time in a pressurized container, comes straight from the fractures and fissures of the bedrock and reflects the true composition of the bedrock groundwater. When drilled wells are sampled, the actual, vertical section of the bedrock represented is not generally known. In many cases bedrock groundwater is mixed with water seeping from the overburden.

The surficial groundwater occurring in the upper part of the overburden and discharging in surface drainage through springs and seeping zones is char-

Table 2. Chemical characteristics of groundwater in overburden and bedrock.

	Rain-water	Groundwater in overburden				Groundwater in bedrock		
		Springs		Dug wells, 2-10 m deep		Drilled wells with depth		
		Sand, gravel	Glacial till	Sand, gravel	Glacial till	<50 m	50-100 m	>100 m
pH	4.6	6.3	6.1	6.4	6.3	6.7	7.1	7.2
EC (mS/m, +25°C)	2.5	7.4	6.5	16.1	18.6	26.0	29.5	28.6
Alkalinity (mmol/l)	-	0.36	0.31	0.61	0.77	1.27	1.66	1.70
SO ₄ ²⁻ (mg/l)	1.0	6.5	5.5	12.5	14.0	15.3	17.0	16.0
Cl ⁻ (mg/l)	0.4	3.0	2.4	7.4	8.2	12.0	13.0	11.8
Ca ²⁺ (mg/l)	0.4	5.5	4.9	14.0	16.6	20.0	21.0	21.0
Mg ²⁺ (mg/l)	0.1	1.6	1.4	2.8	3.5	6.0	5.6	5.5
Na ⁺ (mg/l)	0.3	3.0	2.7	5.6	6.8	10.0	16.0	18.5
K ⁺ (mg/l)	0.2	1.1	1.1	3.2	4.1	3.4	3.1	2.4
No. of samples	35	~740	~2500	~1300	~3990	~1270	~1100	~300

acterized by its acidity and small amounts of dissolved load (Table 2). The composition is closely related to that of rain water although all the concentrations of dissolved solids are 5-10 times as great in groundwater. Typical components with geogenic origin are silicic acid (SiO₂), F⁻, Ca²⁺, Mg²⁺ and K⁺, while SO₄²⁻, Cl⁻ and Na⁺ are partly derived from atmospheric wet and dry fallout. Shallow groundwater sampled from dug wells, generally 3-10 metres deep, contains more dissolved solids than spring water.

Most of the groundwater occurring in the upper part of fractured and fissured bedrock is recharged by shallow groundwater in the overburden. Owing to confining overburden, most often composed of till and fine-grained bottom sediments (clay and silt) or peat deposits, as well as to longer flow routes and transit times, bedrock groundwater contains a higher load of dissolved solids than groundwater in the overburden (Table 2). The rock type controls the type and amounts of dissolved elements and compounds. The highest concentrations are found in groundwater migrating in bedrock systems composed primarily of mafic and ultramafic components or/and rich in carbonates and sulphides. As far as the medium-deep common household wells drilled into bedrock are concerned, the average concentrations increase as a function of well depth. In coastal areas of Finland, however, relict salts in bottom sediments and in fractured bedrock have a much greater effect on the overall chemistry of bedrock groundwater than do structural or petrological peculiarities of the bedrock.

Deep groundwater

A project dealing with deep-seated groundwater was initiated by the Geological Survey of Finland in

1985 to collect basic data for planning of deep disposal of nuclear waste in crystalline bedrock (Blomqvist *et al.* 1987, Nurmi *et al.* 1988). Special sampling methods were developed to collect water from small-diameter bore holes drilled for ore exploration (Nurmi & Kukkonen 1985, Laaksoharju *et al.* 1995). The deepest drill hole in Finland, which is located at Outokumpu, has a total length of 1250 m and vertical depth of 1150 m. Most of the exploratory drill holes are much shallower.

The results of hydrogeochemical investigations have shown that in many of the deep drill holes there is a clear-cut stratification of water layers in the water column from fresh water at the top to brackish or saline groundwater at the bottom. The interface is generally sharp and its vertical position in the drill hole may fluctuate widely due to hydrometeorological changes (cf. tube sampling and packer sampling technique). The fresh water layer is composed of Ca-HCO₃⁻, Ca-Na-HCO₃⁻ and Na-Cl-HCO₃⁻-type water. In some cases Cl and SO₄ concentrations are dominating.

The chemical composition of the upper part of the water column is generally in concert with the shallow groundwater in the neighbourhood. In the superficial part of the fresh water column HCO₃⁻ concentrations are proportionally high. Deeper down the brackish and saline water is mainly of Na-Ca-Cl- or Ca-Na-Cl-type and seldom of Na-Cl-type groundwater (Table 3). In cases Mg and SO₄ concentrations are high. The SO₄²⁻ concentrations derive from local occurrences of sulphide or gypsum minerals (Blomqvist *et al.* 1987). Mafic and ultramafic rocks such as amphibolites, gabbros, peridotites and serpentinites enhance the Ca and Mg concentrations in water. The effect is more pronounced in weakly mineralized than in saline waters or in brines. Carbonate rocks (skarns) and

Table 3. Chemical characteristics of deep groundwater in bedrock. Data from Blomqvist *et al.* (1986), Blomqvist *et al.* (1987), Halonen *et al.* (1990) and Nurmi *et al.* (1985).

Rock type, location	Sampling depth m	pH	EC mS/m	Ca ²⁺ mg/l	Mg ²⁺ mg/l	Na ⁺ mg/l	K ⁺ mg/l	SO ₄ ²⁻ mg/l	Cl ⁻ mg/l	HCO ₃ ⁻ mg/l
Mica gneiss, black schist, serpentinite, skarn, quartzite Outokumpu, Eastern Finland	474	8.2	1650	2900	14	1300	7	1	6130	23
	809	8.5	2230	3900	13	1500	7	1	8900	21
	1065	8.5	3880	5700	1100	3200	32	2	16800	34
Serpentinite, mica gneiss. Miihkali, Eastern Finland	490	10.2	4000	8650	18	5130	49	187	26300	69
	946	8.9	12040	16700	228	38600	520	514	78700	189
Hornblende gabbro, mica gneiss. Kerimäki, Eastern Finland	411	11.2	369	160	3	540	7	1	1084	11
	697	8.7	954	360	26	1600	15	1	3240	7
Mica and hornblende gneisses, skarn. Parainen, Southwestern Finland	409	8.7	187	120	20	240	7	180	406	23
	488	8.0	1022	720	130	1500	37	370	3680	12
Sandstone, Pori, Southwestern Finland	201	7.8	800	650	13	1100	2	167	2870	32
	540	6.8	8400	36000	81	9500	5	23	73700	5
Unmetamorphosed silt and shale. Liminka, Central Finland	400	7.4	2050	1600	240	4000	24	2700	7410	17
	720	6.8	4030	5500	760	8200	51	4100	22140	98

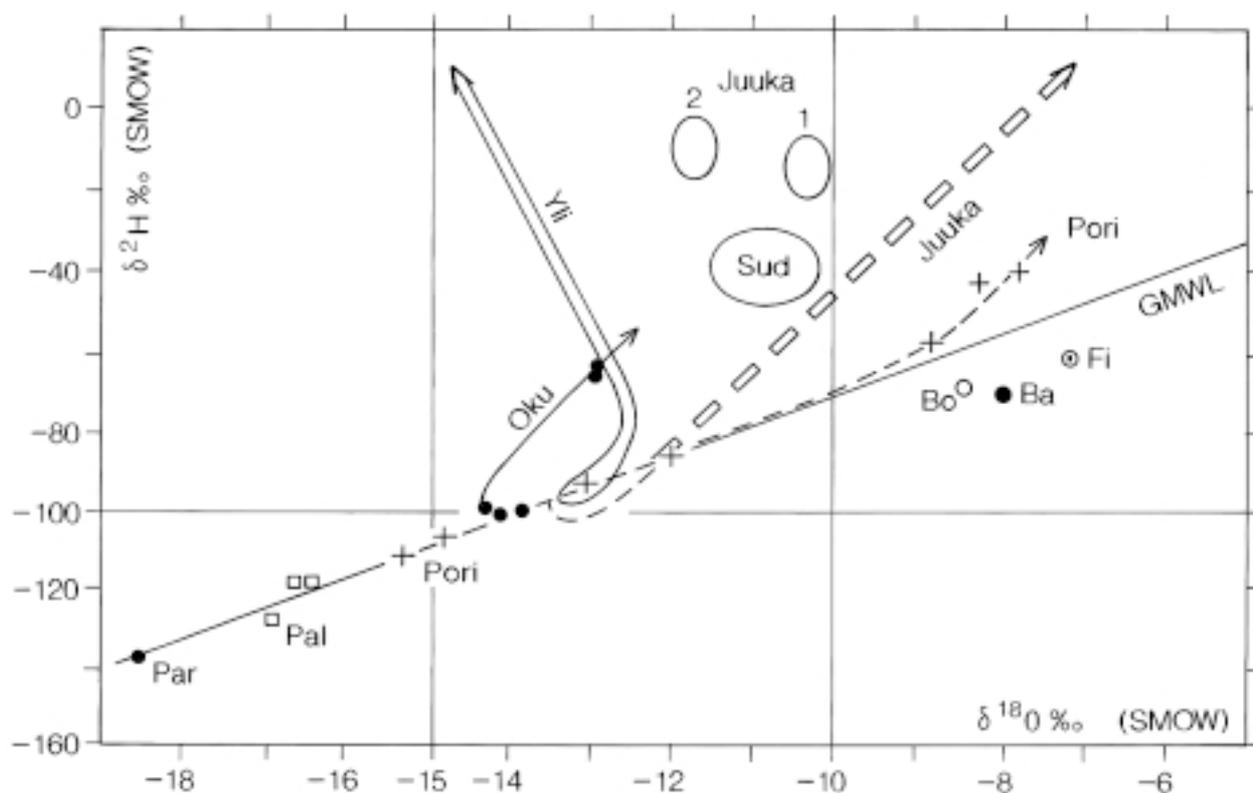


Fig. 2. Stable isotope plot ($\delta^2\text{H}/\delta^{18}\text{O}$) for representative samples of deep-seated groundwater collected from small-diameter exploratory drill holes in Finnish Precambrian bedrock. The isotope composition of the most saline groundwaters and brines deviates to the left of the global meteoric water line (GMWL) with increasing depth and salinity. Oku = Outokumpu H 741, Sukkulansalo. Yli = Ylivieska R-313. Juuka = Juuka DH 114. Pori = Pori DH Po-1, Pinomäki. 1. and 2. Shallow and deep Juuka BH 116. Pal = Palmottu, Nummi-Pusula. Par = Parikkala (drilled well). Sud = Sudbury, Canada. For reference plots are also presented for Baltic Sea (Ba) and Gulf of Bothnia (Bo). Material from Fritz and Frapè 1985, Nurmi *et al.* 1985, Blomqvist *et al.* 1987, Halonen *et al.* 1990, Blomqvist *et al.* 1995 and Lamminen 1995.

gypsum- and sulphide-rich occurrences have a particular impact on water quality. A part from geochemically reactive rock types (as noted above), the rock type has only a minor impact on the general composition of deep-seated saline groundwater and brines.

The saline waters contained in Finnish bedrock often release gas, in most cases mainly nitrogen but sometimes significant amounts of methane as well (Nurmi *et al.* 1988). Exceptionally, the evacuated CH₄ in the deep drill hole at Outokumpu varied from 65% to 82%. In addition, helium may range from 2% to 5% in volume in some deep drill holes (Lahermo & Lampén 1987).

The origin of the brackish and saline groundwater, and in a few cases of brines, occurring in Precambrian bedrock of the Fennoscandian Shield is controversial. Water-rock interaction has served to increase the dissolved load of deep-seated groundwater. The relict salts originating from the postglacial Litorina Sea which inundated large coastal areas 5000 to 7000 years ago, the still larger interglacial Eem Sea, dating back more than 125 000 years, and much older unknown sea phases may also explain part of the salinity of deep groundwater. The two sources of salinity mentioned above are nevertheless the most probable ones. The leaching of salts from fluid inclusions common in many types of rocks may not be adequate to explain the chemistry of strongly saline groundwater (Nordstrom *et al.* 1989a).

The stable isotope composition of deep-seated groundwater and brines, in particular, deviates conspicuously from that of the fresh and brackish superficial bedrock groundwater which, in terms of the ratio of hydrogen and oxygen isotopes, δD (²H) versus $\delta^{18}O$, closely resembles fresh groundwater in overburden and rain water. The fresh and brackish groundwater plots predominantly along the GMWL line (Blomqvist *et al.* 1987). The isotope ratios of fresh and brackish groundwater cluster along the lower end of the water line (δD -130 to -80‰, $\delta^{18}O$ -17 to -12‰), while more saline waters and brines, much heavier in their isotope composition, are located at the upper end of the water line (δD -80 to -40‰, $\delta^{18}O$ -12 to -8‰) (Fig. 2). The values of stable isotopes for very saline groundwater and brines clearly deviate from other waters grouping along the GMWL by forming distinctive groups above the line and being characterized by strong enrichment in deuterium (δD -80 to 0‰) concentrations, and in some cases also in oxygen ($\delta^{18}O$ -15 to -8.3‰) (Halonen *et al.* 1990).

Chemical peculiarities of bedrock groundwater in Finland

Fluorides

The F⁻ concentration in rapakivi granites varies in the range 0.20-0.42% and that in ordinary granites in the range 0.05-0.14%. Concentrations in other igneous and metamorphic rocks are typically only 0.01-0.05%. Among the most F⁻-rich components is fluorite, which commonly occurs as an accessory mineral in rapakivi. Fluorides also occur in the apatite, biotite and amphiboles commonly present in rapakivi granite as well as in topaz and tourmaline (Rankama and Sahama 1950). In OH⁻-bearing minerals, such as micas and amphiboles and sometimes pyroxenes and chlorites, the F⁻ concentrations may range from 0.2 to 1.1% (Simonen & Vormaa 1969). Fluorine occurs in water as fluoride ion (F⁻) and as complexes formed with inorganic and organic ligands. One of the most important inorganic F⁻-complexes is AlF₆³⁻, which may contribute to the mobilization of aluminium into water in F⁻-rich rapakivi areas.

The F⁻ concentrations in groundwaters are distributed unevenly across the country. In the areas covered by rapakivi granites, F⁻ concentrations in water pumped from wells drilled into bedrock generally vary between 0.5 and 3.0 mg/l. These F⁻ concentrations are 1 to 2 orders of magnitude higher than elsewhere in the country. Hence, the median and mean values (0.10 mg/l and 0.42 mg/l, respectively) for the whole of the country are not representative. The highest F⁻ concentrations (1.5-3.0 mg/l) are met in Kymi Province in southeastern Finland (Viborg rapakivi batholith), while in the rapakivi areas of southwestern Finland and in Ahvenanmaa (Åland) (Ahvenanmaa batholith) the F⁻ concentrations are somewhat lower. The flow of the continental ice sheet has spread rapakivi material mixed in till from the Vehmaa and Laitila rapakivi massives throughout southwestern Finland down to the south coast (e.g. Hanko area), where some wells may contain appreciable amounts of fluorides. Part of the fluorine rock material may be derived from the bottom of the Bothnian Sea and from small rapakivi occurrences on the Swedish Bothnian coast (Lahermo & Backman 1999). Small local F⁻-rich areas characterized by coarse-grained granites chemically similar to rapakivi are found at Onas and Bodom in southern Finland, at Nattanen, Pomovaara and Hetta in central Lapland and at Vainospää in northern Lapland.

Fluorine is an important microelement, needed

by man and higher animals as a constituent of teeth and bones. Unlike most of the other essential elements, a large portion of fluorine is ingested from drinking water. Health problems arising from excess fluoride intake (dental and skeletal fluorosis) have not been recorded in Finland. On the other hand, in most of the country F^- concentrations in drinking water are less than the recommended levels.

Uranium and radon

In the Fennoscandian Shield, in Finland and Sweden, the Proterozoic highly differentiated leucocratic alkali-granites with relatively low Ca are among the most uraniumiferous rocks encountered anywhere (Wilson & Åkerblom 1982). These granites are often enriched in F, Mo, Sn and W. In Finland, the highest total U concentrations (4-8 ppm) in the fine fraction of till, reflecting the composition of the underlying bedrock, are found in granite areas to the north and northwest of the Wiborg rapakivi granite batholith and in the north-western and western parts of the pluton itself (Fig. 1). Besides the granites, migmatites intermingled with granite veins and granodiorites in southern and southwestern Finland show elevated U concentrations.

In oxidizing environment uranium migrates in water mainly as reasonably soluble uranyl ion or UO_2^{2-} . The key control on dissolved U concentrations appears to be redox potential, while concentrations of U in rock and the residence time and composition of groundwater seem to be less important (Gascoyne 1989). In the pH range 8 to 10, which is frequently met in deep groundwater in crystalline bedrock (see e.g. Nurmi *et al.* 1988, Blomqvist *et al.* 1989), U may also occur as carbonate complexes. The availability of dissolved CO_2 enhances the dissolution of uranium. The maximum U solubility in groundwater from a typical granite under CO_2 -rich and oxidizing conditions is about 1 g/l (Paquette & Lemire 1981).

Several thousand Rn and U determinations have been made by both the Geological Survey of Finland (GSF) and the Finnish Centre for Radiation and Nuclear Safety (FCRNS), mainly in the south of the country, where the concentrations are the highest

(Asikainen 1982, Salonen 1987, Juntunen 1990, Lahermo *et al.* 1990). High U and Rn concentrations in groundwaters are associated with granites and migmatites with abundant granite and pegmatite veins (Fig. 1).

The hydrogeochemical mapping of Finnish groundwaters carried out by the GSF shows that the median U concentrations in spring waters, in waters from dug wells and in waters from wells drilled into bedrock are all below 1 $\mu g/l$ (Lahermo *et al.* 1990). Because of the strongly skewed distribution caused by sporadically high U concentrations, however, the arithmetic means are appreciably higher: 1.4 $\mu g/l$ (1294 samples), 1.6 $\mu g/l$ (3553 samples) and 21.2 $\mu g/l$ (1027 samples), respectively. In the somewhat larger sample population of bedrock wells covering southern Finland only (1388 samples, includes some of the same material as the country-wide mapping), the median and arithmetic mean values are 5 and 73 $\mu g/l$, respectively (Juntunen 1990). In areas of the most uraniumiferous granites, the U concentrations in bedrock groundwater are frequently of the order 100-1000 $\mu g/l$, whereas the highest values recorded in Finland are 15-20 mg/l (Asikainen 1982, Juntunen 1990). The U concentrations in groundwater from bedrock and the total U concentrations in the fine fraction of till show a fairly good areal correlation.

Radon is the most abundant dissolved radioactive component of Finnish groundwaters. In a survey conducted by the FCRNS, the arithmetic mean of 961 samples from springs and dug wells was 92 Bq/l, while the mean of 2065 samples from drilled bedrock wells was as high as 1020 Bq/l (Salonen 1987). In a study carried out by the GSF, the median and arithmetic mean values of Rn concentrations of 1765 bedrock well samples were 215 and 631 Bq/l, respectively (Juntunen 1990). Some twenty samples gave concentrations exceeding 5000 Bq/l, with a maximum of 43000 Bq/l. The comparatively high Rn concentrations in the bedrock groundwater are partly explained by the over-representation of samples from the southern part of the country, which is characterized by several positively anomalous areas.

As in the case of uranium, the highest Rn concentrations (median 349 Bq/l, 298 samples) were found in groundwater from granites and migmatites rich in granite veins in southeastern Finland (Fig. 1). The

Table 4. The statistics of arsenic concentrations ($\mu g/l$) in groundwater from overburden and bedrock.

Group	Count	Minimum	Median	Mean	Maximum	Std. Dev
Groundwater from overburden	1197	0.0	0.22	0.68	138	4.14
Groundwater from bedrock	472	0.0	0.65	10.50	1040	68.40

bedrock groundwater in granodiorite areas also exhibited somewhat elevated Rn concentrations. The high U concentrations in water do not, however, invariably mean high Rn activities as suggested by the low coefficient of correlation ($r = 0.27$). This finding can be understood if one remembers that extremely mobile gaseous ^{222}Rn is short-lived (3.82 d) compared with its immediate predecessor in the same radioactive decay series, ^{226}Ra (1620 a), and the parent of the series, ^{238}U , and its daughter nuclides ^{234}U and ^{230}Th , whose half-lives range from 475 Ma to 80 Ka (Asikainen 1982, Hess *et al.* 1985). It is therefore not surprising that there is also a discrepancy between U and Rn values in waters from the Wiborg rapakivi granite area, where conspicuous anomalous areas of dissolved U do not show up as elevated Rn concentrations in groundwater (Fig. 1).

No conclusive upper permissible limits of U and Rn have been set for drinking water in Finland so far. A safety guide provided by FCRNS suggests that the maximum concentration of radon in household water should be 300 Bq/l provided no dose is caused by other radionuclides (Anon. 1993).

More than one fifth of the population of Finland, or about 1.0-1.2 million people, rely on their own drinking water sources, at least on a temporary basis in summer dwellings. Depending on the area, an estimated 5 to 20 % of this private water intake is from bedrock wells, where excessive U concentrations are sometimes encountered. High concentrations are particularly common in granite areas in southern Finland, where high U and Rn concentrations in groundwater constitute a notable health risk. Although excess Rn is known to exacerbate the risk of lung cancer, and although the radiation activity exposures are unusually high in southern parts of the country (the Lapinjärvi area in particular), no causal link has yet been established. An estimation 40-60% of lung cancer cases in Finland are nevertheless thought to be due to Rn exposure.

Arsenic

The elevated concentrations of arsenic (Table 4) in groundwaters pumped from single-household wells in rural areas are a source of growing concern in Finland. The alarm was triggered by the lowering of the upper permissible As level in potable water from 50 to 10 $\mu\text{g/l}$ according to the new EC directive (equivalent to the WHO standards), by the recent findings of high As concentrations in bedrock groundwater (as much as 1-2 mg/l), and by the

information from international medical studies suggesting that arsenic is a highly carcinogenic metal. It has been found that the naturally high concentration of As in drilled wells in southwestern Finland is reflected in As concentrations in the hair and urine of those exposed (Kurttio *et al.* 1995). In view of this situation, several areal hydrogeochemical mapping projects were commenced by the Geological Survey of Finland in a few areas of presumed As risk.

The chemical composition of bedrock and soil and the hydrogeochemical conditions control the level of arsenic in groundwater. The values are highest in volcanic-sedimentary rock areas in southern and western Finland and in central Lapland, and are lowest in As-poor areas of Archaean granite gneisses in eastern and northern Finland. Bedrock wells with high As concentrations are mostly found in hydrothermally altered domains in Precambrian bedrock that exhibit elevated or high As concentrations and host mesothermal gold deposits.

Drilled wells with As in excess of 100 $\mu\text{g/l}$ are concentrated in bedrock areas where As minerals (arsenopyrite, FeAsS) occur on fracture wall surfaces, implying that the effectiveness of the water - arsenopyrite interaction is a major factor governing the As concentrations in bedrock groundwater (Idman 1996). Arsenopyrite occurs most frequently in sulphide mineralizations associated with gabbros and amphibolites. Under natural conditions arsenic is also bound to Fe-, Mn- and Al-hydroxides and hydrous oxides and is adsorbed to fine-grained mineral particles, especially clay minerals (Edmunds and Smedley 1996). The As concentrations of till, which veneers most of the bedrock, also are reflected in bedrock groundwater.

The As concentrations differ by several orders of magnitude both regionally and in nearby wells. Highly arsenous well water is most likely to be encountered in As-anomalous areas in till and bedrock. Hence, it is important to establish the local geological conditions, particularly when drilling wells into bedrock. The risk of encountering anomalously high As concentrations in natural and captured springs and in shallow wells is low.

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ANOMALOUSLY HIGH ARSENIC CONCENTRATIONS IN SPRING WATERS IN KITILÄ, FINNISH LAPLAND

by

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Introduction

During the Northkalott Project carried out in 1980-1986 in Finnish, Swedish, and Norwegian Lapland, and later during geochemical mapping of till, stream water, and organic stream sediments throughout Finland, anomalously high As concentrations were recorded in a 80 km x 80 km area in Finnish Lapland (Björklund et al. 1986, Koljonen 1992, Lahermo et al. 1996). Arsenic concentrations in groundwater in the area were not measured since analytical methods allowing accurate determination of low concentrations of arsenic in water were not available at the Geological Survey of Finland (GTK) until just a few years ago. The ICP-MS method became available in 1991 (Kallio 1994). Before the present study began, only a few records of As concentrations from Lapland had been entered in the GTK groundwater database. In August 1998, sampling of groundwater, stream water, organic sediments and rocks was carried out in an area with anomalously high As concentrations in till fines (Fig. 1). Water and sediment sampling in the study area will be continued in August 1999.

The objectives of the study are as follows:

- 1) To obtain reliable data on the chemical composition of groundwater in an area of natural forested terrain with anomalously high As concentrations in till and bedrock.
- 2) To evaluate the applicability of geochemical data for gold exploration purposes.
- 3) To gather information on harmful As com-

pounds dissolved in water and their sorption onto various surface-active compounds (organic sediment) occurring in natural conditions.

Sampling and analytical methods

Samples of the pilot phase of the present study were collected during the last two weeks of August 1998. This time is considered to be the most stable as far as fluctuations in the groundwater table and concentrations of dissolved components in water are concerned. During sampling, however, persistent rains raised the groundwater table and streams were in flood, conditions quite exceptional for that time of year. Water samples were collected from natural springs and from wells either dug into the overburden or drilled into bedrock. In addition, several headwater streams were sampled. Besides water, organic sediment samples were taken from springs and streams.

For the measurement of physico-chemical properties and anion concentrations, 500-ml polyethene bottles were filled with untreated water. For cation analyses 100 ml water was first filtered through disposable 0.45- μm membrane with the aid of plastic syringes, which also were used only once. These samples were preserved by adding 0.5 ml suprapur nitric acid. Temperature, pH and electric conductance were measured and water turbidity and colour were estimated at the sampling site. More detailed analyses were carried out in the chemical laboratory at GTK. In the untreated water samples (no filtering

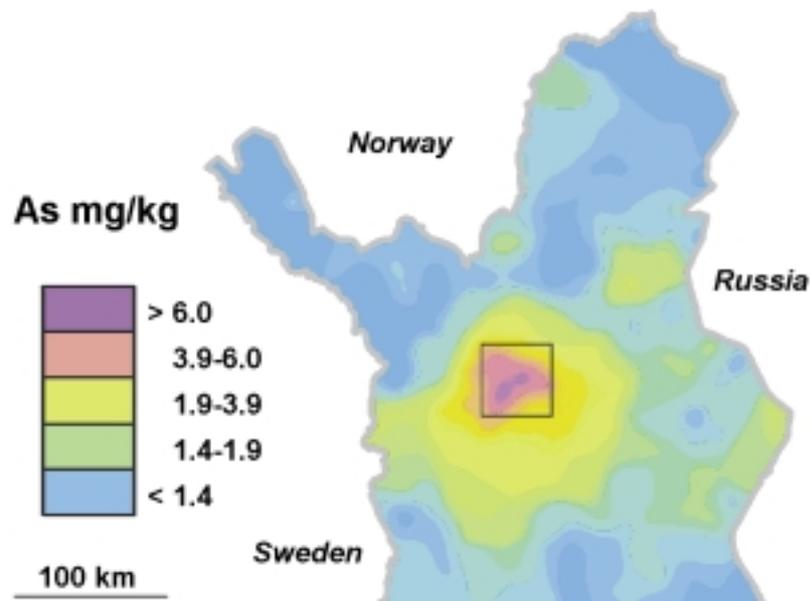


Fig. 1. The study area in Finnish Lapland, an area known to be anomalous with respect to arsenic concentrations in till fines.

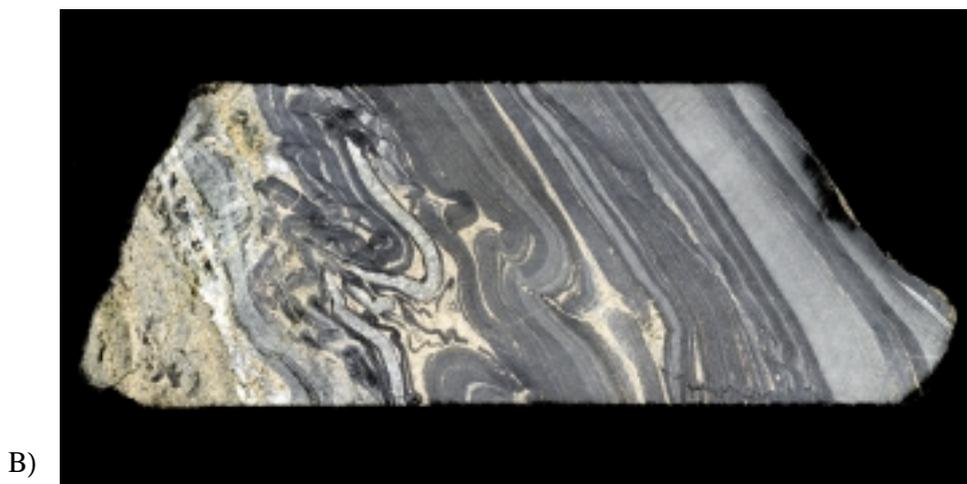
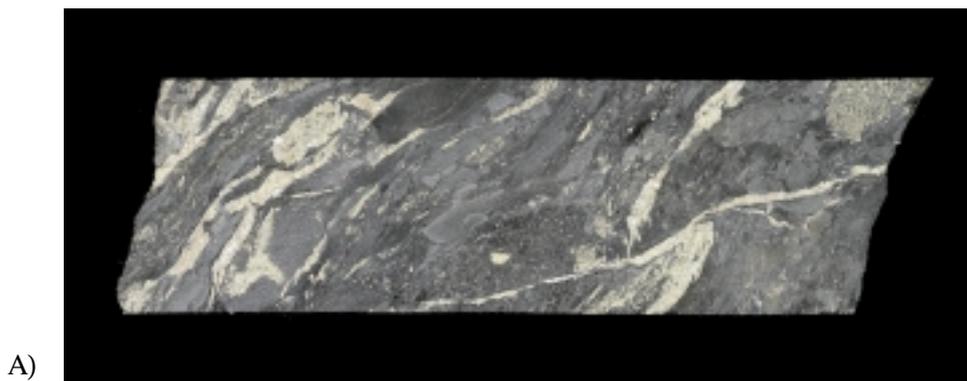


Fig. 2. A) Black shale from the Haurespää prospect, drill core 451, depth 119.35 m. B) Black shale from the Tepsa prospect, drill core 412, depth 197.90 m. The precursor muds of these black shales were deposited on the seafloor under anoxic conditions some two billion years ago and contain hydrothermal addition of elements such as sulfur and arsenic. Haurespää and Tepsa prospects are located in the southern part of the As anomaly shown in Fig. 1. Photos: J. Väättäin.

or preservation), pH and specific conductance were measured potentiometrically. Alkalinity (HCO_3^-) and KMnO_4 consumption were determined titrimetrically by standard methods. Anions (SO_4^{2-} , Cl^- , F^- , Br^- , and NO_3^-) were determined by ion chromatographic method, and phosphate (PO_4^{3-}) was determined spectrophotometrically. Cations were determined in filtered and preserved samples by ICP-AES and ICP-MS methods.

Organic sediments were collected with a nylon net scoop with a mesh diameter 0.06 mm. About 500 ml of organic sediment, composed of varied proportions of allochthonous organic detritus and, sometimes, fine-grained mineral material and secondary iron precipitates, was collected by stirring the bottom sediment up into the water body and scooping up the suspended material. The sediment samples were packed into polyethene plastic bags. The organic sediments were dried by applying freezing techniques and the < 2 mm fraction was sieved for analysis. The prepared fraction was leached with 7-M nitric acid, which dissolves the organic material by simultaneously releasing the adsorbed and complexed metal cations into solution. Determinations were carried out by ICP-AES or ICP-MS methods depending on the detection limits of the elements (see detection limits in Lahermo et al. 1996, p. 29).

Results

Bedrock

Water and sediment sampling covered two separate areas consisting mainly of volcanic rocks and schists (Lehtonen et al. 1998): in the south, part of the Jeesiö 1:100 000 map sheet number 3712 extending from Virttiövaara to Haurespää (ca. 340 km²), and in the north, part of the Kiistala map sheet number 2743 and the Suasselkä map sheet number 2744 extending from Kolvalehto to Yliläki (ca. 220 km²). Both areas are potential for gold prospecting, and several gold showings and occurrences have been found, for example at Suurikuusikko (Eilu 1999). The Porkonen-Pahtavaara banded iron formations are situated close to the study area (Hackman 1925). One reference sample was collected to the south of the study area at Kelontekemä, where the bedrock is composed of granitoids.

Black shales were met in some of the drilled profiles, for example in the Tepsa and Haurespää prospects (Fig. 2). Black shales containing abundant sulfides such as pyrite, pyrrhotite, and arsenopyrite weather more easily than most of the

Finnish bedrock, especially if broken and exposed. Arsenic concentrations in the black shales in the study area were elevated relative to the average for Finnish black shales 2 Ga in age (Loukola-Ruskeeniemi, unpubl. data, Fig. 3A). Sulfide-rich black shales are suspected of constituting an environmental risk, both in Finland and in other countries, when they are in contact with surface waters and groundwater (Loukola-Ruskeeniemi 1992, Loukola-Ruskeeniemi et al. 1998, Pasava et al. 1995).

Groundwater

Most of the arsenic dissolved in groundwater is derived from the overburden and underlying Precambrian bedrock. A small part may have been introduced into the global element cycle as emanations from distant volcanic activity and from human sources such as industrial emissions. In Finland, the median concentration in shallow dug wells is 0.22 µg/L while the maximum is 138 µg/L (number of samples 1197). The mean, median and maximum values for wells drilled into bedrock are 10.5 µg/L, 0.65 µg/L, and 1040 µg/L (number of samples 472), respectively (Backman et al. 1996). Arsenic anomalous areas in till fines below 0.06 mm in grain size (Tarvainen 1996) neatly coincides in the studied area with the areal distribution of the elevated As concentrations in drilled wells.

High As concentrations exceeding the upper permissible concentration of 10 µg/L for household water, set by the Ministry of Social Affairs and Health (Anonymous 1994), are more common in wells drilled in bedrock than in dug wells. More than 15% of samples taken from drilled wells represented in the GTK groundwater database (of altogether 100 samples from Uusimaa, Häme, and Pohjois-Karjala in 1994) exceed the set limit (Backman et al. 1994). In natural and captured springs and shallow dug wells the limit was exceeded in only 1% of cases. In the Kittilä study area the As concentrations in well waters were, with a few exceptions, below 1 µg/L. A few elevated As concentrations have been recorded in other parts of Lapland as well: 5.6 µg/L and 7.1 µg/L in Rovaniemi and in the surroundings of Kemi and Tornio from 4 µg/L to 9.9 µg/L (Ulpu Väisänen, unpublished data).

In August 1998, a total of 30 groundwater samples were collected in the study area: from drilled bedrock wells (9), a shallow dug well (1), and natural springs (20). The As concentrations in drilled bedrock wells varied from <0.05 µg/L up to 3.41 µg/L, while the arithmetic mean was 1.06 µg/L

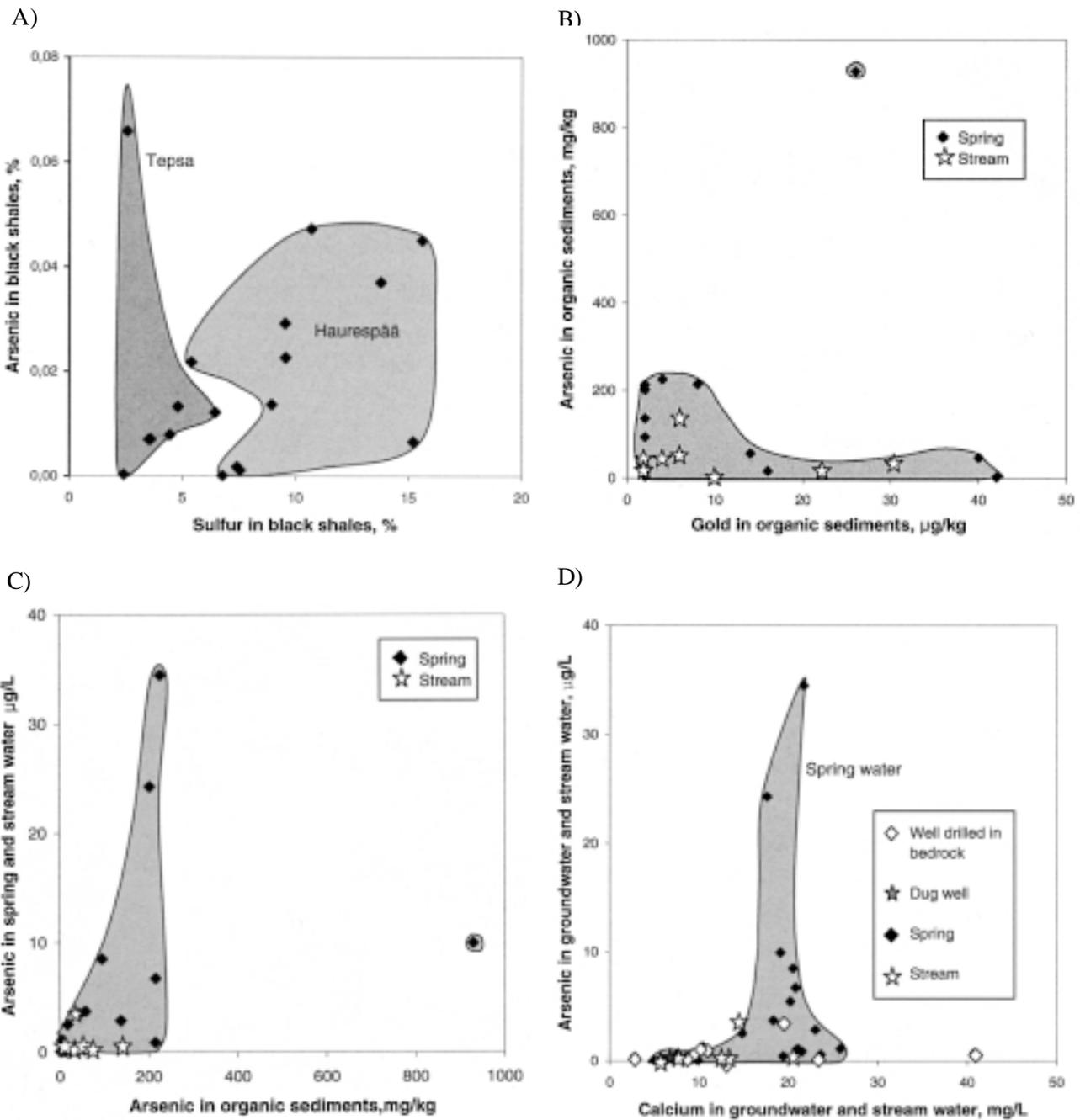


Fig. 3. A) Arsenic and sulfur concentrations in black shales in the Tepsa and Haurespää prospects. B) Arsenic and calcium concentrations in groundwater and stream water. The highest As concentrations were met in spring water in the northern part of the study area. Well waters were everywhere potable. C) Arsenic and gold concentrations in organic sediments in springs and streams. Gold concentrations were not determined for water samples. On the whole, the As and Au concentrations do not correlate with each other. An exception is a spring in the northern part of the study area which exhibited both elevated As and elevated Au concentrations in organic sediment. D) Arsenic concentrations in spring water and stream water compared with those in organic sediments. Springs from the northern part of the study area exhibit elevated As concentrations both in water and in organic sediments.

and the median 0.66 µg/L. The concentration range parallels the general level encountered in Finland. The upper permissible arsenic level (10 µg/L) was not exceeded in any drilled bedrock well in the study area. Hence, according to this preliminary reconnaissance study the household waters do not pose a health risk for the local population. The value recorded in the single dug well sampled in the area was only 0.27 µg/L arsenic. In the natural springs, in turn, As concentrations ranged from <0.05 µg/L up to 34.5 µg/L, with an average concentration of 5.9 µg/L and median value of 1.23 µg/L. The highest allowable As concentration was exceeded in two of the sampled springs (24.3 µg/L and 34.5 µg/L) (Fig. 3B).

Headwater streams

A total of 9 stream water samples were collected during August 1998. Arsenic concentrations in headwater streams are lower than those in springs in the study area (Fig. 3B). In general, arsenic is more abundant in groundwater than in surface waters (Backman et al. 1994, Lahermo et al. 1998). The geographical distribution of arsenic in stream waters suggests that the concentration level depends mainly on the composition of overburden and bedrock. Concentrations are elevated in an extended belt stretching from southeastern Finland southwest up to the Raahe area. The median value of As in stream water in Finland is 0.36 µg/L (Lahermo et al. 1996).

Organic sediments

Arsenic concentrations in the 24 organic sediment samples ranged between 1.3 mg/kg and 929 mg/kg. The arithmetic mean was 110 mg/kg and the median 40 mg/kg (Fig. 3C). These concentrations are high compared with those for organic stream sediments recorded in the nation-wide mapping project, where typical As concentrations in areas composed of mafic intrusive rocks and schists, including greenstones, were only 5.36 mg/kg (Lahermo et al. 1996). Elevated As concentrations both in spring water and in organic sediments are characteristic of the northern part of the study area (Fig. 3D). There is some correlation between Ni, Cu, Co, Mn, Fe, Ba, and V concentrations in stream water and organic stream sediments, but the correlations are much weaker between spring water and organic sediments at the bottom of the springs.

Conclusions

During the pilot phase of the present study, elevated (up to 34 µg/L) arsenic concentrations were encountered in natural spring waters in a pristine area in Finnish Lapland in the vicinity of known gold occurrences. We suggest that gold occurrences and showings may be prospected in Finnish Lapland by following arsenic and gold anomalies in organic sediments and arsenic anomalies in natural spring and stream waters.

Arsenic is also a toxic element which may have serious health effects for populations exposed to high concentrations in drinking water. In a number of clinical investigations, drinking water with high As concentrations has been found to elicit symptoms of chronic arsenic poisoning (Gorby 1994, Niu et al. 1997). The toxicity of As is a function of the prevailing arsenic speciation. In general, inorganic As compounds can be considered more toxic than organic As compounds. Elevated As concentrations encountered in natural spring waters in the Kolva-lehto-Ylilaki area in Kittilä in Finnish Lapland are not, however, a risk for human health since the area is very sparsely populated. Moreover, no household waters studied in the area contained higher than recommended As concentrations.

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EXTREMELY HIGH CONCENTRATION OF ARSENIC AND ITS SPECIATION IN GROUNDWATER FROM BANGLADESH

by
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Introduction

Arsenic of natural origin in groundwater occurs mostly in inorganic forms, where the oxidation state of arsenic is either +3 or +5. The distribution of different species depends on oxidation-reduction conditions and pH-value of water. The understanding of arsenic speciation is important for the evaluation of mobility and leachability of arsenic from soils and sediments by water.

Speciation is of critical importance for arsenic compounds because organic and inorganic forms co-exist in our environment and differ largely with respect to their toxicity (Leonard 1991). Many inorganic and organic As species constitute a complicated interactive system which have an effect on mobility, sorption and ecotoxicity. In fresh water and sediments arsenic occurs in the oxidation states of -3, 0, +3 and +5, which can be changed in the geological environment by chemical and biological processes (Newland 1982). The most common As(+3) and As(+5) species are arsenites (AsO_3^{3-}) and arsenates (AsO_4^{3-}), respectively. Arsenites are more mobile speciation forms which occur in slightly reducing conditions (Moore & Ramamoorthy 1984; Blanck *et al.* 1989). Trivalent arsenic is regarded as the more toxic form of inorganic arsenic than pentavalent arsenic (Hindmarsh & McCurdy 1986).

Because of geomedical implications an increasing number of researchers are carrying out arsenic speciation studies. Analytical methodology for the

speciation of arsenic in environmental and biological samples has been studied in detail by Burguera and Burguera (1997). Gregory *et al.* (1998) have studied the arsenic speciation in geothermally impacted groundwater and surface water at the La Primavera Caldera, Guadalajara, Mexico. Arsenic speciation methods and specifically drinking water have been reviewed by Crecelius and others (1998). Arsenic speciation in drinking water matrices via ion chromatography inductively coupled plasma mass spectrometry has been carried out in the USA by Carol *et al.* (1998). In Yellowstone biota, arsenic speciation studies have been carried out by Koch *et al.* (1998) in order to assess the impact on the terrestrial environment. The study on the stability of arsenic species in urine and water has been carried out by Chris *et al.* (1998). Jozsef and Klara (1998) have studied the chemical speciation of arsenic ions from aerosol sediments and fly ash samples.

The severe arsenic contamination of groundwater in Bangladesh has had a catastrophic effect on the health of the people. The present study has been planned in order to know the degree of As contamination and speciation of arsenic in groundwater from Bangladesh.

Geology of the study areas

Bangladesh occupies the greater part of the Bengal basin and covers part of the Himalayan piedmont plain and the eastern and southeastern hill

ranges of Sylhet, Chittagong and Chittagong Hill tracts. Tectonically, the Basin can be subdivided into a stable area to the west and northwest and the synclinal foredeep to the east and southeast. On the stable shelf the 1-8 km thick sediment sequence from Permian to Recent age has accumulated. By contrast, in the tectonically more active Bengal Foredeep, a more than 16 km thick sequence of Tertiary sediments has been laid down (Paul & Lian 1975). Sandstone, siltstone, shale and claystones are the main rock types existing all over the country.

The alluvium deposits contain mainly silt, sand, gravel and clay. The weathered sandstones, siltstones, shales and claystones in the geosynclinal foredeep region contain mainly quartz together with minor amounts of muscovite, plagioclase, K-feldspar, biotite, carbonate, epidote and the clay minerals such as chlorite and illite (Islam 1996). The alluvial Ganges aquifers are widely used for public water supply. Large parts of them are severely polluted by naturally occurring arsenic, which adversely affects the health of millions of people dependent on groundwater (Nickson *et al.* 1998). The arsenic problem is predominantly restricted to the Ganges River delta aquifers. By contrast, the surface water sources are mainly devoid of excessive arsenic.

The high arsenic concentrations in the alluvial Ganges aquifers in West Bengal are inherited from the dissolution of As-rich iron oxyhydroxides, which in turn are derived from weathering of base metal sulphides (Nickson *et al.* 1998). Arsenic is released when As-rich iron oxyhydroxides are reduced in anoxic conditions caused by a fluctuating groundwater table, a process that solubilizes iron and its absorbed load. Arsenic may also be mobilized from the As-rich pyrite occurring in aquifer sediments as atmospheric oxygen invades the aquifer in response to a lowering of the water level, frequently the consequence of water abstraction.

Methods

Sampling

Altogether 10 groundwater samples were collected from three strongly arsenic affected areas and two from less affected areas, respectively. The location map of the sampling sites in Bangladesh is shown in Figure 1. The representative areas were selected on the basis of preliminary information provided by the health workers. The sampling sites are the following: 1. Charruppur, Ishurdi (alluvial sand), 2. Rajarampur village of northwestern Chapai

Nawabgonj district (alluvial sand), 3. Shamta village, Sharsha, Jessore (deltaic silt), and two less arsenic affected areas, i.e., 4. Mainamoti area of eastern district of Comilla (Pleistocene Madhupur clay residuum), and 5. Andulia, Harinakundu of southwestern Jhenidah District (deltaic silt). At the respective sampling sites, the groundwater samples (100 ml) were acidified with 0.5 ml of concentrated HNO_3 and collected in the polyethene bottles.

Analyses

Acidified groundwater samples were analysed for As concentration with the ICP-MS technique in the Chemical Laboratory of Geological Survey of Finland (GSF), Espoo. In natural waters, the ratio of arsenic species can change rapidly as a result of the changing redox potential and the influence of metal ions, anions and other dissolved constituents of water, as well as by biological activity. To minimize the risk of chemical changes, the separation of the different species should preferably be done immediately after the sample has been taken. However, since it is difficult to bring samples from such a long distance within a short time, and due to the lack of instrumental facilities to make measurements in Bangladesh, an attempt has been taken to continue speciation study of arsenic in order to get more information on arsenic species.

Arsenic(+3) and arsenic(+5) species were separated by using ion exchange. The resin used was a strong anion exchange resin in acetate form. In the acidified sample, the pH was low enough to maintain arsenic(+3) in the neutral state so that it passes through the resin while the arsenic(+5) is retained. The arsenic(+5) can be eluted from the resin with 0.15 M HNO_3 . The 5 ml-portions of the filtered and acidified samples were allowed to pass through the resin in the columns. The columns were leached with 0.15 M HNO_3 and the effluent was collected in four separate 20 -ml fractions.

Results and discussion

The results are shown in Table 1. The highest concentration of arsenic (2210 $\mu\text{g/l}$) has been detected in the Rajarampur area followed by Shamta (1840 $\mu\text{g/l}$), Char Ruppur (684 $\mu\text{g/l}$), Andulia (10 $\mu\text{g/l}$), and Mainamoti (0.25 $\mu\text{g/l}$) areas. The level of natural As contamination in groundwater in Rajar-ampur, Shamta and Char Ruppur is many fold higher than the recommended concentration stipulated by the WHO (10 $\mu\text{g/l}$). On the other hand, in Andulia and Mainamoti area the arsenic level in the

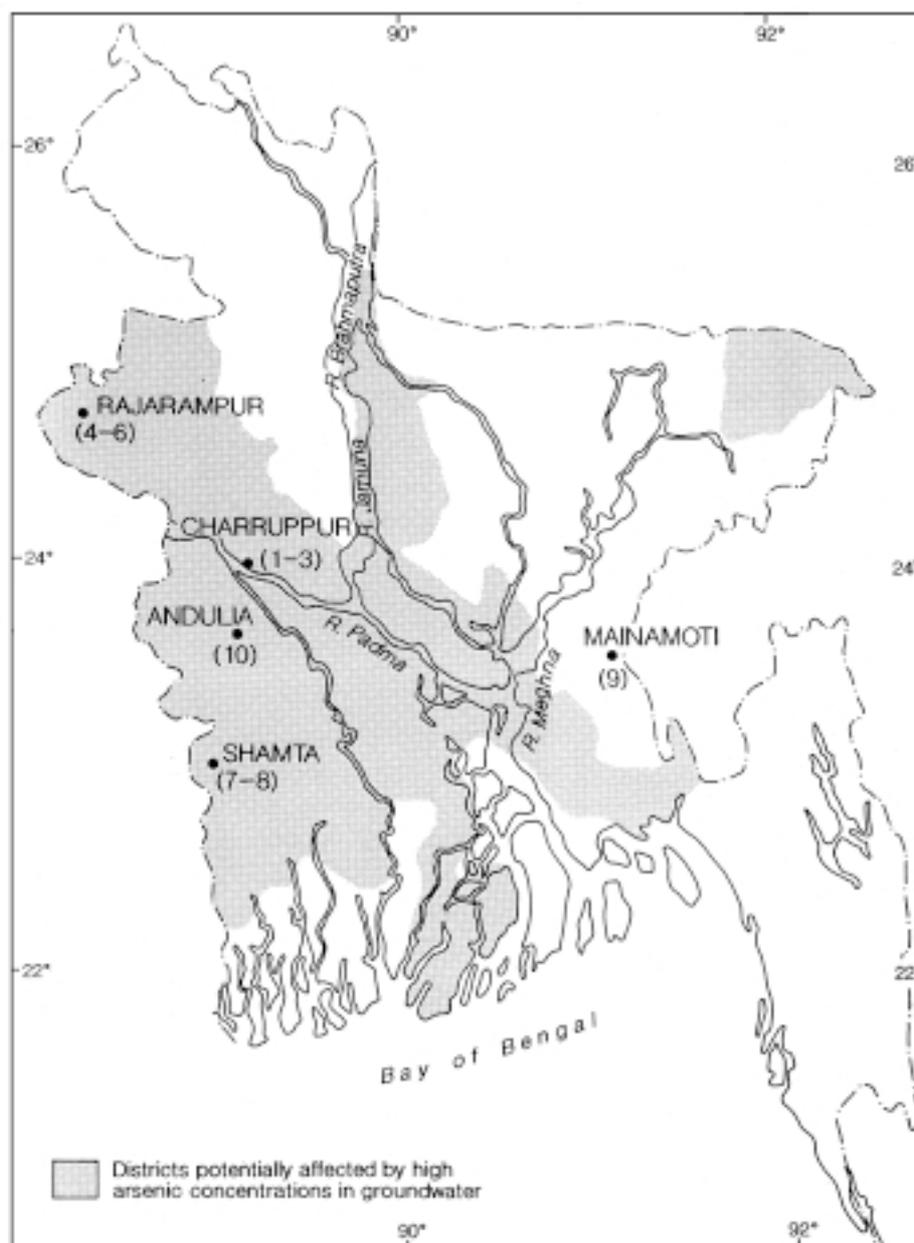


Fig. 1. Location map of the sampling sites in Bangladesh. 1. Charruppur, Ishurdi; 2. Rajarampur, Chapai Nawabgonj; 3. Shamta area, Jessore; 4. Mainamoti area, Comilla and 5. Andulia area, Jhenidah. Strongly arsenic affected areas are marked according to Ratan *et al.* (1997).

groundwater is below the WHO recommended value.

Results of speciation study show that in most of the samples, arsenic(+5) was the predominant form. Only in one sample (the Rajarampur area) was there more arsenic(+3) than arsenic(+5).

The amount of arsenic(+3) varied between 0-53 % of the total arsenic concentration, while the amount of arsenic(+5) ranged 47-100 %. These preliminary results show that arsenic(+3) has not totally been oxidized to arsenic(+5) during storage. In this study the arsenic speciation of acidified groundwater samples was studied several months after the samples had been collected. The total arsenic concentrations (8.76-2190 $\mu\text{g/l}$) were not changed markedly

during storage.

Conclusion

Out of the five areas studied, in three areas i.e. the Rajarampur, Shamta and the Char Ruppur area, the groundwater is highly contaminated by arsenic. Among these three areas the groundwater in the Rajarampur area shows the highest concentration followed by the Shamta and Char Ruppur areas.

The Mainamoti and Andulia areas are quite safe in terms of arsenic contamination. The source for high arsenic concentrations in the alluvial Ganges aquifer material is the dissolution of As-rich iron

Table 1. The total concentration ($\mu\text{g/l}$) and species of arsenic in groundwater samples from five separate areas of Bangladesh.

Sampling sites	Total arsenic concentration		Percentage of arsenic		Recovery (%)
	Before	After several months	As(III)%	As(V)%	
Mainamoti	0.22	0.16	n.d.	n.d.	
"	0.25	0.21	n.d.	n.d.	
Char Ruppur	0.48	0.43	n.d.	n.d.	
"	600	684	0	100	101
Andulia	8.76	8.79	0	100	115
"	10	8.81	1	99	109
Shamta	152	147	0	100	112
"	1840	1784	0	100	99
Rajarampur	1720	1300	36	64	146
"	2190	2210	53	47	99

Note: n.d. - not detected.

oxyhydroxides, which originally are derived from the weathering of base metal sulphides. Arsenic is released when As-rich iron oxyhydroxides are reduced in anoxic conditions caused by a fluctuating groundwater table. Another source is the oxygenation of As-rich pyrites in the aquifer in response to a lowering of the water level. Arsenic(+5) is the main species of arsenic while arsenic(+3) is dominant over arsenic(+5) only in the Rajarampur area as revealed by the speciation study. The amount of arsenic(+3) varied between 0-53% and arsenic(+5) between 47-100% of the total arsenic concentration.

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MIGRATION OF POTENTIALLY HARMFUL ELEMENTS FROM BLACK SHALES TO AQUATIC ECOSYSTEMS AND LOCAL RESIDENTS: PRELIMINARY RESULTS IN EASTERN FINLAND

by

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Key words (GeoRef Thesaurus, AGI): environmental geology, black schists, toxic materials, mercury, migration, surface water, ecosystems, human ecology, eastern Finland

Introduction

Previous studies have revealed that the presence of sulfide-rich black shales in bedrock is reflected in elevated natural baseline levels of a number of potentially toxic elements in till, soil, surface water and groundwater and in organic stream and lake sediments. Environmental impacts may be hazardous if the bedrock is broken and exposed and the rocks are in contact with surface water (Bierens de Haan 1991, Loukola-Ruskeeniemi 1992, Kim & Thornton 1993, Piispanen & Nykyri 1997). Release of harmful elements such as S and As from sulfide-rich black shales to the environment has been associated with fish kills, for example in a river near the Halifax international airport in Canada, which was built in a sulfide-rich black shale area (Pasava *et al.* 1995).

The study of pollution in aquatic environments requires more than the sampling of water. Benthic invertebrates, such as noble crayfish (*Astacus astacus* L.), live and feed directly on sediments and therefore are in direct contact with metals of both natural and anthropogenic origin. Recent studies have suggested that crayfish may be good indicators of sediment-metal levels as they appear to retain tissue

metal concentrations that correlate with environmental levels (Parks *et al.* 1989, Alikhan *et al.* 1990, Bendell & Harvey 1991, Morrisey & Edds 1994). Cautious estimates suggest that the biomass of noble crayfish may be as much as 100-300 kg/ha in small lakes and rivers in Finland. Crayfish thus play a significant role in the migration of potentially toxic elements in some Finnish aquatic ecosystems.

Northern pike (*Esox lucius* L.) is a predator at the top of the food chain, feeding on fish from a few weeks of age. Pike is also a common species, occurring in almost all water bodies in Finland. As an important commercial fish, it acts as a link in the transfer of toxic compounds from the environment to man.

The present study of the migration of harmful elements from black shales to aquatic ecosystems and local human populations began in 1997 in black shale areas in the municipalities of Sotkamo and Kaavi. To date, 120 crayfish and 24 fish samples have been collected. Organized in co-operation with the Health Centres of Sotkamo and Kaavi, 220 people have participated in the research by providing hair and blood samples. Drinking water samples were taken from 88 households.

The research was focused on eastern Finland

because coronary heart disease is more abundant there than in western and southern Finland. Although genetic factors and living habits are significant (*e.g.*, Vuorio 1998, Puska *et al.* 1983), trace elements in drinking water and food are also implicated. Water hardness is reportedly inversely related to CHD mortality (Karppanen *et al.* 1978, Nerbrand *et al.* 1992, Kousa & Nikkarinen 1997). High concentrations of Hg and low concentrations of Se in hair samples may correlate with higher incidence of CHD (Salonen *et al.* 1991, 1995). Fish and fish products are probably the dominant source of methylmercury in food.

Analytical methods

Rock, sediment, water, crayfish, fish, and hair samples have been analyzed at GTK by ICP-MS and ICP-AES methods (Kallio 1994). The detection limits for water and sediments are given in Lahermo *et al.* (1996, p. 29). Hg was determined by cold vapor AAS. In addition, pH, electrical conductivity, color, alkalinity, and KMnO_4 consumption were determined for water samples. SO_4^{2-} , Cl⁻, NO_3^- , and F⁻ concentrations were determined by ion chromatography (Dionex 2000i), while PO_4^{3-} was determined spectrophotometrically by the molybdenum-blue method. Electrical conductivity, pH, CO_2 , and temperature of the water samples were determined in the field during sampling. Clean techniques were employed during all phases of water sample collection and handling. Mercury concentrations in hair, crayfish, and fish samples were determined by cold vapor AAS at the University of Kuopio and at the GTK. Results were in good agreement.

The whole blood and serum samples were analyzed by AAS method at the University of Kuopio. Samples for trace metal analysis were handled under clean room conditions. Zinc and copper were determined in serum samples with flame AAS. Cadmium, nickel, and selenium in the whole blood and selenium in serum samples were determined by graphite furnace AAS. Commercial reference samples (Seronorm Trace Elements Serum, batch no. 300089 and Seronorm Trace Elements, Whole blood, batch no. 404107, Nycomed AS) were included in each analytical batch. The accuracy of the methods was controlled by participation in national intercalibration studies and the whole blood cadmium measurement also in an international intercalibration study, organized by the Karolinska Institute in Sweden.

Background

Certain rock types and ore bodies serve as natural sources of pollution for surface waters and groundwaters. Not only the geochemistry of black shales but also that of other rocks becomes reflected in the chemical composition of the surrounding environment. Ca and Mg concentrations in groundwater are higher, for example, in areas of gabbro, peridotite, and carbonate rocks than in granite areas, and F concentrations are high in groundwater in rapakivi areas. Elevated U concentrations are associated with some granites, and these in turn are responsible for the high radon concentrations in wells drilled into bedrock in eastern parts of Uusimaa county. The As-rich bedrock at Kittilä in Lapland is reflected in elevated As concentrations in natural spring water (Loukola-Ruskeeniemi *et al.* 1999).

Elements are continually dissolving from the bedrock and overburden into water, but especially when the rock and overburden contain easily weathered minerals such as sulfides, and when fractures and cracks in the rock allow water easy passage. The solubility of many elements is enhanced by the acidity of the water, and the longer the water is in contact with the bedrock and overburden the more dissolving occurs. Furthermore, the amount of a mineral that weathers easily affects the tendency of the whole rock to weather: thus, a black shale containing 2% S does not weather and release sulfur compounds to water to the same degree that black shales containing an average of 9% S do.

The concentrations of some elements are much higher in sulfide-rich black shale areas than in the granitic or quartzitic areas and higher than the average values in Finnish bedrock. During 1993-1996, study was made of the environmental impact of Ni-Cu-Zn-rich black shales at Talvivaara in the municipality of Sotkamo in eastern Finland. Geochemistry of the bedrock at Talvivaara, more precisely the Kolmisoppi-Kuusilampi area near Pirttimäki (Loukola-Ruskeeniemi & Heino 1996), was reflected in the chemical concentrations of surface waters, organic stream and lake sediments, and moss. Elevated Ni concentrations in the lake water and organic lake sediments in the black shale area at Talvivaara derive in part from a natural source, and there is evidence that at least one lake in the black shale area was noticeably acidic 9000 years ago (Loukola-Ruskeeniemi *et al.* 1998).

Accumulation of mercury in crayfish, fish, and human hair — preliminary results

Mercury concentrations in fish were higher in two black shale area lakes at Kaavi (0.55 mg/kg) than in four lakes located in an area of sulfur-poor bedrock (0.33 mg/kg, $p < 0.01$). The limit used as a criterion for restricting human consumption of fish (0.5 mg/kg) was exceeded in pike caught from black shale area. Also, muscle of crayfish contained more Hg in lake Mäntyjärvi in the black shale area at Kaavi (0.26 mg/kg, $n=20$) than in lake Kotajärvi, which is located in a sulfur-poor area (0.17 mg/kg, $n=20$, $p < 0.01$). No natural crayfish population was found in the Sotkamo black shale area, but 12 crayfish from the Jormasjoki river in an adjacent S-poor area were set in experimental cages in lake Kolmisoppi. After one year, the average Hg concentration of the caged crayfish was 0.28 mg/kg, which is significantly higher than the original level (0.18 mg/kg, $n=20$, $p < 0.01$). However, even the highest mercury concentrations in the caged crayfish did not exceed the values recommended by the Finnish National Board of Health: 0.5 mg/kg for mercury in crustaceans.

One of the most interesting results was that there was significant difference between crayfish sexes in Hg content of tail muscles in Kaavi, females accumulating 0.22 ± 0.08 mg/kg and males only 0.15 ± 0.08 mg/kg ($p < 0.01$) (Halonen *et al.* 1998). This finding can be explained by differences in the lipid content of tail muscles between the sexes. As Airaksinen *et al.* (1977) have shown, total lipid contents are higher in females than in males.

The Hg content in hair was compared for people living in the black shale areas in Sotkamo and Kaavi. The Hg values for people eating fish products once or more per week were 2.48 mg/kg in Sotkamo and 1.50 mg/kg in Kaavi, whereas Hg values for people eating fish less than once a week were 1.44 mg/kg and 0.73 mg/kg, respectively. Hg values were higher in Sotkamo than in Kaavi, but the values in both municipalities were comparable with those of 1833 men in eastern Finland (Salonen *et al.* 1995).

Conclusions

Preliminary results of the present study suggest that if bedrock contains elevated concentrations of potentially toxic elements, it is reflected in the quality of surface waters, crayfish, and fish. For example, Hg concentrations in fish exceeded the

recommended 0.5 mg/kg in the sulfide-rich black shale areas that were studied, even though the fish were of small size. The next step will be to compare the chemical concentrations in drinking water, fish, and human hair and blood.

Although potentially harmful elements are abundant in natural waters in a few areas in Finland, in most cases the bedrock is not a source of problems. In some areas, instead, elements essential or useful to humans, animals, and plants are insufficiently present in surface water and groundwater. In contrast to the situation in many European countries, it is still possible in Finland to study the impact of the bedrock and overburden on the chemical concentration of surface waters, aquatic ecosystems, and the transfer of the elements to local human populations under natural conditions.

Acknowledgments

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COMPILATION OF MAPS OF BLACK SHALES IN FINLAND: APPLICATIONS FOR EXPLORATION AND ENVIRONMENTAL STUDIES

by

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Key words (GeoRef Thesaurus, AGI): metasedimentary rocks, black schists, maps, geophysical methods, mineral exploration, graphite, sulfides, Precambrian, Finland

Introduction

Metasediments in the Fennoscandian Shield rich in graphite and sulfides are encountered in the vicinity of most massive sulfide deposits, for example the Outokumpu Cu-Co-Zn deposits in eastern Finland, the Vihanti Zn-Cu-Pb deposit in western Finland and the Pechenga Ni deposits in the Kola peninsula in NW Russia. Formations of metamorphosed black shales are particularly thick and widespread in eastern and northern Finland. Relationships between black shales and ore-forming processes have been established in some ore provinces (Loukola-Ruskeeniemi 1992, Loukola-Ruskeeniemi et al. 1993, Loukola-Ruskeeniemi et al. 1997, Loukola-Ruskeeniemi, in press). Environmental impacts of sulfide-rich black shales are pronounced, because black shales weather more easily than most other rock types in the Fennoscandian Shield. Study of a small lake in a black shale area indicated that it has been acidified already for 9000 years ago (Loukola-Ruskeeniemi et al. 1998).

Because they are good conductors, graphite and sulfide bearing rocks are easily located by geophysical measurements. In addition to their good conductivity, pyrrhotite-bearing black shales also cause magnetic anomalies. The geophysical properties of black shales have been studied in graphite exploration projects covering the whole country (Kukkonen 1984) and in more detailed regional

studies in eastern Finland (Tervo 1980, Airo & Loukola-Ruskeeniemi 1991) and western Finland (Niskanen et al. 1992, Loukola-Ruskeeniemi et al. 1997). Magnetic and electromagnetic airborne low-altitude data were available in 1998 over most of the volcano-sedimentary formations in the country for map production and interpretation. Apparent resistivity was calculated from airborne electromagnetic data by Heikki Hautaniemi and others with methods described in Pirttijärvi (1995).

During the present project, Distribution Map of Black Shales in Finland, the magnetic and apparent resistivity datasets from different flight areas were compiled and processed with the ER Mapper program (Figs. 1 and 2). Map composites were used to assist the location of graphite and sulfide bearing formations in areas covered by airborne data. Information from other relevant and available GSF databases was visualized on map composites. Information on graphite bearing rocks from the petrophysical and geological databases, and from the archives of individual geologists like Olli Sarapää, who has done graphite exploration all over Finland, was added to the maps.

Petrophysical properties of black shales vary due to textures and concentrations of graphite and sulfides. For example, black shale formations at Polvela in Juuka contain 20% of graphitic carbon and 1% of sulphur, whereas in the Vihanti area in western Finland there are layers with 1% C and 20%

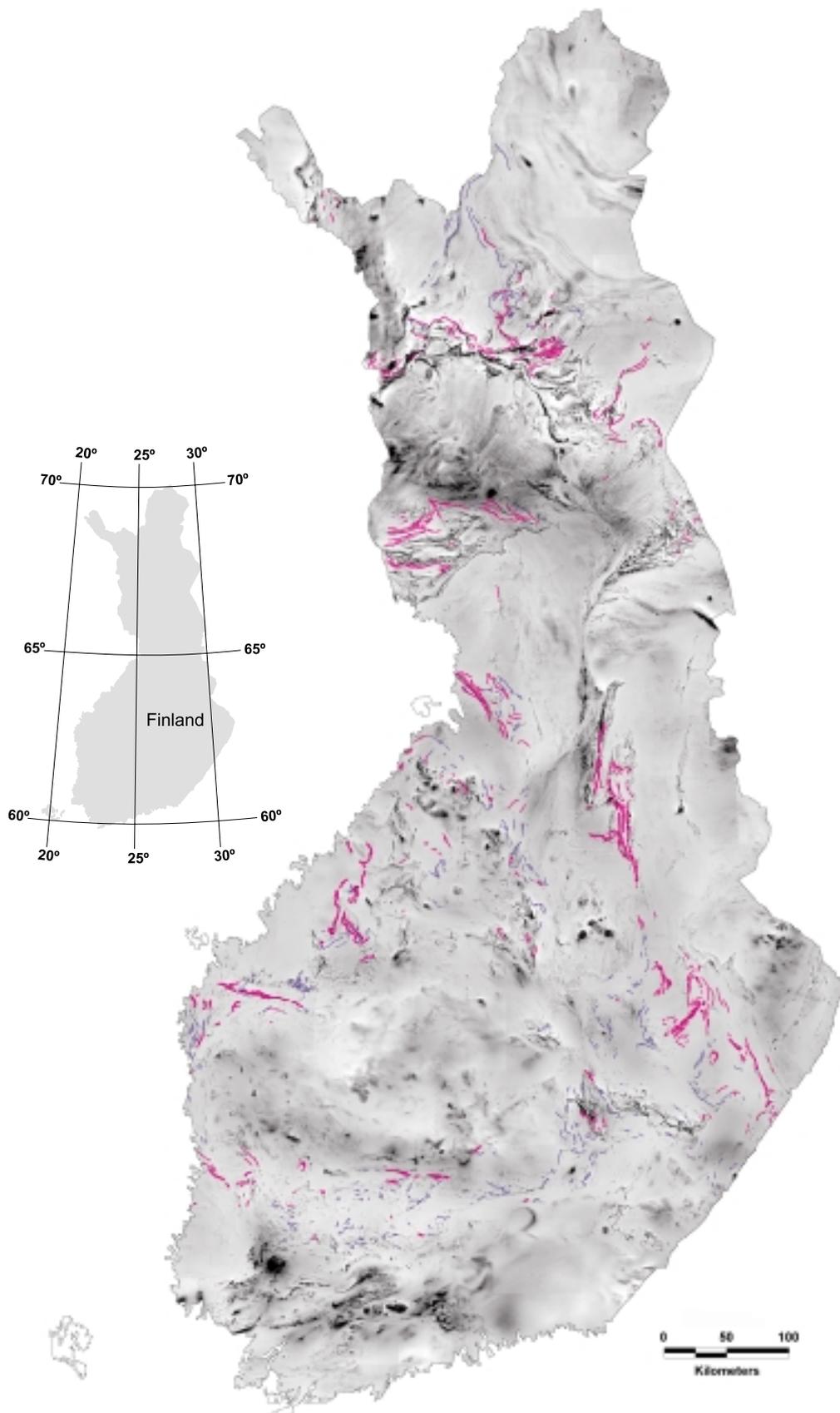


Fig. 1. Preliminary version of map showing known and probable black shale bearing formations. The greytone-scaled low-altitude airborne total intensity magnetic map covers more than 80% of the area, while the high-altitude airborne data covers the areas shown in white in Figure 2. Known black shale bearing formations are shown in red and probable ones in blue.

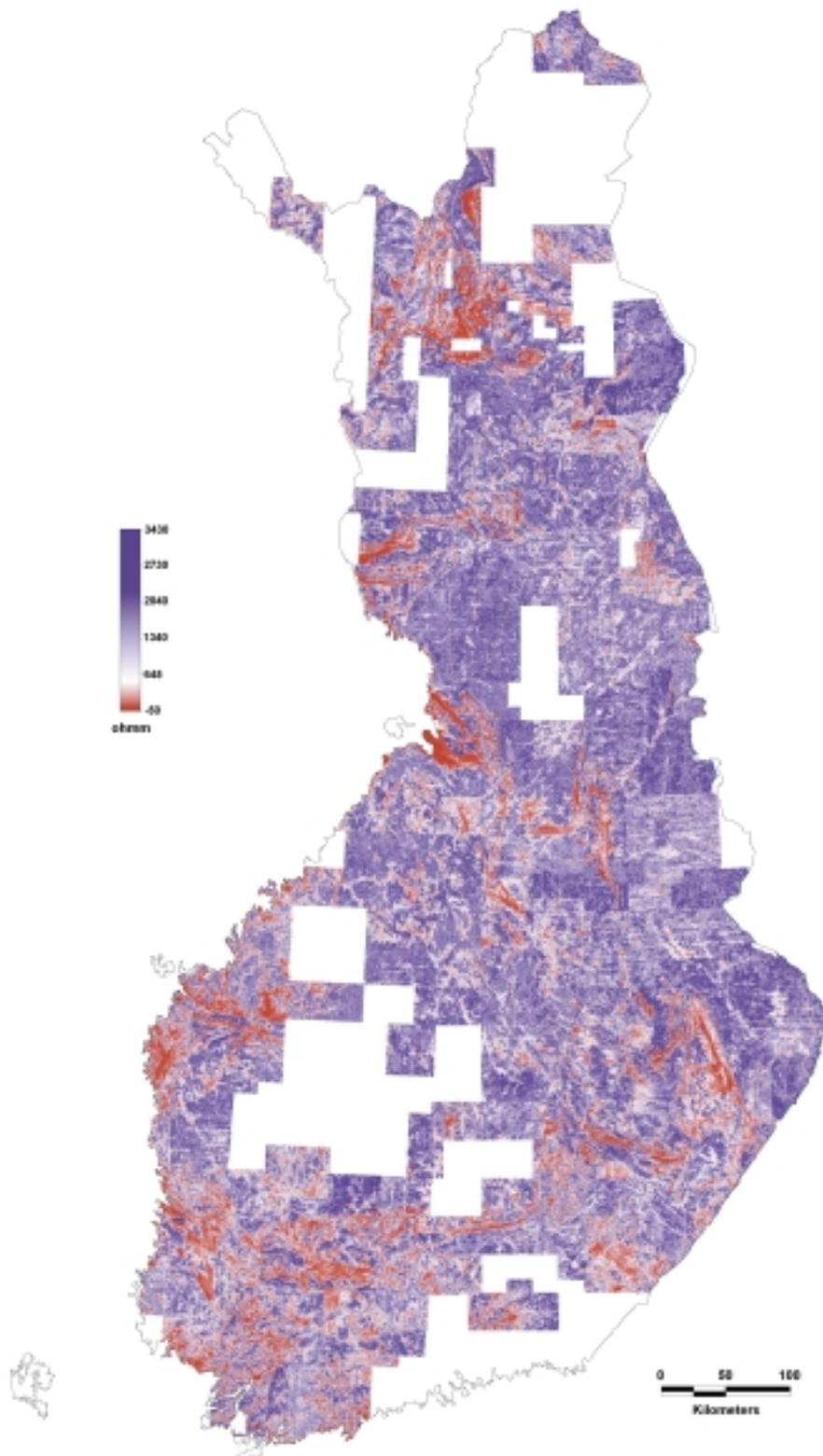


Fig. 2. Apparent resistivity map calculated from low-altitude airborne electromagnetic data.

S. In the Kainuu-Outokumpu area and in the Arpela target at Tornio in Lapland, average concentrations of C and S are 7%. In the Outokumpu area in eastern Finland, the average resistivity of black shales varies between 10^{-2} and 10^{-1} ohmm and the average susceptibility between 1000 and $40\,000 \times 10^{-6}$ SI (729 samples, Lehtonen 1981).

During April 1998, map composites in scale 1:200 000 were produced and sent, together with a questionnaire, to geologists working in different parts of the country. The purpose of the map was to provide field geologists with the most recent geophysical data before the field work season began, and the questionnaire was intended to elicit information about known outcrops of graphite and sulfide bearing rocks for entry into the dataset. Drill cores from volcano-sedimentary formations have also been studied throughout the country. The exact observation points and the type of the graphite and sulfide bearing rocks have been correlated with the geophysical airborne data.

Information in digital form will be entered in the dataset for 1) known black shale bearing formations, evident in either outcrops or drill cores and in the geophysical map composite, and 2) proposed black shale bearing formations with no outcrop or drill core evidence but whose geophysical anomalies are similar to those of known formations. The ultimate objective of the project is to create a database for known and probable formations rich in graphite and sulphides. Maps in different scale are being and will be produced from the database and probably a map in 1:1 000 000 will be printed for the whole country. The maps will find application in exploration, bedrock mapping, regional planning, and studies of natural background levels in the environment. Already during the project, while carrying out a systematic study of all sites in Finland with low apparent resistivity, we identified several areas with potential for the exploration of sulphide ores about which we need to know more.

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ENVIRONMENTAL HAZARDS AND THEIR CAUSES IN TWO AREAS OF NICARAGUA WITH DIFFERENT AGRICULTURAL PRODUCTION AND GEOLOGY

by

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Key words (GeoRef Thesaurus, AGI): environmental geology, soils, ground water, surface water, stream sediments, pollution, agriculture, pesticides, mercury, heavy metals, Nicaragua

Introduction

Nicaragua is a little over one-third the size of Finland. In the north it is bounded by Honduras, in the south by Costa Rica, in the west by over 300 km of Pacific coast, and in the east by 500 km of Caribbean coast. Throughout the country the climate varies between tropical and subtropical, and the vegetation between rain forest and the subtropical zone of the Interior Highlands. There are two seasons in the most densely populated areas on the Pacific coast and in the western highland areas, the dry season from November to April and the rainy season from May to October. There is considerably more rain on the Caribbean coast than in the western parts of the country.

The country falls into three main regions: the Pacific coastal region, the Interior Highlands of the central part and the Atlantic coastal region (Fig. 1). The Pacific coastal region consists of the coastal plain, the Nicaraguan Depression and the chain of volcanoes between them, formed during the Quaternary period. The Nicaraguan Depression is 500 km long and about 50 km wide, extending from the NW part of the country to the border of Costa Rica. The agriculture of Nicaragua is concentrated in the Pacific coastal region, where the majority of the country's over four million inhabitants live.

The bedrock of the Pacific coastal region consists

of Cretaceous and Tertiary sedimentary rocks. The Tertiary rocks extend into the Nicaraguan Depression. Millions of years of wear and erosion have sculptured the terrain, giving it a hilly topography, in places with deeply eroded canyons. The plate-tectonic movements of the Earth's crust have raised the Pacific coastal block and caused the formation of the Nicaraguan Depression. The depression contains sedimentary rocks and material from Pliocene volcanic eruptions overlying older Tertiary deposits (Weyl 1980). The eruption of the Masaya volcano, which was formed during the Quaternary, produced mainly basalts and pyroclastic lavas containing abundant iron. East of Masaya there are dense basalts, agglomerates and tuff breccia which are older than the Masaya and are called the volcanic strata of the Las Sierras group. The volcanic strata are, in many places, covered by flood deposits containing sand, silt and clay mixed with volcanic material.

Study areas

Tisma is the most important study area of UNA (the Agricultural University in Managua) which aims to develop agriculture, and it was thus selected for the present study and included in the UNA project for development of the countryside. Instruction and opinion building regarding environmental

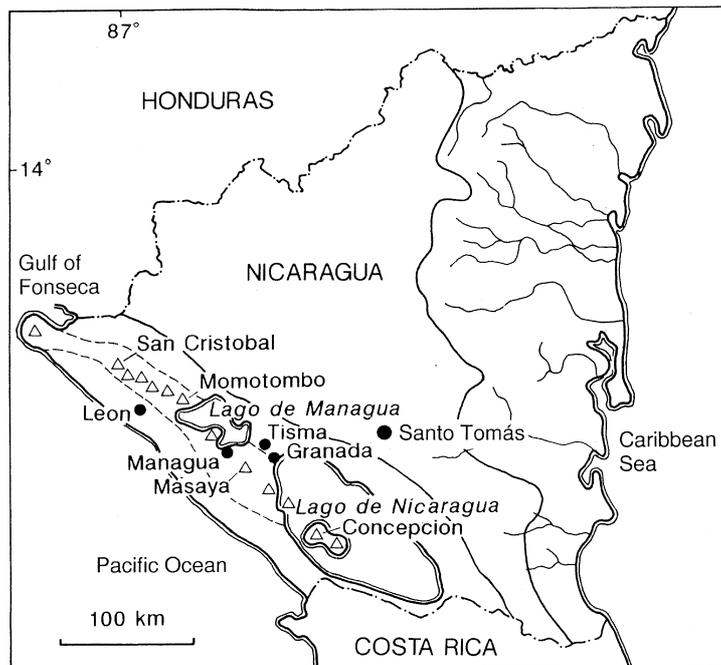


Fig. 1. Nicaragua and its regions.

protection are also among its central development objectives. Some of the UNA personnel took part in the study.

In the agricultural region of Tisma, about 35 km east of Managua, the focus of the study was on soil composition, water quality and amount of pesticide remnants in tilled soil, surface and ground water. The topography of the Tisma region has been affected by the eruptions of the Masaya volcano which have been recorded since 1529 (McBirney 1956). Tisma is a part of the intensively cultivated area of western Nicaragua, where grain and fruit is grown to supply the Managua region. Information on used pesticides and erosion control methods was collected from this area in cooperation with UNA (Fig. 2). In 1994 a pilot study was carried out in Tisma together with the UNA (Kukkonen et al. 1995) concerning groundwater quality and also the composition of the compact talpetate soil layer and the hazards which it presents to agriculture.

In Santo Tomás, which is located in the Interior Highlands of central Nicaragua, groundwater shortage is a problem, and for this reason the groundwater conditions of the area were investigated at the request of the city authorities. At present the household water for Santo Tomás is obtained from the Quipor reservoir and four wells in the valley area to the south. The wells are 60-80 metres deep, extending to the surface of the unweathered rock. Their total capacity is 133 - 333 m³/day. Both surface and ground water is chlorinated. During the dry season the water in these wells and the Quipor reservoir is

not sufficient for the needs of Santo Tomás. The most difficult time is from April to early June, when the reservoir runs dry and water is rationed, sometimes being available only every eighth day. Water is supplied to 43% of the population of Santo Tomás. The study also included the water quality of Río Mico, a river considered as a potential water source and the amounts of heavy metals and mercury that have spread from small gold panning stations into the water and alluvial sediments.

In La Libertad and Santo Domingo near Santo Tomás, gold panning has been in progress for more than a century. The mining causes environmental hazards (Fig. 3), of which the most serious are considered to be the release of lead and mercury into the environment and the water turbidity caused by mud suspension that gets into the rivers. The newer cyanide method has also been criticised to some degree. The spreading of mercury and lead into the environment is a consequence of the amalgam method used by both mining companies and private gold diggers. They still use lead-bearing (about 20% lead) mercury, some of which ends up in rivers (Vázquez 1996, Mendoza 1997, Información 1994). It is estimated that 2 million tonnes of ore have been treated by the amalgam method in the La Libertad-Santo Domingo area since 1856. The amount of mercury released into the environment is estimated at 16 tonnes, of which 6 tonnes has been bound in the alluvial sediments and 10 tonnes has been transported by the waters of Río Mico and by air. Since 1946 the cyanide method has been used in



Fig. 2. Soil sampling in Tisma. In the background the Masaya volcano. Photo by U. Väisänen 1997.

some of the gold ore processing. Initially the waste fluids of the process were released directly into the rivers Siquia and Mico. However the cyanide compound is not stable but disintegrates fairly quickly (Información 1994). Demands for newer, even cleaner methods have been put forward and such methods have also been developed (Vásquez 1995).

Information on pesticides used in agriculture

Pesticides are traditionally classified according to use and chemical structure, i.e., according to their active ingredient (Turunen 1985). The insecticides, i.e., pesticides for use against insect pests in agriculture, are classified according to their active ingredient into organic chlorine compounds (i.e., chlorinated hydrocarbons); organic phosphorus compounds; carbamates, which have similar effects to organic phosphorus compounds and vegetable insecticides and their derivatives. All these insecticide groups affect the nervous system in both insects and mammals. Besides the traditional insecticides, new substances called insect growth controllers have been developed, which selectively affect insects. Nowadays the trend is away from the use of chlorinated hydrocarbons, which are stable and the most hazardous to the environment, towards less stable compounds. However in Nicaragua such hazardous compounds as DDT, lindane and endo-

sulphane are still available. Their properties include low water solubility and high fat solubility, which cause them to accumulate in fatty tissue. Rodent pesticides include hydrofluoric acid derivatives. Most generally used is the anticoagulant group, which works by preventing blood coagulation.

The most widespread use of herbicides involves phenoxy herbicides (2,4-D, MCPA), carbamate compounds, propachlor and atrazine. Herbicides also include benzoic acid derivatives and quaternary ammonium compounds, such as the toxic paraquat, which may cause lung damage. According to interviews made as part of the study, various forms of this substance are used in Nicaragua. The stability of herbicides in the soil depends on the volatility of the substance, its chemical stability against various disintegrating effects and its water solubility. The herbicides are effective by damaging the structures of cell membranes and hampering the assimilation of plants.

In fungicides (i.e., pesticides against vegetable diseases), numerous different active ingredients are used, including both inorganic heavy metal compounds and organic compounds. These substances for use against fungi are often less toxic to mammals. However exceptions do exist, such as dinitrophenol derivatives and organic mercury compounds. Organic mercury compounds accumulate in the brain, kidneys and liver and via the placenta in the



Fig. 3. Former gold mining area in the vicinity of La Libertad. At this and other quarries heaps of fine-grained waste soil are left, which are transported by rainwater into Río Mico, impairing the water quality. Photo by U. Väisänen 1997.

fetus and via the mammary glands in the milk. The effect of fungicides is based on disturbance of intercellular activity.

In Nicaragua, as in other developing countries, the abundant and uncontrolled use of agricultural chemicals and pesticides is a big problem. Pesticide remnants are found both in humans and the environment. On the basis of a decision by the Comisión Nacional de Agroquímicos of Nicaragua, a prohibition was issued on 8 August 1993 by La Dirección de Sanidad Vegetal de Ministerio de Agricultura against the use of the following chemicals in agriculture (Beck 1996): DBCP, aldrin, endrin, DDT, 2,4,5-T, heptachlor, EDB, chlordan, BHC, dieldrin, dinoseb, pentachlorofenol, parathion ethyl, toxaphene and lindane. A recommendation to limit the use of chlordimeform, aldicarb and parathion met-

hyl was also issued. These products are classified by the OMS (Organización Mundial de la Salud, WHO) as carcinogenic and mutagenic.

Pesticides in the environment

The binding of pesticides in the soil and their release and migration into surface and ground waters depends on the properties of the soil and pesticides, as well as on weather conditions (Matinvesi et al. 1994). The properties of the pesticides include chemical reactivity, that is the kind of chemical bonds the compound may form with soil particles; photolytical stability, which is how resistant the compound is to disintegration under influence of ultraviolet or visible light; biological activ-

ity, how easily the compound is decomposed by microbes in the soil; and adsorption properties, that is how easily the compound is bound to the soil. In general the pesticides are bound to soil particles by hydrogen bonds or by ion exchange. The capacity of all soil types to bind and break down pesticides emitted into them depend on the amount of organic matter and clay fraction in the soil (Laitinen 1989). The properties of soils that affect the binding or transport of pesticides are: grain size and specific surface area of the grains, amount and character of the organic matter, pH and redox conditions, humidity, temperature, hydraulic conductivity, density and porosity, sorption properties (binding capacity) of the clay minerals and precipitates, and amount of exchangeable cations.

The transport (migration) of pesticides into surface and ground water depends on both the character of the soil and climatic factors. Chemicals may flow directly from the fields with surface runoff into rivers and lakes. They may also get into the water in the form of solutions which migrate through the soil, more easily in coarse-grained than in fine-grained soil. The pesticides may also migrate through cracks in the ground and through root canals of plants to a lower, microbe-poor layer, where disintegration is slow. From there they may migrate further into the groundwater. In the ground the pesticides are either dissolved in the water or bound to the soil. When a pesticide is bound in the soil, this decreases its evaporation and migration in the ground, and in most cases it also slows down chemical disintegration. Biological decomposition also slows down because the microbes are unable to separate the substance from the soil particles.

Sampling and analytical methods

Sampling

In Tisma the amount of pesticides in soil and groundwater was investigated. At the same time the general composition of soil and groundwater was studied by analysis of samples from farms where different types of plant were cultivated. On some farms cotton had previously been grown with the abundant use of pesticides. The aim was to take groundwater samples from wells and soil samples from the same farms. Surface water samples were also taken from two lakes.

In the areas of Santo Tomás and La Libertad samples were taken from Río Mico and its stream sediments. The purpose was to study the concentrations of heavy metal and mercury in the water and

stream sediments and the impact of gold mines on the concentrations near the lower reaches of the river. Some groundwater basins in Santo Tomás were evaluated using map interpretations and field observations as well as earlier studies in the area. In addition the soil composition and quality of well water were investigated around Santo Tomás. At the sampling sites of both Tisma and Santo Tomás farmers were interviewed, and information was gathered on the cultivation history of the farms, crop cultivation and cultivation methods and the use of pesticides and problems caused by them.

Soil samples were taken from the topsoil (A samples), a depth of about 20 cm (B samples) and deeper, from the subsoil (C samples). Samples were taken for grain-size analysis, specific surface area measurements, clay composition analysis and determinations of elements and pesticides. Determinations of pesticides and mercury were made in Managua, Nicaragua, in the laboratory of Universidad Nacional de Ingeniería (UNI), while the grain-size analyses, surface measurements, mineralogical determinations and element analyses were carried out in Finland, in the laboratory of the GTK. For the sake of comparison, pesticide determinations were made on some samples in Finland, in the laboratory of MTT (the Finnish Agricultural Research Institute). The water samples were taken and pretreated in accordance with the instructions and usage of the GTK. The water analyses of pesticides, bacteria and mercury were carried out in the laboratory of UNI, the sampling and pretreatment were done according to the instructions of UNI. Pesticide remnants in two water samples were also analysed in Finland in the MTT laboratory.

Analytical methods

The pesticide analyses at UNI were performed on a Cromatógrafo Varian 3400 apparatus using the analytical methods 6431-LLE GCM and 6630 b and c, in accordance with the recommendations of the international handbook "Standard Methods" (for investigation of water and wastewater, 18th edition). EPA METHOD 608 and ASTM METHOD D4861-88 were then applied to the check samples. The following organic chlorine compounds were analyzed from the samples:

HCB, HCH, lindane, aldrine, oxychlorane, heptachlor, PP'DDE (4,4'-DDE), dieldrin, PP'TDE and PP'DDT. Analysed organic phosphorus compounds are: dichlorphos, diazinon, ronnel (fenchlorphos), chlorpyrifos, malathion, ethyl parathion, ethion and carbophenothion.

Bacteria concentration, coliform bacteria (total) and fecal coliform bacteria were determined in the microbiological laboratory of UNI. The analyses were performed according to the Standard Methods handbook, by the NMP method, which is a two-phase bacteria culture method. The cultures were performed at 37.5 and 37.8 degrees, which yielded the total amount of coliform bacteria. For the fecal coliform bacteria the culture was performed at 44 degrees. According to the OPS/WHO recommendations the highest permissible concentration of coliform bacteria in household water is <2.2 NMP/100 ml.

The soil samples analysed at GTK were leached with 1 M ammonium acetate solution at pH 4.5 and 7.0 and with aqua regia at 90°, and the analyses were done by ICP-AES. From untreated water samples the anions Br, Cl, F, NO₃ and SO₄ were analysed by ion chromatography. Phosphate concentrations were determined by spectrometry, alkalinity and potassium permanganate consumption (KMnO₄) by titration, pH by potentiometry and colour number by comparison. Multiple element determinations from water samples conserved with nitric acid and filtered were done by ICP-MS and ICP-AES.

Results

Tisma

The soil of Tisma consists of weathered volcanic rocks, ash spread from the volcanos and in a part of the area a hard weathered crust, the talpetate layer, which lies near the ground surface. A study in 1994 showed that the talpetate layer, which is detrimental to agriculture, is a weathered crust cemented by volcanic ash. It contains sufficient amounts of nutrients important to agriculture, i.e., calcium, potassium, magnesium, sodium and phosphorus. In contrast the surficial soil contains less nutrients, which is due to long-term agriculture and leaching. The talpetate layer near the surface prevents the plants from sinking their roots into the subsoil making it difficult to prepare the soil and increasing erosion. Breaking the talpetate layer would improve the absorption of water into the soil.

Concentrations of toxaphene, which in Nicaragua is usually mixed with other chemicals such as methyl-parathion, ethyl-parathion, malathion and DDT, were, in the 1994 study, found to be the following: 8.9 mg/kg in a cotton field that had been left fallow for two years, 2.2 mg/kg in a tomato plot and 2.8 mg/kg in untilled subsoil. The remnants of DDE, the hydrochlorinated form of DDT, were 0.52

- 0.21 mg/kg in the cotton field. The Finnish Ministry of the Environment recommends 0.02 mg/kg as a maximum for unpolluted soil.

During the 1997 study soil samples were collected from five farms in Tisma: El Rodal, La Montañita, Cuatro Esquinas, Las Conchas and Santa Cruz. They were studied for the following properties:

1. Grain-size distribution and specific surface area

The concentration of clay (grain size <0.002 mm) in the soil is 26-41%, on average 33.4%. The total concentration of very fine sand (grain size 0.002-0.02 mm) and clay is 65-75%, the coarsest material is mainly fine sand (grain size 0.02-0.2 mm) with a small amount of sand. The concentration of organic matter is 2.5-4.3% (determined by colorimetry). The specific surface area of the samples measured from <0.06 mm fraction are 123.9, 68.5, 62 and 78 m²/g. The specific surface area of the soil is extremely large, which is mainly due to the origin of the material. The soil consists partly of volcanic ash and partly of strongly weathered material, which is also reflected by the composition of the clay minerals (see 4 below). A study at GTK shows that in Finland the specific surface area of fines in till (<0.06 mm fraction) is 3.75-34.06 m²/g (Vallius 1993), on an average 10 m²/g. The specific surface area of the soil particles and the amount and character of the clay minerals are of great importance for the adsorption of chemicals in the soil.

2. Soil pH

The pH values of the soil at La Montañita are 7.35, at Cuatro Esquinas 6.74, at Las Conchas 6.95 and at Santa Cruz 6.93 (aqueous extraction). The average pH is 7, and therefore on average the soil is neutral. It differs from the soil of Finland, which is on average acidic, with pH values between 4 and 6, increasing from the surface downwards. The reactivity of various pesticides differs depending on the pH of the soil.

3. Readily soluble and exchangeable cations

The readily soluble and cation exchangeable elements calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na), and in addition strontium (Sr) and barium (Ba) from the <2 mm grain-size fraction were determined by ammonium acetate extraction (pH 7). In the soil strontium and barium react much in the same way as calcium. The amount of exchangeable cations is significant because these

Table 1. Concentrations of sodium, potassium, magnesium, calcium, strontium and barium (exchangeable cations) in the Tisma soil samples, mg/kg.

Sampling site	Na	K	Mg	Ca	Sr	Ba
La Montaña 1997	13	288	693	6590	263	510
Cuatro Esquinas 1997	11	2340	780	4120	59	159
Las Conchas 1997	23	1200	875	5640	53	103
Santa Cruz 1997	18	820	843	5440	68	225
El Rodal 1994	13	304	784	3800	90	437
16 de Julio 1994	12	410	576	3240	79	329
Noel Morales 1994	69	934	830	5900	42	83

may combine with organic pesticides. According to Laitinen (1989) besides hydrogen ions, calcium, magnesium and potassium may also combine with compounds such as organophosphates and slow down their disintegration. The total of cation milliequivalents ($Ca^{2+} + Mg^{2+} + K^+ + Na^+ + Sr^{2+} + Ba^{2+}$), which in this study is used to reflect the cation exchange capacity of the soil, is distributed as follows: La Montaña 41 me/100 g, Cuatro Esquinas 33 me/100 g, Las Conchas 33 me/100 g and Santa Cruz 37 me/100g. Table 1 shows the concentrations of exchangeable cations in analysed samples from these farms. The concentrations from three farms studied in 1994 are also included.

4. Clay mineralogy

Mineral determinations show that the samples contain mostly swelling, smectitic clay minerals. In the clays from La Montaña and Cuatro Esquinas another important mineral is quartz. The samples from Las Conchas contain mainly smectite and zeolite, and the clays from Santa Cruz smectite, quartz and plagioclase. The ion-exchange capacity of a clay depends on its composition, in particular on the amount of clay minerals and zeolites. For example, the ion-exchange capacity of clay containing abundant montmorillonite (i.e., smectitic clay) is 90 me/100 g. In Finland the ion-exchange capacity of clays is only 10 - 30 me/100 g due to their composition; they contain mainly quartz and feldspar, and as clay minerals mica and hydromica group minerals, some of them forming mixed-lattice minerals, chlorite, and minor amounts of vermiculites (Soveri 1950, 1956).

For any study of the adsorption and migration of chemicals, it is important to know the mineral composition of the clays. In this case a great deal of the clay minerals are smectitic, i.e., they have swelling lattices (e.g., montmorillonite), which have a particular capacity of adsorbing cations, anions and even organic molecules, such as pesticide com-

pounds. When conditions change, they also release the adsorbed substances readily. The zeolite group also has a high ion-exchange capacity and can furthermore adsorb organic molecules.

5. Pesticides

The remnants of organochloridic pesticides in the soil with a comparison of results obtained by different laboratories are shown in Table 2. Significant amounts of pesticides of organic chlorine compound type such as DDT and its variants (DDD, DDE) and dieldrin were found in the soil samples from the Tisma area according to the determinations done in the laboratory of the Agricultural Research Institute. The check samples were analysed in the UNI laboratory in Nicaragua, and only in one of them, a subsoil sample from the farm of Santa Cruz, a considerable amount of pp'DDE, 0.124 mg/kg was found. The El Rodal farm sample contained 0.152 mg/kg of pp'DDE in the surface part of the soil, 0.164 mg/kg at a depth of 13 cm and 0.186 mg/kg at 25 cm. In a sample from the same farm taken in 1994 the department of environmental studies at the University of Jyväskylä in Finland found considerable amounts of DDE, 0.52 mg/kg and in addition 8.9 mg/kg of toxaphene.

The Ministry of the Environment has set 0.04 mg/kg as a limit value for polluted soil. Determinations made at the MTT show that concentrations of dieldrin and endosulphanes in the Las Conchas farm sample were higher than permissible. In addition concentrations of pp'DDE were high, 0.432 in the topsoil sample and 0.730 mg/kg in the subsoil sample.

Results show that concentrations of pesticide remnants are generally lower in the topsoil than at a depth of about 20 cm. The Santa Cruz farm is an exception, where MTT determinations showed concentrations of pp'DDT in the topsoil to be 0.265 mg/kg and in the subsoil 0.028 mg/kg, and pp'DDE in the topsoil 0.426 mg/kg and in the subsoil 0.070 mg/kg. Analyses performed in Nicaragua showed a concentration of 0.124 mg/kg DDE in the subsoil, while in the topsoil it was not detected. In the field of this farm sugar durra was cultivated and apparently pesticides containing DDT are still used.

Abundant elements and salts may be dissolved into the groundwater from the volcanic and weathered soil in the Tisma area. Water analyses show that in places pesticides have ended up even in water wells. The water quality of shallow wells is easily affected by dirty surface water, as there are no proper sewers and sewage water is often emptied

Table 2. Organochloridic pesticide remnants in the Tisma soil samples 1994 and 1997.

Organic chlorine compounds mg/kg, The Agricultural Research Centre of Finland (Maatalouden tutkimuskeskus) 1997.						
	Atrazine	o,p'-DDE	p,p'-DDE	p,p'-DDD	o,p'-DDT	p,p'-DDT
La Montañita A	<	<	0.109	<	0.01	0.028
La Montañita B	<	<	0.028	<	<	0.007
Cuatro Esquinas A	0.025	0.007	0.417	<	0.06	0.105
Cuatro Esquinas B	<	0.012	0.536	<	0.088	0.109
Las Conchas A	<	0.007	0.432	<	0.043	0.122
Las Conchas B	<	0.014	0.73	0.008	0.098	0.201
Santa Cruz A	<	0.007	0.426	0.012	0.058	0.265
Santa Cruz B	<	<	0.07	<	0.009	0.028

	Dieldrin	α-endo-sulphane	β-endo-sulphane	endosulphane sulphate
La Montañita A	<	<	<	<
La Montañita B	<	<	<	<
Cuatro Esquinas A	<	<	<	<
Cuatro Esquinas B	<	<	<	<
Las Conchas A	0.025	0.006	0.018	0.029
Las Conchas B	0.067	<	<	<
Santa Cruz A	<	<	<	<
Santa Cruz B	<	<	<	<

Organic chlorine compounds mg/l, Universidad Nacional de Ingeniería, Managua 1997.

	Toxaphene	DDE	Oxychlorane
El Rodal 1	-	0.152	<
El Rodal A	-	0.1642	<
El Rodal B	-	0.1861	<
La Montañita A	<	<	<
La Montañita B	<	<	<
Cuatro Esquinas A	-	<	<
Cuatro Esquinas B	-	<	0.087
Cuatro Esquinas C	<	<	<
Las Conchas A -	<	<	0.246
Las Conchas B -	<	<	0.123
Santa Cruz A	<	<	0.059
Santa Cruz B	<	0.124	<

Concentrations of DDD, DDT, TDE, HCB, HCH, lindane, aldrin, heptachlor and dieldrin were below the detection limit in all samples.

Organic chlorine compounds mg/kg, University of Jyväskylä, Finland, Department of Environmental Studies 1994.

	Toxaphene	DDE	DDD	DDT
El Rodal B	8.90	0.52	0.02	0.06
16 de Julio A	0.80	0.21	<0.01	0.01
16 de Julio B	0.09	0.04	<0.01	<0.01
Noel Morales A	2.20	0.48	<0.01	0.06
Noel Morales B	2.80	0.92	<0.01	0.11

Table 3. Chloride, nitrate and sulphate concentrations (mg/l) in groundwater samples from wells studied in the Tisma area 1994 and 1997.

	Cl	NO ₃	SO ₄
Well 1	17.3	16.0	8.0
Well 2	13.5	6.2	5.0
Well 3	48.0	96.0	9.0
Well 4	11.3	10.3	3.3
Well 5	70.0	<0.2	30.3
Well 6	13.0	43.0	13.5
Well 7	64.4	206	18.8
Well 8	11.8	2.3	4.3
Well 9	17.4	107	7.3
Well 10	9.6	6.1	3.1
Well 11	18.7	47.5	24.3
Well 12	11.8	11.1	10.3
Well 13	35.2	23.1	30.6
Well 14	56.1	53.3	35.3

from the houses directly into the yard. The wells are often poorly protected. Dirt and bacteria from animal droppings are transported by surface water, which then infiltrates into the groundwater.

The quality of well water analysed in the 1994 study was mostly good as regards physico-chemical properties. However some high element concentrations were found in surface waters. For example, the water of Laguna de Tisma in the vicinity of Tisma contained 46 µg/l of lead and 71 200 µg/l of zinc. Recommendations for maximum contents in household water in Finland are 10 µg/l of lead and 3 000

Table 4. Groundwater quality in 14 Tisma area wells, sampled 1994 and 1997.

	Min.	Max.	Mean	Median	Quality of household water in Finland (Sosiaali- ja terveystieteiden ministeriö 1994)
Temperature °C	27	29.7	28.4	28	
pH	7.6	8.2	8.0	8.0	6.5-9.5
Electrical Conductivity mS/m, 25°C	41.1	114	67.9	63.3	
Colour Pt mg/l	<5	5	5	5	<15
Alkalinity mmol/l	3.6	8.6	5.0	4.6	
KMnO ₄ consumption mg/l	1.1	4.6	2.4	2.4	12
Br mg/l	<0.1	0.3	0.1	0.1	
Cl mg/l	9.6	70	28.4	17.4	100
F mg/l	0.19	0.77	0.43	0.34	1.5
NO ₃ mg/l	<0.2	206	44.9	19.5	25
PO ₄ mg/l	0.04	0.55	0.19	0.12	0.3
SO ₄ mg/l	3.1	35.3	14.5	9.7	150
Ag µg/l	0.03	1.73	0.55	0.32	10
Al µg/l	3.5	105	19.2	7.5	200
As µg/l	4.2	16.8	8.5	7.2	10
B µg/l	125	461	235	229	300
Ba µg/l	17.5	139	78.7	79.5	700
Be µg/l	<0.1	<0.1	<0.1	<0.1	
Bi µg/l	<0.03	<0.03	<0.03	<0.03	
Ca mg/l	15.7	71.4	35.2	35.1	100
Cd µg/l	<0.02	0.26	<0.02	<0.02	5
Co µg/l	<0.02	0.16	<0.02	<0.02	
Cr µg/l	<0.20	3.25	0.57	0.29	50
Cu µg/l	<0.04	10.2	2.6	1.5	1000
Fe mg/l	<0.03	0.07	<0.03	<0.03	0.2
K mg/l	16.3	55.8	22.9	19.5	12
Li µg/l	0.56	9.44	3.86	3.16	
Mg mg/l	4.76	26.1	11.4	9.76	50
Mn µg/l	0.2	97.4	13.5	2.9	50
Mo µg/l	2.41	8.43	4.79	4.31	70
Na mg/l	59.2	183	88.2	79.4	150
Ni µg/l	<0.06	0.88	<0.06	<0.06	20
Pb µg/l	<0.03	14.0	1.4	0.1	10
Rb µg/l	5.22	14.50	9.26	8.62	
Sb µg/l	0.07	0.16	0.11	0.11	5
Se µg/l	<0.50	4.99	1.44	1.02	10
Si mg/l	22.9	36.3	29.4	30.1	
Sr µg/l	91.3	315	189.6	187	
Th µg/l	<0.02	<0.02	<0.02	<0.02	
Tl µg/l	<0.02	<0.02	<0.02	<0.02	
U µg/l	1.36	5.77	2.23	1.73	
V µg/l	182	930	365	323	
Zn µg/l	3.1	67.1	17.8	11.4	3000
Hg µg/l					1

µg/l of zinc (Sosiaali- ja terveystieteiden ministeriö 1994).

The 1997 study shows that the groundwaters of Tisma are slightly basic with pH values of 7.6-8.2. Electrical conductivities are 40-114 mS/m, reflecting a rather high concentration of dissolved substances. The effect of human activities is evident especially in shallow wells in the form of rather high concentrations of chloride, sodium, nitrate and

manganese. Table 3 shows the concentrations of chloride, nitrate and sulphate in the wells of Tisma. However concentrations of heavy metals and some rare elements (i.e., Be, Bi, Cd, Co, Fe, Ni, Th and Tl) are extremely low, often below detection limit. Bromide concentrations are also low (Table 4).

Four of the Tisma water samples were also analysed for bacteria in the UNI laboratory. In the

farm well of Las Conchas the amount of coliform bacteria was 22 000/100 ml and that of fecal coliform bacteria 2 200/100 ml. The high bacterial content shows that dirty surface water has seeped into the well. Risk of pollution is increased by poor protection of the well and by its shallowness. At the farm there is a spring which also showed high concentrations of bacteria: 17 000/100 ml coliform bacteria and 4 500 /100 ml fecal coliform bacteria. Bacterial content was also high at the San Jeronimo farm: 7 000/100 ml coliform bacteria and 6 800 /100 ml fecal coliform bacteria. The physico-chemical properties of the water samples were good (Kukkonen et al. 1998).

From the wells at the farms of El Rodal, El Espejo, Las Conchas and San Jerónimo, pesticide remnants (organic chlorine and phosphorus compounds) were analysed in the UNI laboratory. The well water of El Rodal contained 0.0020 mg/l lindane and 0.0045 mg/l oxychlordane. These chemicals were also found in the wells of El Espejo and San Jerónimo, but the concentrations were not reported in the analysis results. For the sake of comparison some well water was analysed in the Finnish MTT laboratory for the most common pesticides. In the sample from El Rodal 0.87 µg/l atrazine was found, and in that from Las Conchas the concentrations were below the detection limit, which for organochlorine compounds is 0.02 µg/l and for other pesticides on an average 0.50 µg/l. The results of analyses performed in Nicaragua and those performed in Finland on check samples differed substantially from each other due to differences in analytical techniques and sample treatment.

Water samples from a lake in Tisma, Laguna de Tisma, were analysed in 1994 and again in 1997. In 1997 the concentration of aluminium was 665 µg/l and that of zinc 11.2 µg/l, whereas in 1994 the amount of zinc was 71 200 µg/l. The bacterial content was also high: coliform bacteria 22 000/100 ml and fecal coliform bacteria 7 800/100 ml. Nicaraguan studies show that cholera-causing bacteria occur in Laguna de Tisma. Regardless of this, the lake is generally used for fishing.

Results from Santo Tomás

The soil in the area of Santo Tomás and La Libertad consists mainly of weathering products of old lava rocks. The stream sediments are sand and fines, formed from the weathered soil and sorted by water. Extremely iron-rich laterite occurs in the

vicinity of Santo Tomás. Stream sediment samples were taken at the same sites as the water samples: along Río Mico and its tributary San Juan. Table 5 shows the element concentrations of soil samples analysed at GTK, and mercury concentrations determined from check samples in the UNI laboratory.

The mercury concentrations determined in the UNI laboratory differed rather considerably from those determined at GTK. The clay concentrations of the samples are 12 % (Sample 11), 9 % (12), 13.5 % (14) and 44.5 % (20). Their average grain-size compositions are fine sand, sand and very fine sand (silt).

The stream sediment samples of La Libertad contained a maximum of 0.914 mg/kg metallic mercury (Sample 12) about 2 km from the mining area, but 10 km downstream at the lower reaches of the river it was 0.285 mg/kg (Sample 14). The limit value for polluted soil in Finland is 0.2 mg Hg/kg. Mercury evaporates readily into the atmosphere and comes down again with the rain. The sample highest in mercury (12) was fine sand with 9 % clay. It also contained more gold and silver than the other samples. Sample 14 was sand and fine sand with 13.5 % clay. The most coarse-grained sample (11) was sand, and it contained very little mercury. Coarse-grained soil does not adsorb mercury as well as finer-grained sediments. Mercury is a very volatile active element, which readily forms compounds with soil particles and substances dissolved in the water. The soil of the investigated area contains considerably more aluminium, iron, manganese and especially titanium than the weathered material formed in cooler climates. High concentrations are typical of the laterite soil of tropical areas, which are characterized by advanced weathering.

Water investigations in Santo Tomás focused on groundwater quality and the water of Río Mico and also on the potential of the groundwater for economic use. There are plans to pump water from Río Mico to the town of Santo Tomás, which suffers from water shortage. It is feared that the gold mines of La Libertad near the upper reaches of the river

Table 5. Concentrations of silver, gold, mercury and lead in stream sediments of the rivers San Juan and Río Mico.

	Ag mg/kg	Au g/kg	Hg mg/kg	Hg mg/kg (UNI)	Pb mg/kg
Sample 11	2,5	154	0,035	0,11	35
Sample 12	5,2	1250	0,914	0,20	43
Sample 14	1,0	790	0,285	0,002	17
Sample 20	1,0	9	0,037	0,002	5

Table 6. Water quality in the Quipor reservoir, Río Mico and San Juan.

	Quipor reservoir	San Juan, La Libertad	Río Mico, La Libertad	Río Mico, San Pedro de Lóvago	Río Mico, Santo Tomás
Temperature °C	26.1	26.8	26.8	26.0	24.9
pH	7.8	7.2	7.3	7.5	7.5
Electrical conductivity mS/m. 25°C	23.3	7.2	8.0	9.8	12.2
Colour Pt mg/l	40	10	15	20	60
Alkalinity mmol/l	2.2	0.37	0.53	0.74	0.96
KMnO ₄ consumption mg/l	17	3.0	3.8	5.0	16
Br mg/l	<0.1	<0.1	<0.1	<0.1	<0.1
Cl mg/l	6.9	5.8	5.6	5.8	6.4
F mg/l	<0.1	<0.1	<0.1	<0.1	<0.1
NO ₃ mg/l	<0.2	0.8	<0.2	<0.2	0.2
PO ₄ mg/l	0.04	<0.02	<0.02	0.02	0.04
SO ₄ mg/l	0.5	4.2	2.4	2.0	1.2
Ag µg/l	0.93	0.19	0.39	0.28	1.92
Al µg/l	165	4.2	17.6	112	178
As µg/l	0.5	0.16	0.22	0.45	0.6
B µg/l	10.6	15.0	11.8	12.1	12.9
Ba µg/l	19.0	55.1	26.3	25.6	32.2
Be µg/l	<0.1	<0.1	<0.1	<0.1	<0.1
Bi µg/l	<0.03	<0.03	<0.03	<0.03	<0.03
Ca mg/l	21.4	4.4	5.4	7.7	11.0
Cd µg/l	<0.02	<0.02	<0.02	<0.02	<0.02
Co µg/l	0.21	0.76	0.17	0.09	0.1
Cr µg/l	0.54	<0.02	<0.02	0.28	0.32
Cu µg/l	1.8	0.5	0.3	1.1	1.1
Fe mg/l	0.17	0.2	0.22	0.21	0.27
K mg/l	1.17	0.81	1.42	1.38	1.87
Li µg/l	<0.3	1.28	0.92	1.05	0.9
Mg mg/l	10.9	2.36	2.41	3.08	3.37
Mn µg/l	29.8	260	80.8	16.0	12.6
Mo µg/l	0.03	0.09	0.08	0.09	0.08
Na mg/l	11.4	5.3	5.9	7.7	9.4
Ni µg/l	0.87	0.18	0.15	0.24	0.29
Pb µg/l	0.11	0.08	0.06	0.54	0.08
Rb µg/l	1.04	0.93	1.82	1.60	1.67
Sb µg/l	<0.02	0.02	0.02	0.03	0.03
Se µg/l	<0.5	<0.5	<0.5	<0.5	<0.5
Si mg/l	17.1	6.9	9.6	9.8	10.3
Sr µg/l	78.5	24	32	43	51.6
Th µg/l	<0.02	<0.02	<0.02	<0.02	<0.02
Tl µg/l	<0.02	0.03	<0.02	<0.02	<0.02
U µg/l	0.04	<0.01	<0.01	0.06	0.03
V µg/l	7.62	0.24	0.66	1.44	2.48
Zn µg/l	11.4	3.3	4.8	7.8	27.4
Hg µg/l		0.07	0.07	0.07	0.07

have polluted Río Mico. The mining companies claim not to have caused pollution of the waters. However during the rainy season, large amounts of solid substances are washed into the river in suspension and private gold-diggers use mercury to separate the gold. Regardless of the recycling of cyanide used in separation of gold and silver, it is suspected that some of it ends up in the water.

The physico-chemical properties of the water

were mainly good in the seven wells studied in the Santo Tomás area, considering their protective structures, which were poor in places. Most of the wells in this area are so deep that pollutants do not easily reach groundwater even when protection is poor. Neither do pesticides constitute a threat in this area as it is mainly cattle farming country. High aluminium concentrations (347µg/l and 1280µg/l) were found in two wells. The pH value was 5.8 in a soil

sample from the close vicinity. Aluminium is dissolved into the groundwater in acidic or extremely basic conditions.

The environmental effects of the gold mines in La Libertad were studied by analysing four water samples from Río Mico and its tributary San Juan. These samples were almost neutral and their electrical conductivities low, which shows that the amount of substances dissolved in the water is low. The colour of the water grows stronger towards the lower reaches, mainly due to the amounts of solids and humus carried in suspension by the river. The humus concentration is also reflected by the KMnO_4 consumption, which increases towards the lower reaches of the river, as does aluminium concentration (from 4.2 $\mu\text{g/l}$ to 178 $\mu\text{g/l}$). However, manganese concentrations decrease towards the lower reaches from 260 $\mu\text{g/l}$ to 12.6 $\mu\text{g/l}$. Manganese is released by weathering and by the mining industry (Reimann et al. 1998). The concentrations of analysed compounds and elements, including heavy metals, are low except for two rather high concentrations of manganese at the upper reaches of Río Mico. Concentrations of nitrate and potassium, which indicate water pollution, and electrical conductivity, as well as calcium, magnesium and sulphate concentrations, which indicate influence by human activities, are also low (Lahermo et al. 1990). The results of water analyses from the Quipor reservoir, Río Mico and San Juan are shown in Table 6.

Discussion

The problems of the Tisma area include abundant use of pesticides, shortage of irrigation water, erosion and pollution of the environment. The breakdown of pesticides in the soil is favoured by the abundant sunlight, heat and microbes, where they have not been destroyed by excessive use of pesticides. On the other hand the character of the fine-grained soil and its adsorption properties add to the binding of pesticides to the soil, thus preventing their chemical breakdown. Results of the study show that the composition of the clay component of the soil and the large proportion of smectite (a swelling clay mineral) contribute markedly to the binding of pesticides to the soil. Smectite and other clay minerals and zeolite are typical of soil that has undergone advanced weathering. They have a large specific surface area and a capacity of binding to themselves cations and anions of chemical compounds, as well as organic molecules. As a conse-

quence the disintegrating effect of light, heat and microbes is weaker than generally presumed in countries with a warm climate.

In volcanic agricultural areas, where the soil consists partly of wind-blown ash, the light soil is susceptible to wind erosion. The wind may spread the soil and chemicals bound to it over a large area thus increasing pollution of surface and ground waters. Soil is also loosened and transported by water erosion especially in areas where talpetate layers, which prevent the water from infiltrating, are present near the ground surface. This soil material travels in the rivers, and at the same time pesticides are dissolved in the water and some remaining in the river sediments.

In general the pesticides adsorbed in the soil are released when pH conditions change. An example is shown by a study made at the Pacific coast of Nicaragua, where in the deltas of the rivers Leon and Chinandega high pesticide concentrations were found in sea organisms and in the sediments of the lagoons (Lacayo et al. 1997). By comparing these results with the environmental conditions of the study area in question, it can be concluded that the pesticides contained by the soil material from the agricultural areas were released when they were transported along with the solids through swampy, acidic delta environments to a marine, basic environment.

In neutral soil a pesticide still not adsorbed by the topsoil is washed with the rainwater to underlying, compact layers, which contributes to the fact that topsoil contains less pesticide remnants than the underlying, more clayey deposits. In addition, the breakdown of pesticides decreases in the subsoil due to lack of light and microbe action. During the dry season wind erodes the cultivated layer of the soil, which is then washed away during the rainy season. As a consequence it is necessary to cultivate the soil layer where the greatest amount of pesticides has accumulated, and thus hazardous chemicals become available to the plants. Examples are old cotton fields, which give no crops for years although cotton is no longer cultivated. Topsoil erosion thus increases the risk that pesticides adsorbed by deeper-lying deposits reach the plants.

The strong adsorption capacity of the substrate is a potential hazard to the cultivated land. Organic pesticide compounds are adsorbed by smectite, one of the minerals in the soil. At the same time the adsorption and storage capacity of the soil and substrate is weakened, so that fertilizers cannot be stored in the smectitic soil as it therefore has to compete with the pesticides.

In Nicaragua it is still possible to buy organochlorine compound pesticides although it is officially prohibited. They are very resistant, as some of them have a half-life of 10-20 years in the soil, and in addition they are extremely toxic and accumulate in organisms. There should be an absolute ban on sales of these pesticides.

In the countryside the majority of the population get their household water from private wells. In Tisma the water supply system comprises 447 households, i.e., 37% of the inhabitants. Sufficient household water is available and it is mostly of good quality, partly due to the depth of the wells, but there is a shortage of irrigation water. Abundant water is needed for cultivation, but excessive use of groundwater would cause lowering of the groundwater table and a permanent decrease of groundwater resources. For this reason land use planning and water-saving cultivation methods should be further developed. In the Tisma area water in shallow wells is threatened by pollution. The wells are often poorly protected and nitrate, chloride and sodium compounds, bacteria and pesticides get into the wells along with dirty surface runoff water. Protection of the wells and general improvement of the sanitary conditions would prevent pollution of the groundwater. The groundwater table lies at a depth from a few metres to more than 100 metres depending on the elevation of the terrain, which in this area ranges from 40 metres to over 240 metres above sea level.

The proposed solutions to the water supply problems of Santo Tomás include extension of the present reservoir of Quipor, pumping of water from Río Mico or some smaller and cleaner river to a planned water purification plant. The estimated amount of available household water would then be 6 000 m³/day. The present water requirement in Santo Tomás is about 2 600 m³/day. The Quipor reservoir receives its water from several streams that flow down the surrounding mountains. The water in the reservoir is of fairly good quality as to its physico-chemical properties (Table 6), but at times silt suspension is a problem. The water sample for analysis was taken during the rainy season, when water was abundant.

Drilling has been done and new drilled wells made in Santo Tomás with poor results, as no water has been found. During the last few years the valley of Llano el Jobo has been investigated as a possible site for a new reservoir. However the bedrock of the area was estimated to be too porous to contain the water of the reservoir. The negative attitudes towards construction of the reservoir are also due to

the fact that it would submerge several farms. The present four wells of the town of Santo Tomás are situated in this valley and yield groundwater of good quality. According to map interpretations and field observations there is probably more groundwater to be found in the fluvial deposits of the river valley plains, for example in the valley of Las Halillas, which is 10 km² in extent, and where groundwater is found at only a few metres' depth. An arrangement of the water supply of Santo Tomás so that surface water would not be used at all or be kept as a reserve system for the dry season would require construction of wells in a number of separate areas in order to obtain sufficient amounts of groundwater.

The water quality of Río Mico proved to be better than expected from information obtained beforehand. However it should be monitored all year round, in order to find out how the quality changes during the rainy and dry seasons. It is not known how much unpurified sewage water, cyanide and mercury is released into the river. Concentrations of solids were not determined either. If the water of Río Mico was found to be usable, it could be the solution to the water supply problems of La Libertad and Santo Tomás. Río Mico contains abundant water all the year round, whereas the smaller mountain brooks and streams become dry during the dry season.

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THREE DIFFERENT TYPES OF SVECOKARELIAN GRANITOIDS IN SOUTHEASTERN LAPLAND: MAGNETIC PROPERTIES CORRELATED WITH MINERALOGY

by
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Introduction

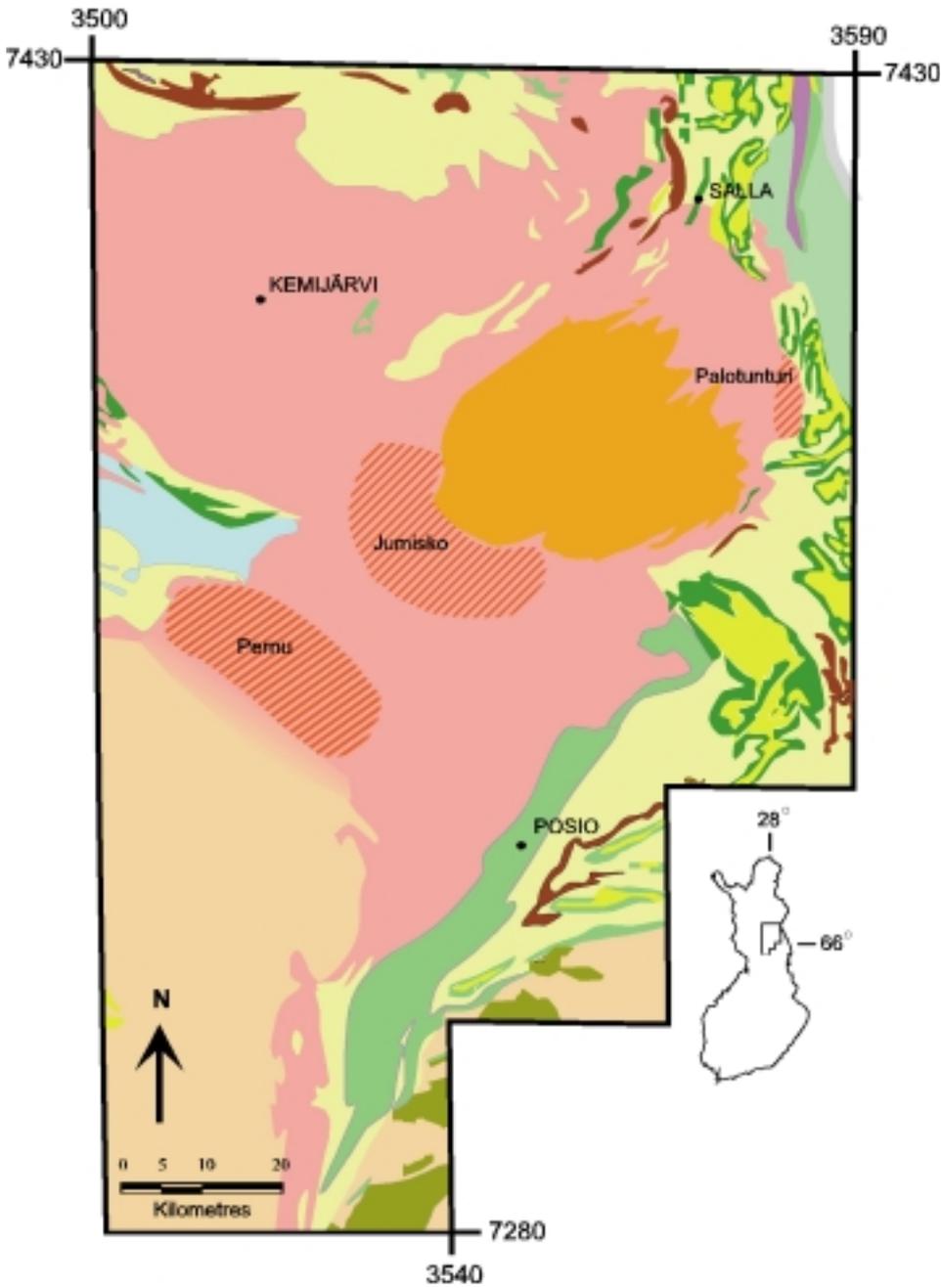
The predominantly highly magnetic early Proterozoic granitoids in central and southeastern Lapland are related to the intensive and areally one of the largest regional positive magnetic anomalies in Finland. Instead of being an isotropic granitoid pluton, the granitoids reveal strong internal variation of magnetic intensities and patterns, observed particularly on high-resolution aeromagnetic data. The systematic high-resolution aeromagnetic measurements (terrain clearance of about 35m), conducted by the Geological Survey of Finland (GTK), have proved to be effective in mapping even detailed bedrock structures. By one look at the aeromagnetic image the contact zones and continuous structural, as well as deformational patterns, can be localized and the gaps between adjacent outcrops can be filled. The aeromagnetic signatures reflect the magnetic variations in rocks, which are principally based on variations in concentration and grain fabric of ferrimagnetic grains (mainly magnetite) and ferromagnesian silicates (mainly biotite), and the orientation of biotite and magnetite grain fabrics. Hence the aeromagnetic data is a sensitive reflector of tectonic and lithologic variations in the crust.

The southeastern part of the Finnish Lapland has been studied by the University of Oulu (OU) since 1995. Intergrated geological (Niina Ahtonen, OU) and magnetic (Meri-Liisa Airo, GTK) investiga-

tions of different types of granitoids have been constructed as part of the geological mapping and interpretation of the area. The granites in southeastern Lapland can macroscopically be divided into three main types, which also have distinctive magnetic characteristics: granites of Palotunturi, Jumisko and Pernu (Fig. 1). Similar magnetic patterns are observed everywhere within the granitoid region, and therefore the three types can be used as representatives for the whole granitoid complex. This article summarizes the compositional variations of the three granite types and the present stage of the petrological, petrophysical and aeromagnetic comparisons. The ultimate goal is to discuss the origin, emplacement mechanism and conditions of the early Proterozoic granitoids in the southeastern part of the Finnish Lapland.

Geological and geophysical setting

Extensive remobilisation of the older crust characterizes the early Proterozoic Svecokarelian (Svecofennian) orogeny (at 1.9.-1.8 Ga ago) in the Karelian domain of the northern Fennoscandian shield (e.g. Gaál & Gorbatshev 1987). Large volumes of granitic material were generated in central and southeastern Finnish Lapland, referred to as the Central Lapland Granitoid complex or the Kemijärvi complex. According to Silvennoinen et al. (1980) the granites of the Kemijärvi complex formed during the main folding stage of the Svecokarelian



LEGEND

EARLY PROTEROZOIC

- Granite and granodiorite with gneissic inclusions
- Mica schist, black schist, conglomerate and arkosite
- Mafic and felsic metavolcanic rocks
- Carbonate- and calc-silicate rocks, black schists, metavolcanic rocks, BIF
- Quartzite
- Gabbro (2.2 Ga)
- Quartzite, arkosite and mica schist
- Mafic and ultramafic metavolcanic rocks
- Gabbro and peridotite (2.44 Ga)
- Intermediate and felsic metavolcanic rocks
- Carbonatite (2.0 Ga)

ARCHAEAN

- Tonalite-trondhjemite-granodioritic gneiss and migmatite
- Mostly Archaean ortho- and paragneisses

Fig. 1. Lithological map of the southeastern Finnish Lapland and the locations of the Palotunturi, Jumisko and Pernu granite areas. Modified after Korsman et al. (1997) and Ahtonen et al. (in prep.).

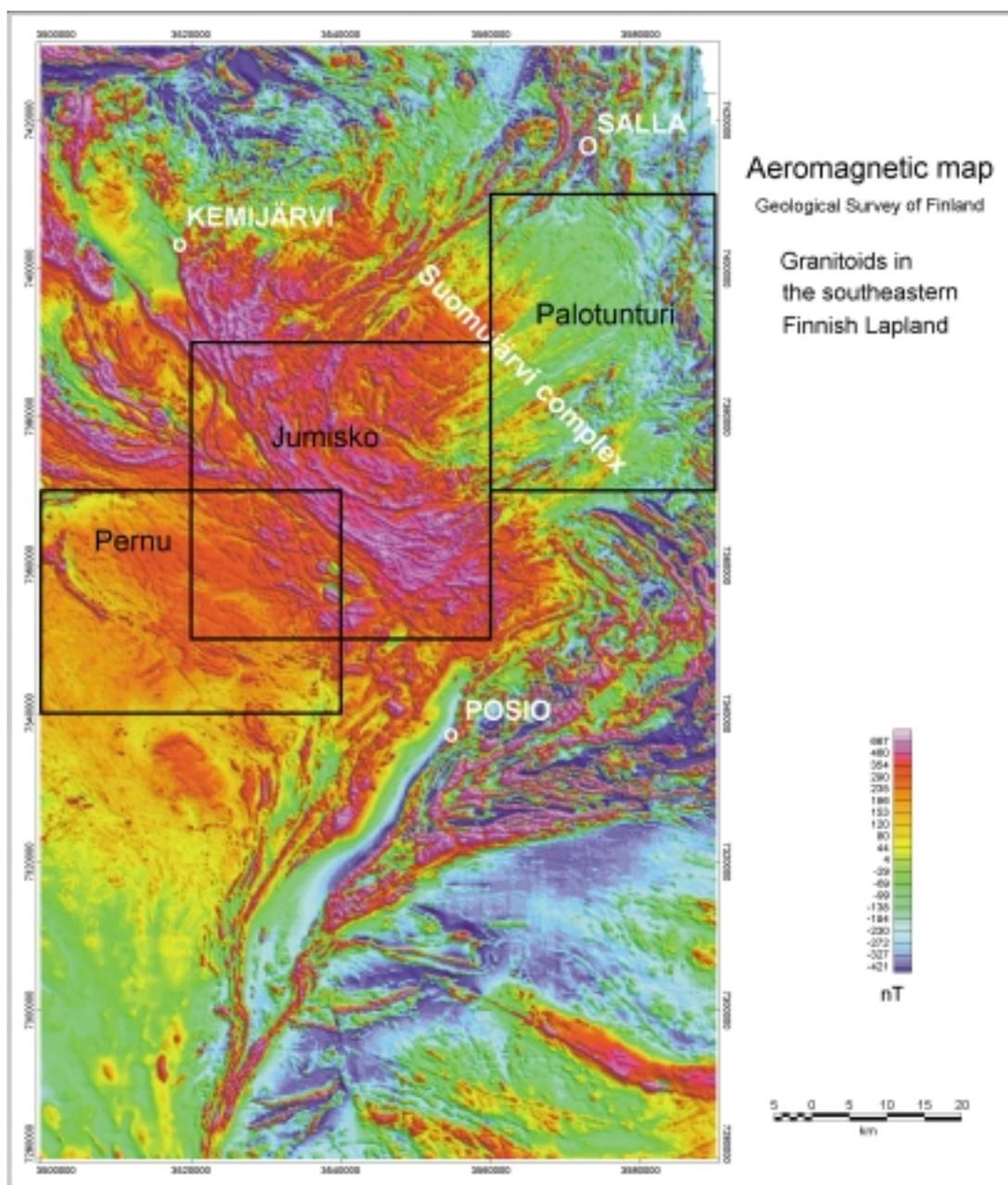


Fig. 2. Aeromagnetic anomaly map of the southeastern Finnish Lapland. Image frames of Figures 3-5 are outlined.

orogeny mainly as melting products from the Archaean basement complex. Also Huhma (1986) suggests that there was a considerable involvement of Archaean crustal material during the generation of the granitoids of the Karelian domain in eastern and northern Finland. Puranen (1989) has studied the iron- and magnetite-contents in the granites of Lapland on the basis of their densities and magnetic properties in relation to their chemically analysed iron content. In spite of the low average iron content in comparison to granites from other areas of Finland, the proportion of ferrimagnetic magnetite-bearing varieties in the Lappish granites is higher than it is in other areas of Finland. According to

Puranen, the even magnetite distribution in Lappish granites could be based on their high oxidation ratio, which has been inherited from a highly oxidized Archaean source material.

On aeromagnetic maps the intensive NW-SE trending regional positive anomaly, associated with the granitoids of the Kemijärvi complex, extends from eastern Finland to northern Sweden. Typical magnetic patterns for the whole Kemijärvi complex are represented in the magnetic image for the eastern part of the granitoid area (Fig. 2). The dominant magnetic feature is the general NW-SE orientation of magnetic patterns, especially related to the Jumisko granite area. The Pernu granitoids are separated

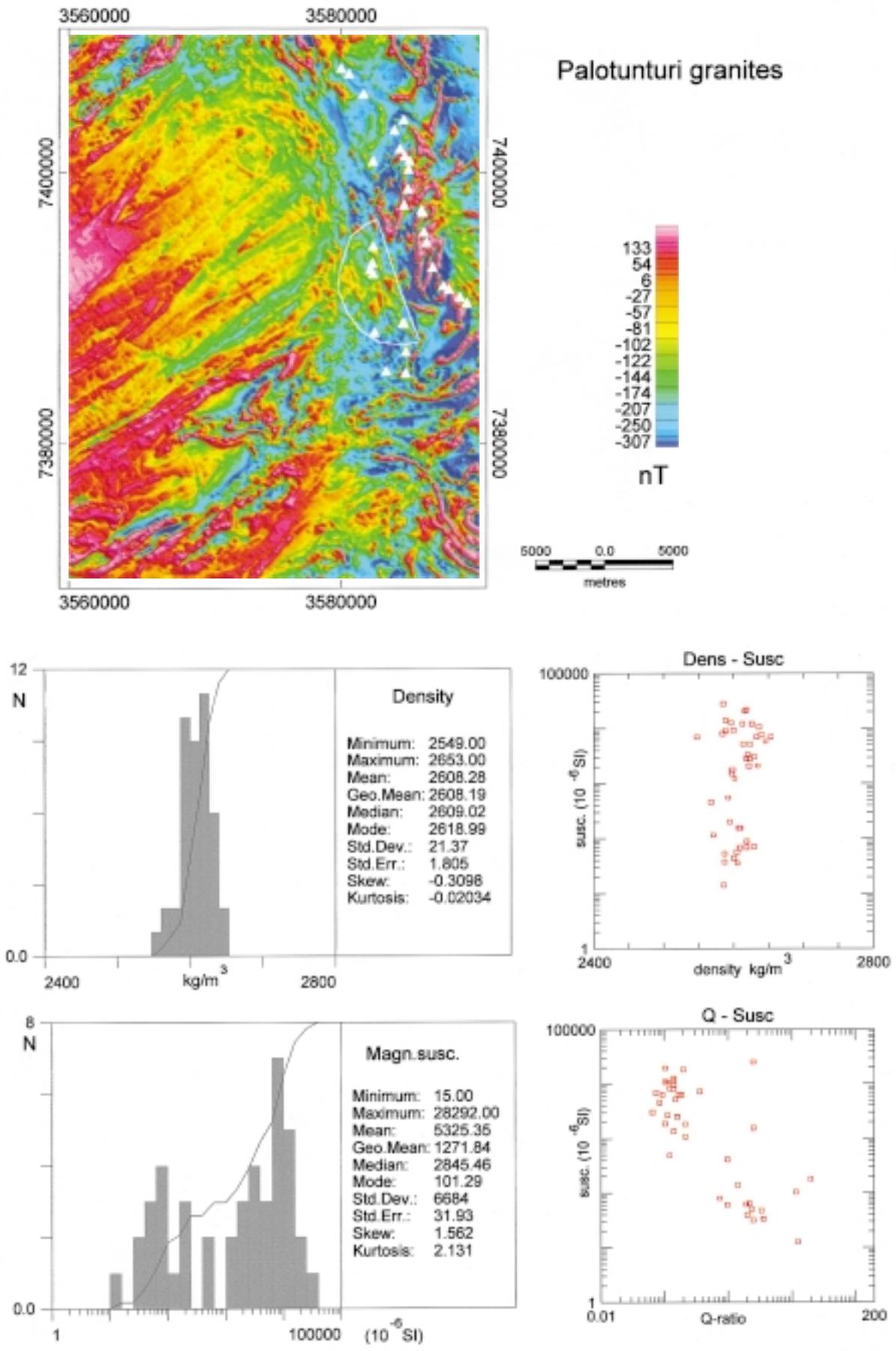


Fig. 3. Magnetic properties of Palotunturi granites. Palotunturi stock is outlined in the aeromagnetic image and granite sampling sites are shown by white triangles. Diagrams illustrate the petrophysical properties for the same samples.

from the Jumisko area by a fracture and fault zone with the same orientation. Structurally the Jumisko granites belong to the ortho- and paragneiss unit of the Suomujärvi complex (Evins et al. 1997), which is characterized by the overall NE-SW trend in aeromagnetic images. The Palotunturi granitoids occupy the chain of granite hills in the tectonic zone between the Archaean Suomujärvi complex and the early Proterozoic schists and greenstones in the Salla district.

A positive gravity anomaly is related to the Suomujärvi structural unit, and proves the existence of heavy material beneath the granites and granite gneisses, close to the surface in the Jumisko granite area (Airo 1999). Based on modelled gravity profiles, densities of mafic or granulite facies rocks are needed to explain this gravity anomaly. Similar gravity highs are associated with the southern parts of the granitoid area in central Lapland, and in northern Sweden at the Vettasjärvi granite of about the same age (1.8 Ga). Öhlander et al. (1987) have interpreted, that the Vettasjärvi granite is the product of crustal anatexis, and not connected at depth to a large granitic batholith.

The granitoid gneisses of the Kemijärvi complex cannot be sharply delineated on aeromagnetic images, but the boundaries smoothly disappear. This is different from typical Proterozoic late- and post-tectonic granitoids in Finland, which often have roundish shapes and sharp contacts with their country rocks, and are readily distinguished on aeromagnetic maps. Within the regional anomaly, the magnetic intensity increases towards the centre, and there are local anomaly bands which are remnants of supracrustals (Fig. 2). The structural variation follows the deformational structures of the surrounding Svecof Karelian supracrustal rocks. According to intergrated aeromagnetic and petrophysical investigations by Airo (1999), the tectonic framework for southeastern Finnish Lapland was created already during the pre-Svecof Karelian time. Most probably it originated during the Archaean doming, folding and faulting periods, and dominated later by the fracturing of the Karelian continent block during repeated early Proterozoic rifting episodes. The disruption of the Archaean continent is enhanced by the extensive NW-SE trending fracture zones crossing central Lapland. These fractures run parallel to the trend of the regional granite anomaly, and have their eastward continuations in Russian Karelia.

Aeromagnetic and petrophysical characteristics

The detailed magnetic appearance and internal structures of three distinctive granitoid types are displayed in aeromagnetic images for Palotunturi, Jumisko and Pernu granites in Figures 3-5. The petrophysical properties of the granite types are compared as frequency histograms of density and magnetic susceptibility, and as scatter diagrams of the magnetic susceptibility versus density or Q-ratio (the ratio of the remanent to the induced magnetization).

The Palotunturi granites form a roundish, weakly magnetic stock which is discordant with the country rock structures, outlined in Figure 3. According to the aeromagnetic image and petrophysical reference data, there are other, similar small-area granitoids in the same tectonic zone. Although no conspicuous internal structures are observed in the Palotunturi stock, such as magnetic zoning, there is a weak irregular magnetic pattern. Some magnetic signature would be expected, as about 50% of the samples from Palotunturi contain magnetic minerals according to their magnetic susceptibilities > 4000 ($\times 10^{-6}$ SI). The overall weak magnetization on the magnetic map is probably due to the surrounding regional magnetic low, which is related to the tectonic zone.

The narrow, elongated NW-SE trending bodies of the Jumisko granites are associated with strong, flame-like magnetic anomalies, and they form part of the magnetic arc which characterizes the southern part of the Suomujärvi complex (Fig. 4). They are typically highly magnetic, and 70% of the samples have susceptibilities > 4000 ($\times 10^{-6}$ SI). The Jumisko granite bodies intruded into the old NW-SE trending regional fracture zone, which can be followed for several hundreds of kilometers on aeromagnetic maps. The magmatic foliation in the Jumisko granites aligns with the NW-SE strike, as observed on outcrops.

Pernu granites introduce moderate, oval-shaped magnetic anomalies with an overall NW-SE trend (Fig. 5). They have no clear contact zones, but the anomaly amplitudes gradually decrease outwards. The magnetic patterns are slightly oriented, and there are remnants of anomalies due to more highly magnetic supracrustal rocks. Pernu granites are divided into three magnetic groups. The lowermost group with susceptibilities < 2000 ($\times 10^{-6}$ SI) predominates. About 50% of the samples have susceptibilities < 4000 ($\times 10^{-6}$ SI).

The frequency histograms of magnetic suscepti-

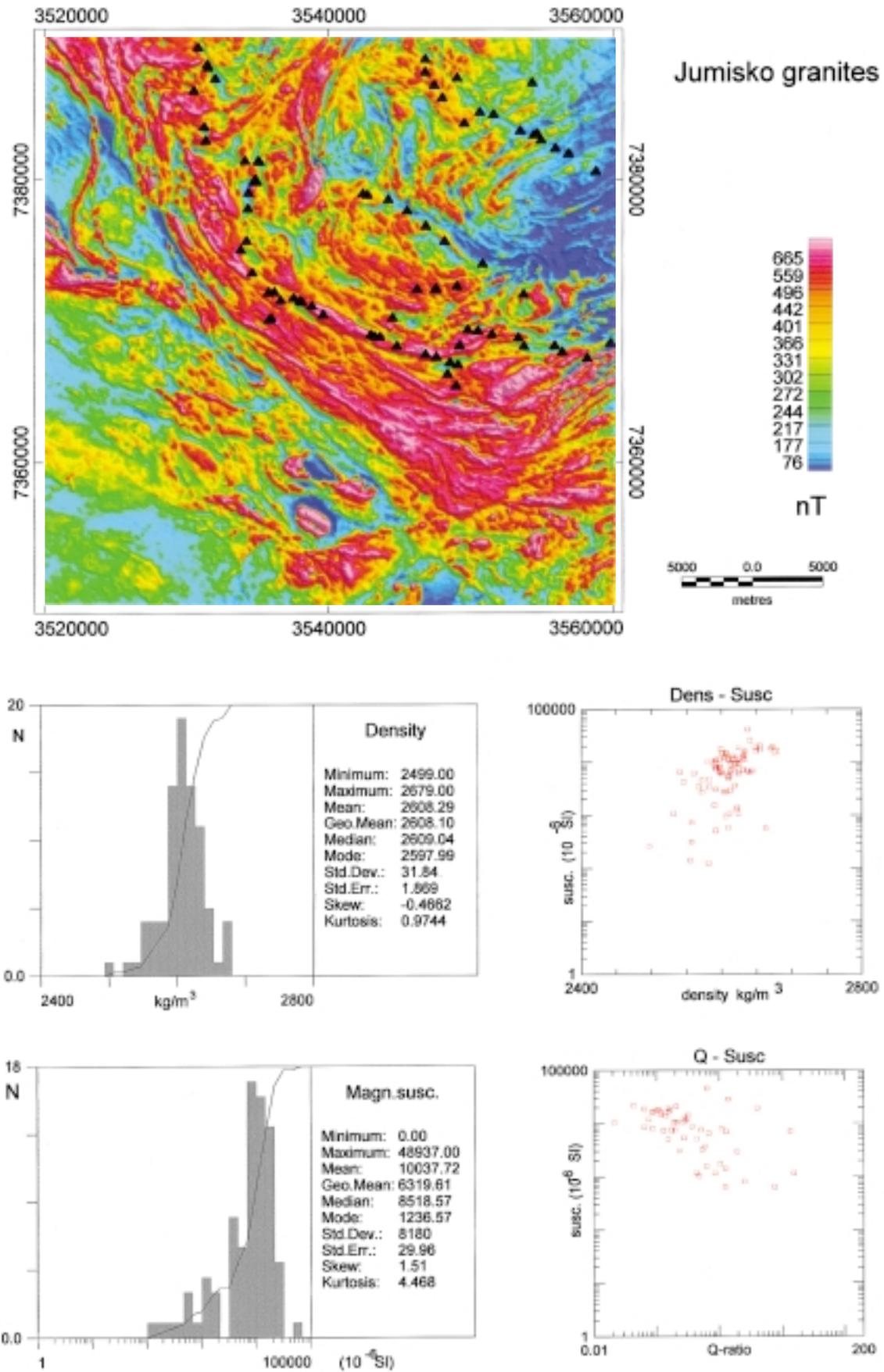


Fig. 4. Magnetic properties of Jumisko granites. Sampling sites of granites are shown by black triangles on the aeromagnetic image. Petrophysical properties for the same samples are illustrated by the diagrams.

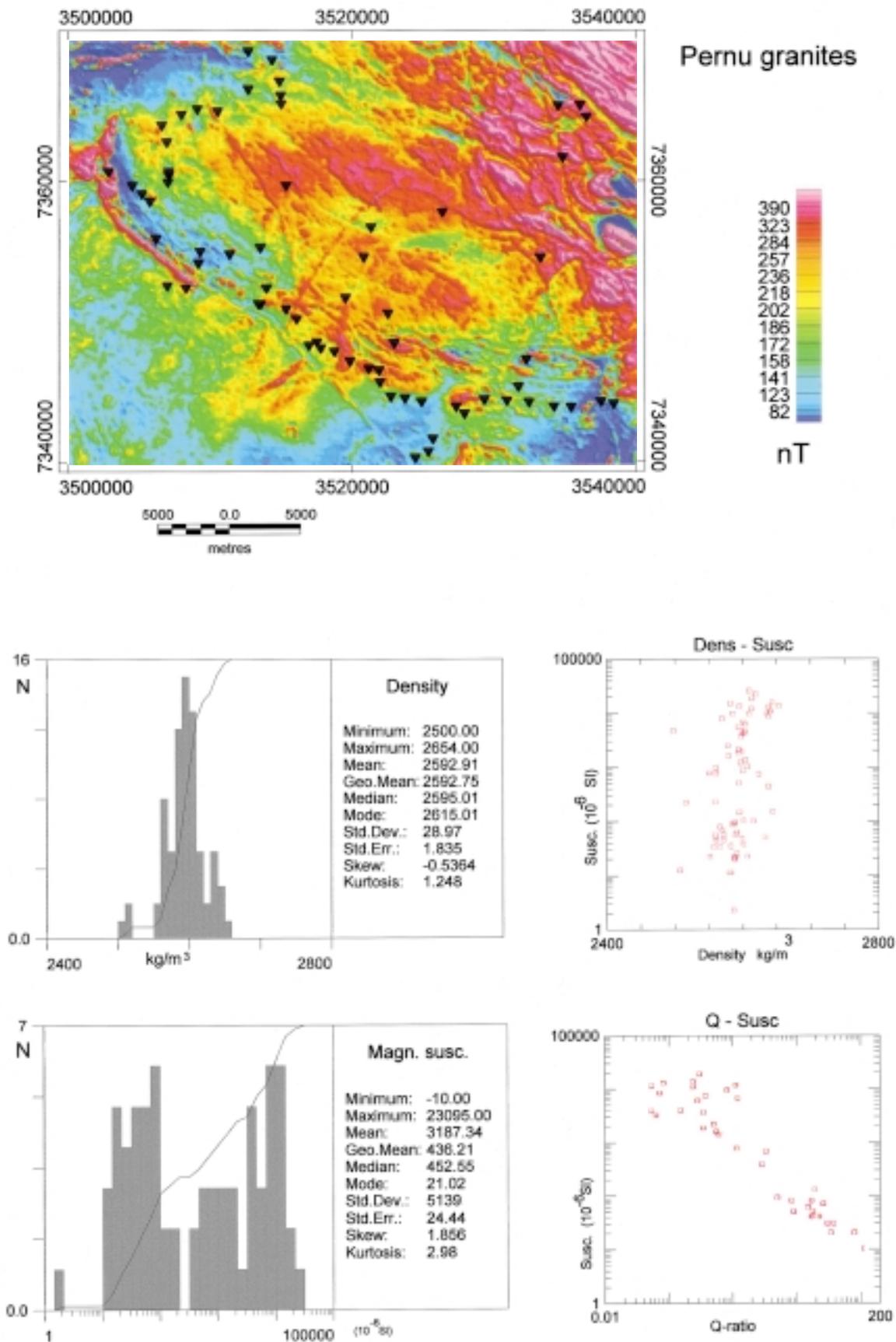


Fig. 5. Magnetic properties of Pernu granites. Sampling sites of granites are shown by black inverted triangles on the aeromagnetic image. Petrophysical properties for the same samples are illustrated by the diagrams.

bility in Figures 3-5, show the division of granite samples into three magnetic groups, with average susceptibilities of (a) 100-200, (b) 800-1000 and (c) 10000 ($\times 10^{-6}$ SI). These groups reflect (a) granite type containing practically no iron-bearing silicates, (b) magnetite-free granite with biotite as the principal iron-bearing mineral, and (c) magnetite-bearing granite. All three groups are represented in Pernu granitoids, while group (b) is absent from Palotunturi, and Jumisko displays group (c) almost totally. The explanation for the different magnetic

anomaly intensities between Palotunturi, Jumisko and Pernu granites on aeromagnetic maps is in the varied relative proportions of the ferromagnetic samples. In Jumisko granites, almost all of the samples are ferromagnetic, while in Palotunturi and Pernu the less magnetic varieties predominate.

Petrography and opaque minerals

All three studied granites have SiO_2 -content higher

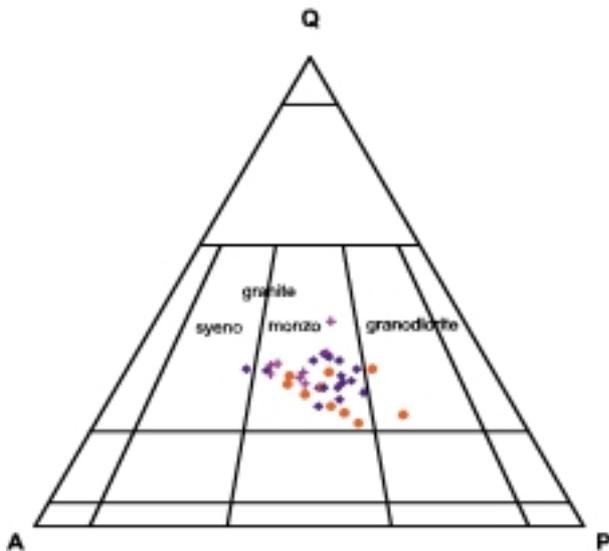


Fig. 6. The composition of granites in southeastern Lapland as indicated by the QAP-diagram after Streckeisen (1976). Q = quartz, A = alkali feldspars and P = plagioclase. Crosses denote the Palotunturi granites, filled red circles the Jumisko granites and blue diamonds the Pernu granites.

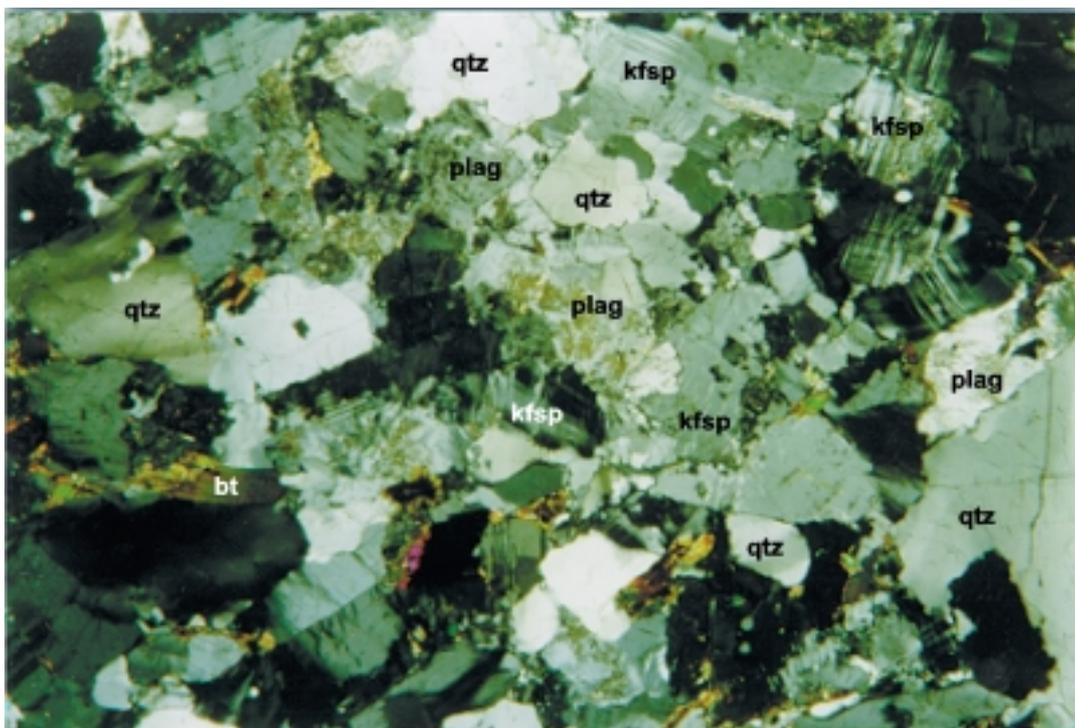


Fig. 7a)

than 69 wt% and they are slightly peraluminous. The main minerals are oligoclasic plagioclase, potassium feldspar, quartz and sometimes biotite. In the modal classification diagram (Fig. 6) after Streckeisen (1976), the granites of Palotunturi and most of the granitoids of Pernu are monzogranites. Also

most of the granites of Jumisko are monzogranites, but their composition changes to more granodioritic towards the northwest.

The granites of the Palotunturi area are medium grained, light grey to dark red in colour and deformed to a varying degree (Fig. 7a). The Pernu

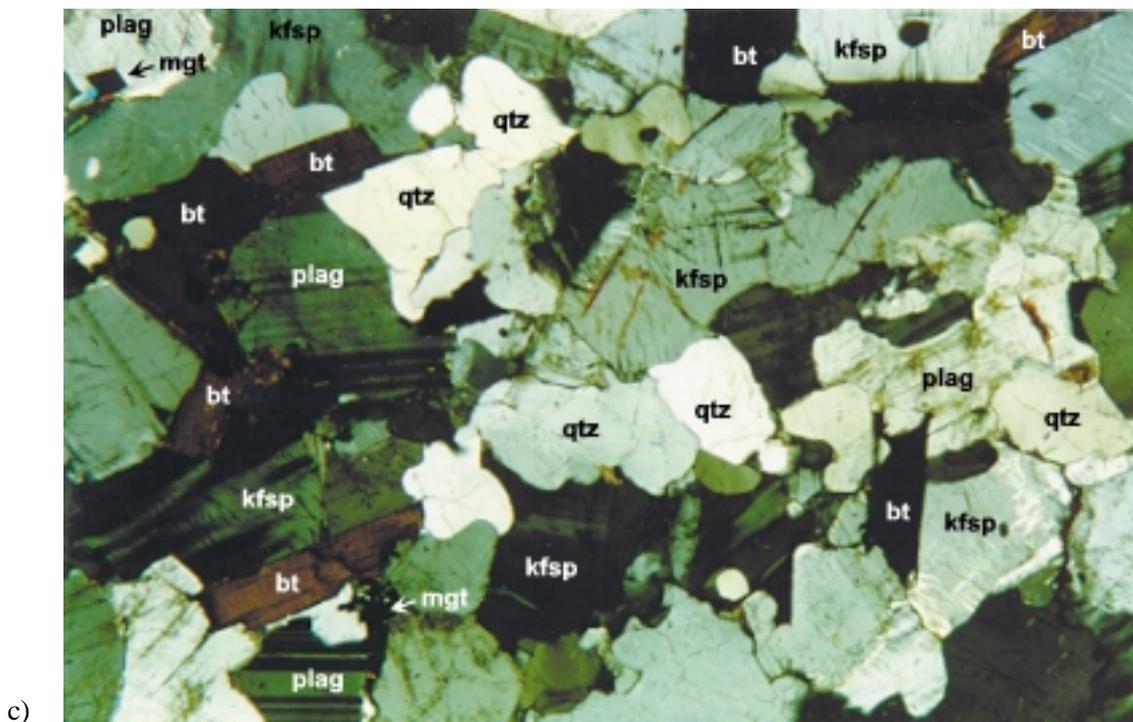
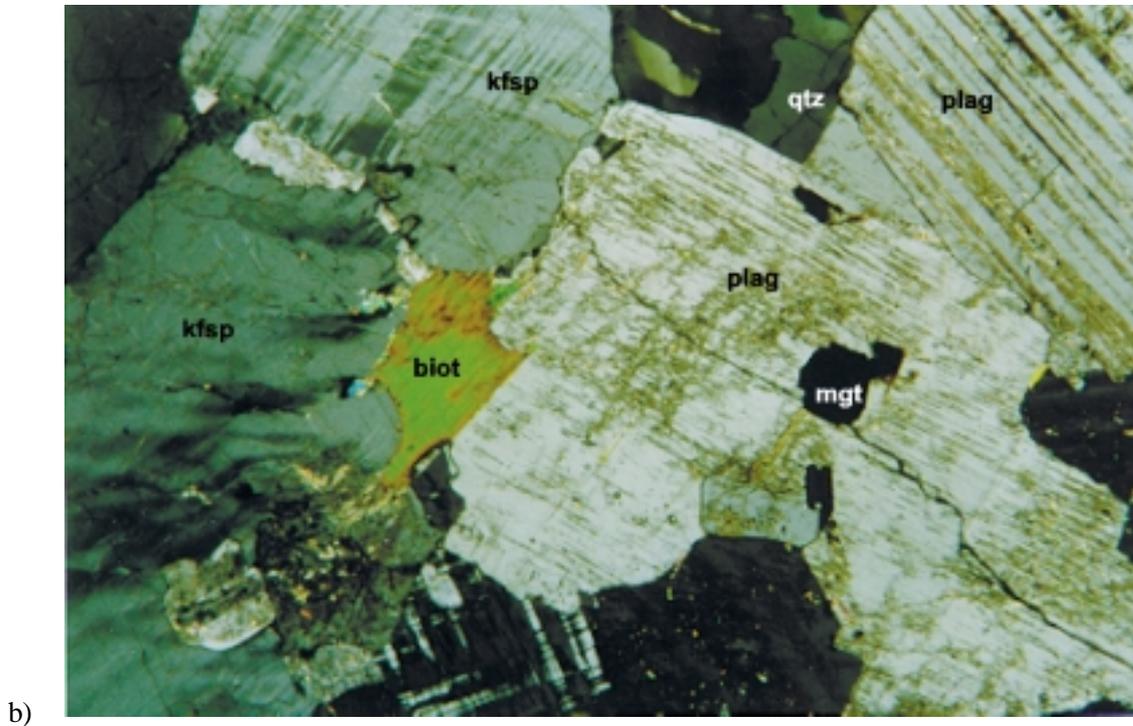


Fig. 7. Petrographic photographs of granites from a) Palotunturi, b) Jumisko and c) Pernu areas. Plag = plagioclase, kfsp = potassium feldspar, bt = biotite, qtz = quartz. Crossed nicols, magnification 33x, field of view is 4.5 mm wide.

granite area consists of three main granite types. The most abundant type is medium grained, reddish and slightly deformed granite (Fig. 7b). Other granitoid types are medium grained, lighter coloured, plagioclase richer and slightly deformed granite, and medium to coarse grained, porphyritic granite, which is biotite poor. Jumisko type granites are medium to coarse grained, K-feldspar porphyritic, red to greyish red, and slightly deformed (Fig. 7c). Feldspar phenocrysts have often NW-SE orientation. Pegmatites are very common in the area of Pernu and Jumisko, whereas in the area of Palotunturi they are more uncommon.

The content of dark minerals in the studied granites varies between 1.5 and 12%, generally being under 10%. Most of the dark minerals are biotite. The amount of opaque minerals is under 1%. Studies with reflected light microscope showed that nearly all of the opaque minerals are Fe-Ti-oxides. A great part of them in the Palotunturi granites is magnetite, which occurs as subhedral to euhedral grains. Grain size is typically 0.1-0.3 mm, but some larger grains with a diameter up to 0.6 mm are also present. The replacement of magnetite by hematite along the fractures and grain boundaries is common and sometimes very strong. Some large euhedral hematite crystals have remnants of magnetite. In addition to these, some crystals composed of ilmenite with hematite inclusions are also present. They are anhedral and have corroded grain boundaries. A few pure hematite crystals are also met.

The amount of Fe-Ti-oxide minerals is higher in the granites of Jumisko than in the other types studied. Most of these are magnetites which exhibit euhedral to subhedral grain shapes. Their grain size varies between 0.1-0.9 mm, and typically is below 0.4 mm. Small magnetite grains form sometimes groups close to biotite flakes, whereas larger grains occur separately. A part of magnetites is replaced by hematite along fractures and grain boundaries. Ilmenite and hematite form together irregular grains with corroded grain boundaries. These grains are sometimes large, having a diameter up to 1.7 mm.

The granitoids of the Pernu area contain less Fe-Ti-oxides than the other studied granitoids, especially the coarsest type is very poor in opaques. Magnetite grains are small with typical grain size of ca. 0.1 mm. Often they are situated near biotite flakes. The replacement of magnetite by hematite is not very common. Some grains consisting of ilmenite with hematite inclusions are also present. They are skeletal and larger (up to 3 mm) than magnetite grains. Magnetite forms sometimes polycrystalline aggregates with larger ilmenite grains.

The chemical composition of biotites and Fe-Ti oxides were determined with an electron microprobe at the Department of Electron Optics, University of Oulu. The iron content of biotites is higher in the Palovaara and Pernu granites than in those of Jumisko. Magnetites are nearly pure iron oxide. The contents of elements replacing Fe²⁺ and Fe³⁺ in magnetites are low; for example Ti content is always less than 0.1 at. %.

Petrophysics correlated with petrography

Compositional factors controlling magnetic mineral concentration in granites. In paramagnetic granites the iron-bearing minerals (mainly biotite or amphibole) determine the paramagnetic susceptibility, which is approximately proportional to the iron-content of the rock (Puranen 1989). In ferromagnetic granites the oxygen fugacity of the magma has favoured magnetite crystallizing with ferromagnesian silicates. Cooling trends involving biotite and K-feldspar have steeply oxidizing paths (Frost 1991), resulting in pure magnetite (Ti-poor titanomagnetite) in granites. The required iron concentration is provided by the protolith of the granite magma. Puranen (1989) has proposed that the high oxidation ratio, the relatively high iron/magnesium-ratio and the low titanium content have favoured magnetite formation in the Lappish granites, in spite of their quite low overall iron content. He concludes that the iron of the Archaean source material of these granites has been highly oxidized, and that the oxidized iron probably derived from sediments formed on the surface of the Archaean crust, later to be buried deeper in the crust and melted. The sedimentary origin would not, however, explain the positive gravity anomaly associated with, for example, the southern part of the Suomujärvi complex (Airo 1999). According to the modelled gravity profiles by Airo, densities higher than 2800 kg/m³ are needed for the anomaly source. Therefore either rocks of a high metamorphic grade (amphibole- or pyroxene-gneisses) or of mafic composition should underlie the exposed granitoid rocks.

After the original crystallization, metamorphic and deformational episodes may affect the abundance, composition and grain fabrics of magnetic minerals. The total content of magnetic material is generally not, however, drastically changed in these processes (Airo 1999). The original concentration of magnetic minerals still dominates over the secondary magnetic properties, which only enhance the original properties.

Ilmenite and hematite exist together with magnetite in Palotunturi granites more frequently than in the Pernu or Jumisko granites, which may be indicative of more oxidizing conditions during the emplacement and cooling. The replacement of magnetite with hematite (martitization) was observed especially in the Palotunturi granites. Martitization results generally from deuteric oxidation of Ti-poor titanomagnetite in acid rocks (O'Reilly 1984), and thus in Palotunturi granites it is regarded to have occurred during the primary cooling. The decreasing effect of martitization on magnetization is indicated by the lower average susceptibility for the ferromagnetic group in Palotunturi than for Pernu or Jumisko. The low average magnetization and the overall low concentration of magnetite in Pernu granites may be explained by the high iron content in biotites, with the result that less iron could be used to form magnetite. Apart from Pernu and Palotunturi, the biotites in Jumisko contain less iron, leaving more iron to be consumed for magnetite production. As a result, the Jumisko granites contain abundant, large magnetite grains.

Magnetic grain fabrics related to structural features in granites. Magnetite, either as individual grains or as elongate clusters, has a tendency to align preferentially parallel to the other crystals in the magma, such as biotite. Thus the orientations of the subfabrics of biotite and magnetite are more-or-less parallel, and they control the orientation of magnetic fabric (Bouchez et al. 1997). The magnetic anomaly patterns are related to biotite and magnetite grain fabrics and orientation, and thus reflect the overall magnetite petrofabric. In aeromagnetic images the local variations are smoothed out. For example in the Pernu granites the occurrence and orientation of magnetite grains is closely related to biotite flakes. An overall NW-SE orientation for the Pernu area is illustrated in the aeromagnetic data, and enhanced by parallel biotite-rich gneissic relics and foliated ghost-structures. The gradual transition from magnetite-bearing granite-type into magnetite-free granite outside the magnetic oval-structures, suggest a gentle emplacement for the Pernu granites, and a genesis involving crustal anatexis. As this same orientation also characterizes the surrounding Svecokarelian supracrustals, the NW-SE trending oval shapes and their internal magnetic fabric orientation must have resulted from compression from the southwest at a late stage of cooling.

In the Jumisko granites the optically determined coarse magnetite grain size is illustrated also in petrophysical properties as low Q-ratios mainly

below unity, and indicate a predominant multidomain magnetic behaviour. Multidomain magnetite has a specific magnetic anisotropy degree which is proportional to the grain shape ratio. The magnetite petrofabric orientation in the Jumisko granites follows the magmatic foliation indicated by K-feldspar grains and the overall tectonic patterns in the area. A synkinematic emplacement into the reactivated fracture zone during the Svecokarelian deformation is suggested. The magmatic foliation which parallels the NW-SE trending faults and fractures, implies a compressional stage during the cooling of granite magma, possibly during the closing of the deep faults.

The Palotunturi granites form a roundish stock, discordant to the country rock structures. Only weak internal magnetic structures or patterns can be observed. This is partly due to their low magnetization but also related to the antiferromagnetic nature of hematite, which meshes the magnetite petrofabric orientation. The existence of hematite indicates cooling under more oxidizing conditions, possibly at a higher crustal level than the Pernu and Jumisko granites.

Summary

In the southeastern Finnish Lapland, petrographic and magnetic correlations explain well the magnetic variation between the three granite types. Differences in biotite and magnetite grain fabrics explain the magnetite petrofabrics observed on aeromagnetic high-resolution data. Also elsewhere in the Finnish Lapland, the magnetic structures interpreted from aeromagnetic data of the highly magnetic porphyritic granitoids correlate well with biotite and magnetite grain fabrics (Wennerström & Airo 1998). The gradual transitions from country rock to granite in southeastern Lapland and observed especially in the Pernu area, together with the biotite-rich gneissic relics and the foliated ghost-structures, suggest a gentle emplacement and a genesis involving crustal anatexis, with local variations in its intensity. The large-scale northeast trending banded aeromagnetic patterns in the granitoid area in central Lapland, and the Archaean ages in tonalites within the granitoids, support the theory that the granites were derived by crustal reactivation, at least partly from Archaean rocks.

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PALEOPROTEROZOIC SUUKISJOKI MAFIC-ULTRAMAFIC INTRUSION IN NORTHERN FINLAND: COMBINED AEROGEOPHYSICAL, GEOLOGICAL AND TECTONIC STUDIES

by
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Introduction

Aeromagnetic data sets reveal a strong, local positive magnetic anomaly, in the region of the Pöyrisjärvi wildmark, close to the Norwegian-Finnish frontier (Fig. 1). This anomaly is related to a gabbro intrusion at the Suukisjoki-river valley, and according to the bedrock map of Finland (Korsman et al. 1997) the gabbro formation belongs to the early Proterozoic, intracratonic to craton margin sequences and mafic intrusions, 2.15–2.00 Ga in age. The Suukisjoki gabbro-intrusion is surrounded by granitic and granodioritic ca. 1.8 Ga old intrusions, which post-date the crustal thickening in the northern Fennoscandian shield. Meriläinen (1976) has regarded them as reworked Archaean basement rocks. On the Norwegian side this granitoid complex is referred to as the originally Archaean (Jergul) granitoid-gneiss complex. According to regional aeromagnetic and Bouguer-anomaly data, the Suukisjoki gabbro-intrusion is situated at the junction of regional scale fault zones. In topographic data these faults are illustrated by river valleys, and will be hereafter referred to as the Valkamajoki and Pöyrisjoki faults.

In order to interpret the regional scale tectonic features which control the emplacement of the gabbro-intrusion, local scale studies were carried out, based on the available results of the systematic aerogeophysical mapping program by the Geological Survey of Finland (GTK). Special emphasis was

made to explain in more detail the nature of magnetization and the magnetic aureole surrounding the intrusion. For that purpose petrophysical sampling and in situ measurements were carried out in the surroundings of the magnetic anomaly. The Pöyrisjärvi wildmark is characterized by sequences of granite hills, emerging from the lowland areas which are heavily covered by glacial overburden, moraine, sand and swamp. The source rocks of the strong magnetic anomaly were found exposed only in the ravine of a small brook hauling down from northeast into the Suukisjoki-river. In the small ravine, the strong weathering of gabbros associated with shearing, and the extremely highly magnetic, roundish nodules of different sizes, were particularly interesting and noteworthy. The results demonstrate that even by using almost solely the high-resolution, multisensor aerogeophysical data, the interpretation can be made to a very detailed and informational stage.

Regional tectonic features revealed by magnetic data

NW-SE-trending faults and fractures cut sharply the typical NE-SW magnetic structure in the Pöyrisjärvi wildmark. The most prominent of them is the Pöyrisjoki fault, which outlines the step in magnetic field level within the granitoid region in Figure 1. The disappearance of magnetic minerals from weakness and fracture zones indicates that the

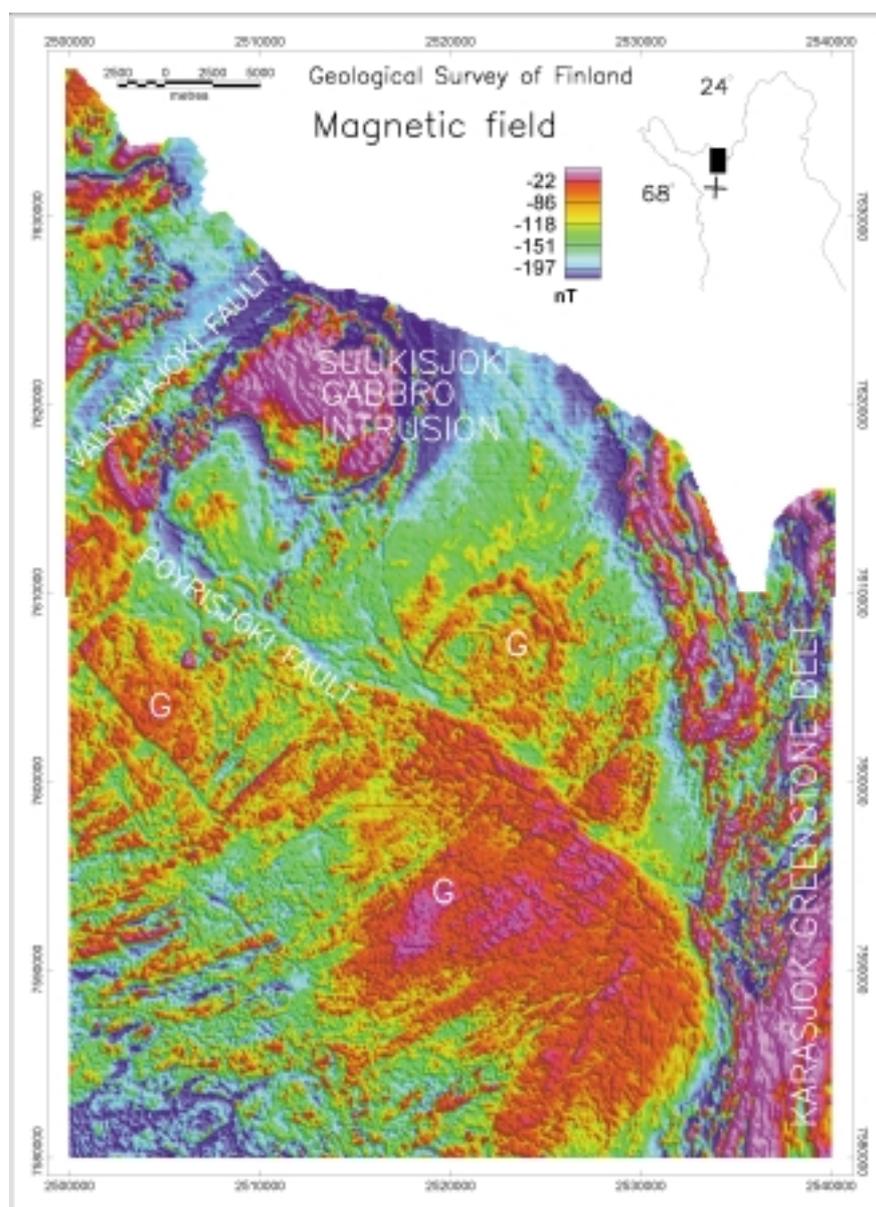


Fig. 1. Magnetic anomaly map of the Suukisjoki gabbro intrusion and the Pöyrisjärvi wildmark area. Airborne surveys by GTK with 200 m line spacing and 35 m terrain clearance.

present erosional level represents earlier deeper crustal depth, where magneto-mineralogical changes have been possible. The reactions involving biotite and magnetite require conditions of mid-crust, and temperatures of at least 500-600 °C. It is proposed that the weakness zone at Pöyrisjoki is inherited from the pre-granitoid period, possibly originating from the continental rifting period at 2.4-2.1 Ga, at first as an extensional fault, and later reactivated as a thrust fault during the overthrust of the Lapland granulite belt (Airo 1999). The close vicinity of the Lapland granulite belt is enhanced by small slips and thrusts within the Karasjok Greenstone Belt, but also within the granitoids.

NE-SW-trending deep faults control the emplace-

ment of many Proterozoic mafic and felsic intrusions in northern Finland. The Valkamajoki fault (Fig. 1), which is tangent to the Suukisjoki-intrusion, can be followed on potential field maps for more than 150 km. It is parallel to the Mierujavri-Svärholt Fault Zone (MSFZ) in Finnmark, Norway (Olesen et al. 1992), and also has several parallels all over Finnish Lapland. The regular distances (about 50 km) between these faults and their great length (hundreds of kilometres) give reason to believe that they are deep, transcrustal faults, possibly formed as transcurrent strike-slip faults. The overthrust of the Lapland granulite belt from NE at 1.9 Ga ago also benefited these faults. The original emplacement direction of the layered intrusions

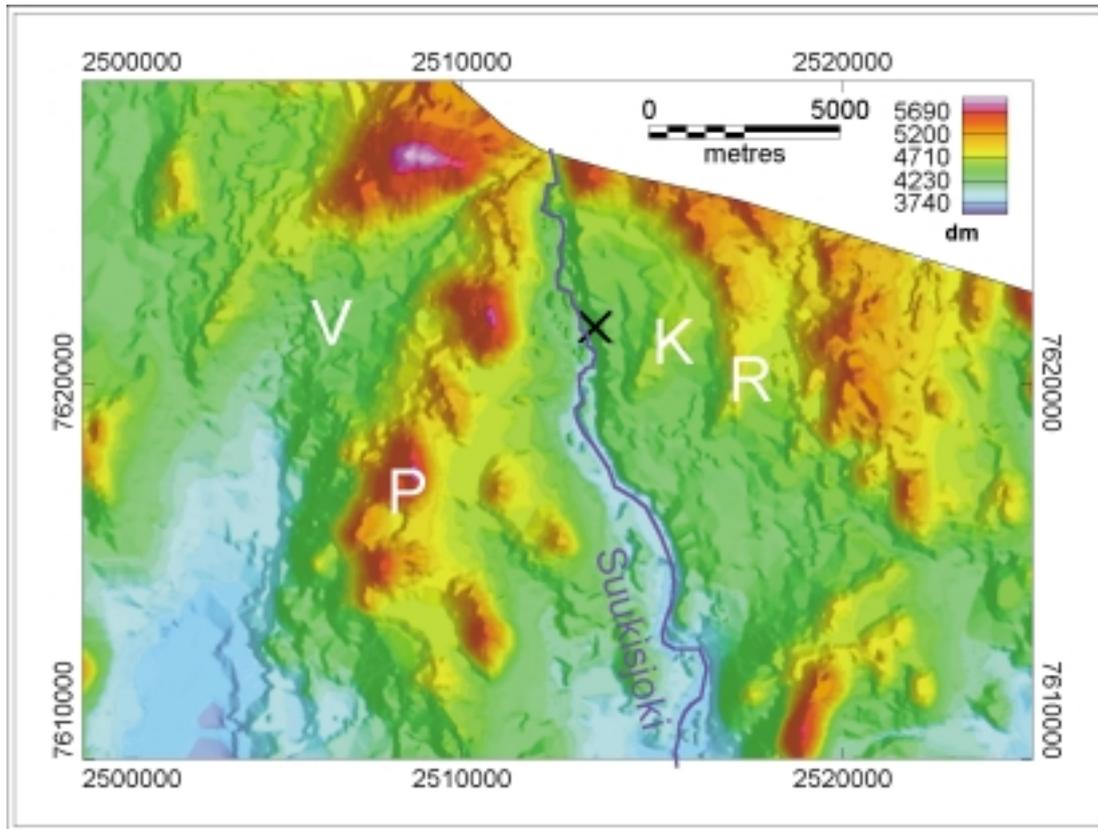


Fig. 2. Suukisjoki gabbro intrusion: Digital elevation model (DEM). Copyright National Land Survey of Finland.

associated with the early stages of the 2.4-2.1 Ga rifting period, namely the Tsipringa belt in Russian Karelia (Turchenko 1992), and the Koillismaa and Kemi layered intrusions repeat this trend (Airo 1999). Later these transcurrent faults were reactivated for several times, as evidenced by their controlling role of the emplacement of for example the Suukisjoki intrusion (2.1-2.0 Ga) and the Nattanen-type granitoids (1.8-1.7 Ga, Wennerström & Airo 1998). The MSFZ has been intruded by albite diabases at about 1.8 Ga ago (Olesen & Sandstad 1993). Later the Laanila and Kautokeino dyke swarms (1.0 Ga) and the Caledonian nappes (Olesen & Sandstad 1993) reactivated these faults.

Magnetic, irregular to banded structures within the granitoid region ("G" in Fig. 1) are parallel to the Valkamajoki fault. Such structures characterize also other granitoid regions of similar age in the Finnish Lapland. Based on in situ measurements on the exposed granite hills in the Pöyrisjärvi wildmark, the magnetic susceptibilities of the granites are about 0.004 SI. This means that the granites contain magnetite in addition to mafic paramagnetic silicates. To be able to produce magnetite in the processes were granite magma was formed, the precursor of granites must have contained (Fe, Mg)-bearing silicates. Relics of earlier formations were

observed in many outcrops, and they were composed of mafic rocks, more magnetic than the granites. As referred to earlier, the Valkamajoki fault is compared with the MSFZ in Norway. According to contact studies by Olesen and Sandstad (1993), the fault zone itself is older than the Kautokeino-rift. The Kautokeino Greenstone Belt was formed at ca. 2.28 Ga ago, and its eastern limb, the Karasjok Greenstone belt at ca. 2.08 Ga ago (Gaál & Gorbatshev 1987). If the granitoids in the region are the result of ultrametamorphism of gneisses at 1.8-1.7 Ga, the mafic relics in granitoids may derive from, except for Archaean, also remnants of supracrustal formations, of early Proterozoic age. Most likely this is also applicable to the parallel magnetic structures observed in other granitoid areas in northern Finland. Possibly the present magnetic NE-SW orientation was received under a compressional stage during the cooling of granitoids.

N-S-trending weakness and fracture zones, manifested as topographic depressions, associated with the Kautokeino- and Karasjok-rifts, outline the Pöyrisjärvi wildmark. The foliated rift-related volcanic and supracrustal rocks have been more susceptible to erosion than the granitoid areas between these belts. The Suukisjoki river and the related sandur are dominated by the N-S orientation.

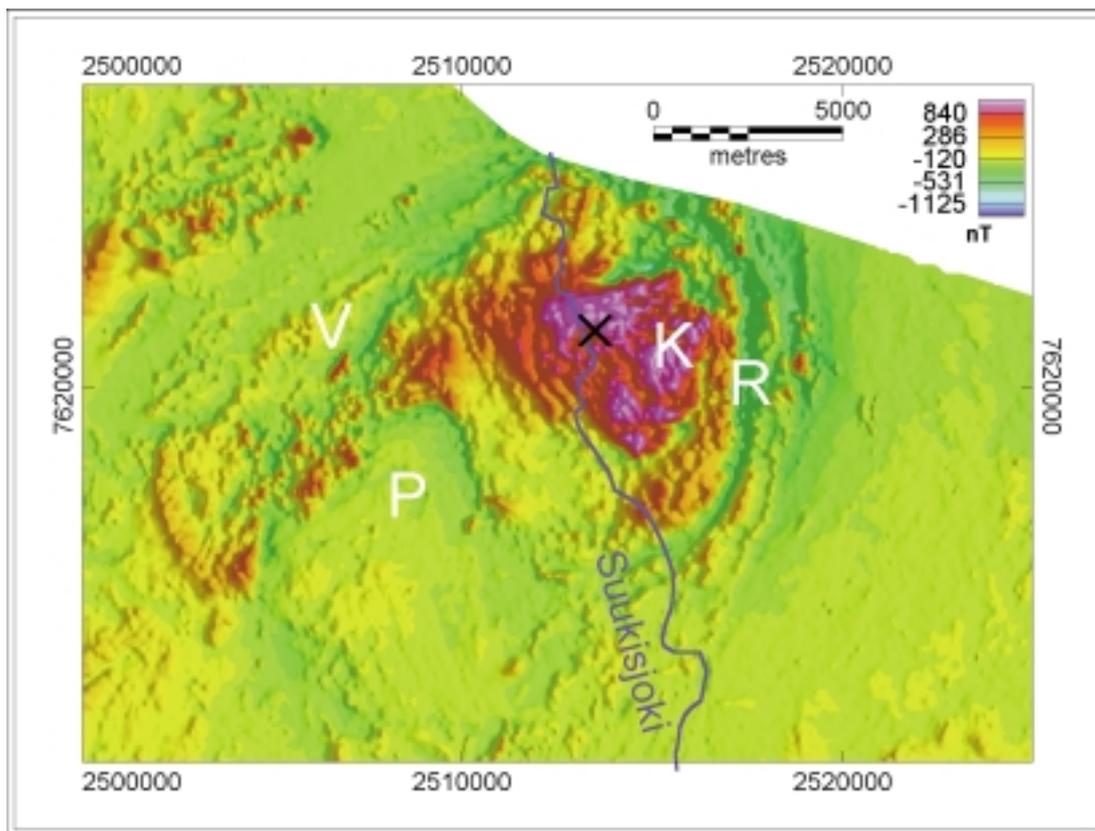


Fig. 3. Suukisjoki gabbro intrusion: Magnetic anomaly map.

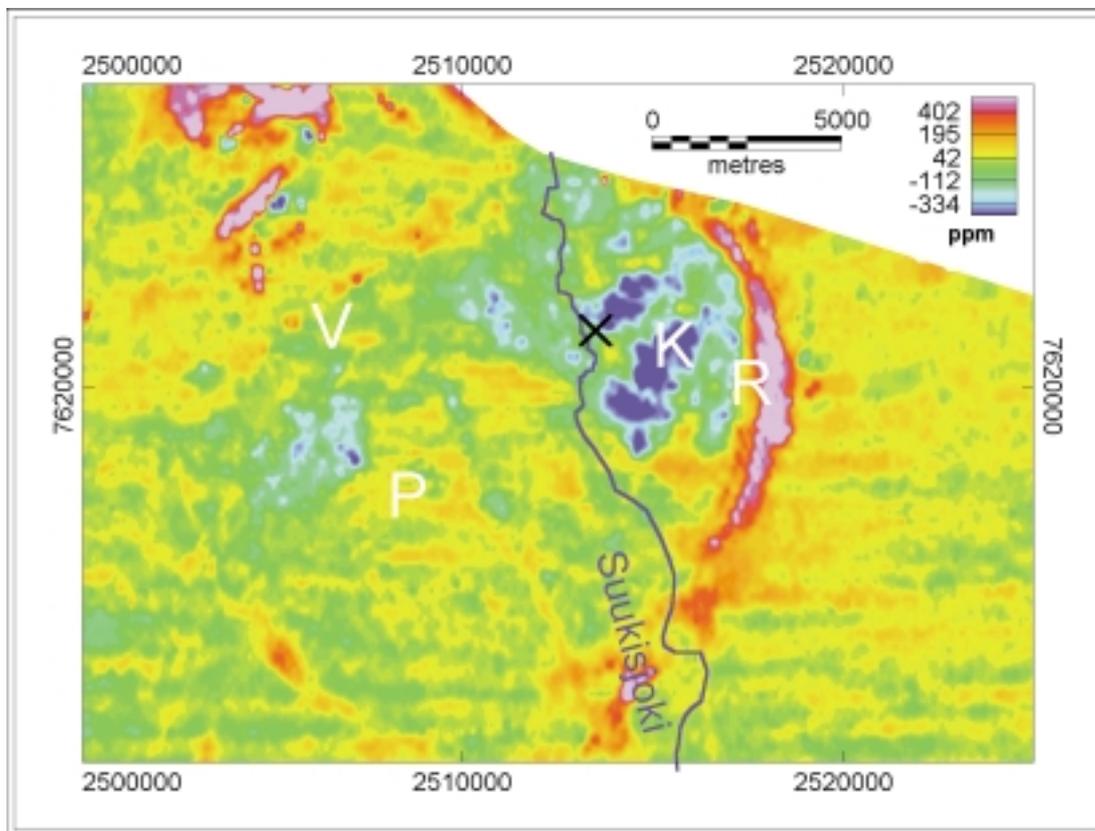


Fig. 4. Suukisjoki gabbro intrusion: Airborne electromagnetic (AEM) map, in-phase component.

In Norway to the north of Suukisjoki there are signs of N-S shearing, which have been related by Olesen and Sandstad (1993) to the formation of the N-S directed megashears in northern Fennoscandia (Berthelsen & Marker 1986), at the late stage of the Svekokaralian deformation.

Local scale aerogeophysical and digital elevation data

Digital elevation data. The elevated regions in Figure 2 are mainly connected to the exposed granite hills. The Pöyrisjoki fault limits the southern end of the chain of granite hills, which contains the Porrastunturi hill ("P" in Figs. 2-6) and is tangent to the Valkamajoki river valley ("V" in Figs. 2-6). The Suukisjoki river valley is limited in the east by the hills of Riehtiskero ("R" in Figs. 2-6), which composed of glacial till and moraine. The area of the Katajamarasto plateau ("K" in Figs. 2-6), between Suukisjoki and Riehtiskero, seems to have been more susceptible to weathering and erosion.

Aeromagnetic data. The strong magnetic anomaly, caused by the Suukisjoki intrusion, is divided areally into two parts by the river Suukisjoki (Fig. 3). Locally it is composed of three separate anomaly maxima in the area of Katajamarasto ("K") which are surrounded by a magnetic aureole, characterised by eastwards attenuating magnetic arcs. The easternmost arc is located in the valley aligning the Riehtiskero till formation ("R"). The magnetic aureole is hard to interpret as representing something other than zones of alteration. As the gabbro intrusion is older than the granitoids around it, the alteration zones were possibly produced in the gneisses predating the granites, and formed as contact aureoles in the host rock gneisses due to the increase of temperature caused by the emplacement of gabbro. Oxidizing fluids moving in the deep fault controlling the intrusion, enabled production of magnetite in the (Fe,Mg)-silicate bearing gneisses.

Electromagnetic (AEM) data. The negative AEM in-phase anomalies are caused by magnetite-bearing formations, and are always located right above the non-conductive magnetic source. The river Suukisjoki outlines the major negative in-phase anomaly peaks on its eastern side (Fig. 4). The two negative anomalies at "K" are due to unexposed highly magnetic formations underlying the glacial drift. There is a negative anomaly also between "V" and "P". This anomaly is related to an irregular magnetic pattern (Fig. 3) and a topographic low (Fig. 2), and is most probably also caused by an unexposed part of the intrusion. The highly conduc-

tive zone east of Riehtiskero ("R") is at the same time weakly magnetic and thus caused by pyrrhotite instead of magnetite. Such a high conductivity may not merely be explained by the pyrrhotite content, but it also must contain graphite. The reducing effect of graphite has favoured the formation of pyrrhotite instead of magnetite.

Petrophysical data. The only outcrop of gabbroic rocks was met at the small ravine on the eastern side of Suukisjoki (the site of petrophysical sampling in Figs. 2-6). In order to exclude the effect of the assumed remanence and to estimate the induced magnetization for the whole formation, the apparent magnetic susceptibility was calculated from the negative in-phase AEM values, using the formulas by Keller and Frischknecht (1966). The distribution of the calculated susceptibilities is shown in Figure 5, combined with the aeromagnetic shaded relief image. Susceptibilities of about 0.01 SI characterize the whole area of the magnetic anomaly, whereas susceptibilities of 0.05 to 0.08 SI are centred in the area at Katajamarasto ("K") and represent the main gabbroic body. These calculated values are in good agreement with the laboratory measurements of gabbroic block samples collected from outcrops (Table 1). In order to exclude the assumed and unknown effect of remanence, the calculated values were used as the overall susceptibility for the whole formation in modelled profiles.

Radiometric data. High concentrations of both K, U and Th in the ternary image (white in Fig. 6) mark areas of good exposure, with the highest radiation reflecting the predomination of granitoids. The black areas in Figure 6 denote wet soil, swamps or small lakes. The Suukisjoki-river valley and the Katajamarasto area ("K") east of Suukisjoki are lowlands, where the glacial drift cover attenuates the radiation. Katajamarasto is dominated by a high K- but low Th- and U-concentration. This can be explained either by the high relative proportion of gabbroic material within the till, or by the weathering of the Th- and U-bearing minerals, leaving K behind. The river bank-sands of Suukisjoki are shown as a zone of high U- and Th-concentration.

Gabbro intrusion and ultramafic nodules

The Suukisjoki gabbro intrusion is composed of sequences of gabbro, hornblende- and amphibole-gabbro, some more ultramafic parts, and talc-chlorite-rocks which are possibly alteration products. The gabbro formation is intruded by narrow granitic dikes. The hornblende- and amphibole-gabbros are strongly sheared and altered, and for a

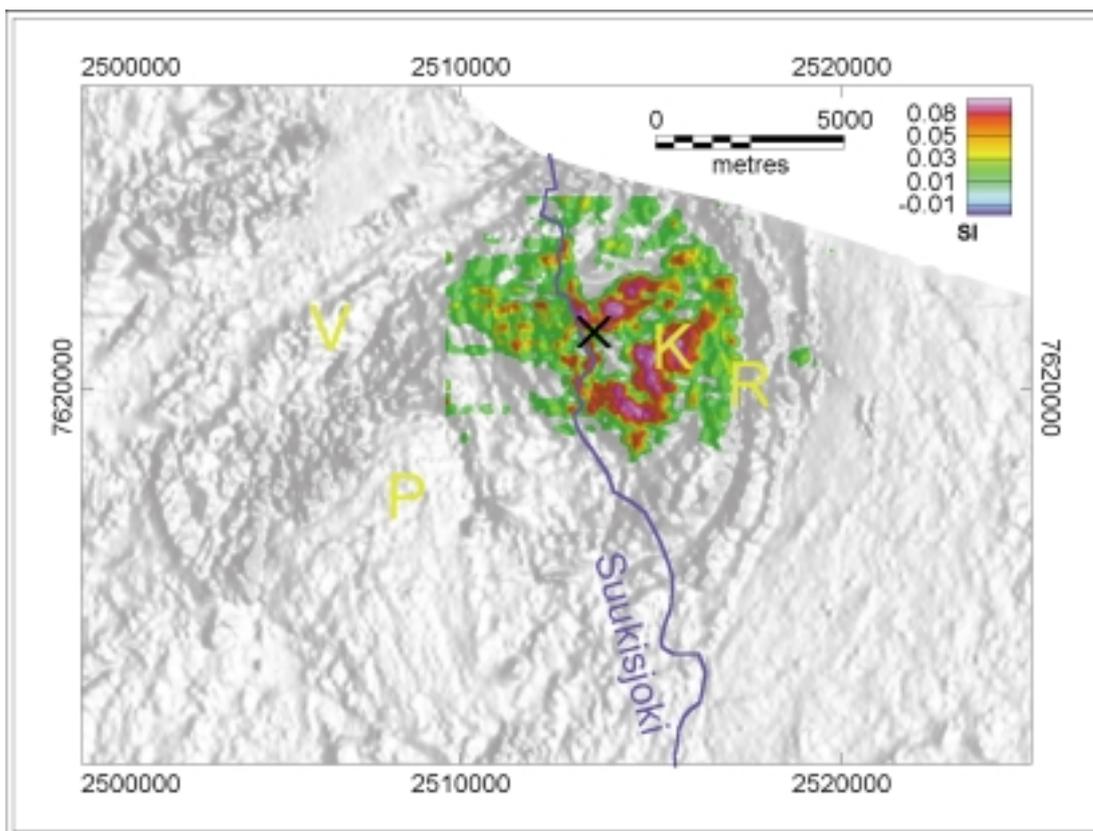


Fig. 5. Suukisjoki gabbro intrusion: Apparent magnetic susceptibility, calculated from negative AEM in-phase anomaly values using conductive half-space model, combined with shaded magnetic anomaly relief.

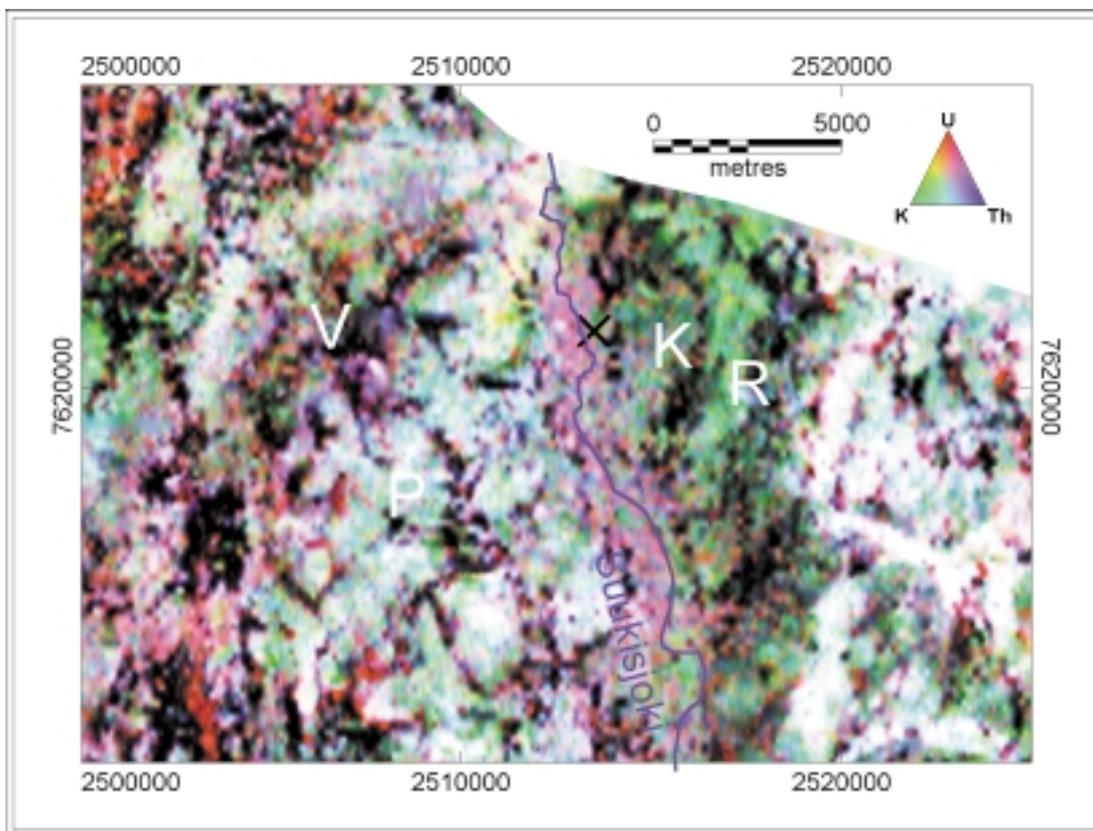


Fig. 6. Suukisjoki gabbro intrusion: Radioelement ternary image.

Table 1. Petrophysical data. Y, X mark the sampling location, d = density, s = magnetic susceptibility, r = intensity of remanent magnetization, Q = Königsberger ratio. Opaques: mgt = magnetite, ilm = ilmenite, tit = titanite, Fek = Fe-sulphides, hem = hematite.

Y	X	d kg/m ³	s 10 ⁻⁶ SI	r mA/m	Q	rock type	sample type	opaques
3388.960	7623.876	2652	38220	180	.11	granite (red)	outcrop	
3391.380	7623.800	2913	97620	750	.19	talc-chlorite rock	boulder	mgt/ilm
3391.570	7623.860	2947	65370	380	.14	talc-chlorite rock	outcrop	mgt/ilm
3391.650	7623.840	2958	1430	30	.49	hornblende gabbro	outcrop	mgt, tit
3391.760	7623.830	2955	181000	1460	.2	gabbro	outcrop	ilm abundant
3391.960	7623.840	3183	56110	14290	6.22	peridotite	boulder	mgt (fine-grained), ilm, Fek
3390.700	7620.250	2595	160	50	8.28	granite (light coloured, striped)	outcrop	
3388.900	7624.540	2671	51110	340	.16	granite	outcrop	
3391.570	7623.860	3067	2320	90	.93	ultramafic rock?	boulder	
3391.620	7623.830	3048	40490	12730	7.67	olivine gabbro	nodule	mgt (coarse-grained), ilm, Fek, rutile needles in augite
3391.620	7623.830	2956	3270	10	.06	amphibole gabbro	outcrop	small amounts of mgt, tit, ilm, hem
3391.690	7623.840	2572	1730	30	.36	granite (light coloured)	outcrop	
3391.720	7623.860	2984	1640	40	.61	hornblende gabbro	outcrop	mgt, tit
3391.720	7623.860	2610	9320	100	.26	granite	outcrop	
3391.720	7623.860	2897	11850	270	.55	ultramafic rock (amphibolite)	outcrop	mgt, hem

large part totally weathered to sand and gravel. Determined by optical studies (made by Marit Wennerström, GTK) the gabbro contains a rather high concentration of magnetite (3-5 wt %) and ilmenite (20-30% of the opaques). Magnetite occurs typically as anhedral grains filling the space between other minerals, sometimes as very coarse-grained. The Q-ratios for different gabbro samples are 0.2-0.5 (Table 1) and reflect the overall quite coarse magnetic grain size and the multidomain magnetic behaviour. Concluded from the great number of ultramafic boulders in the ravine, the intrusion contains also ultramafic (peridotitic) parts. Both the gabbros and the ultramafic rocks are highly magnetic, but the ultramafic samples are also characterized by a high remanent magnetization. Also the altered parts of the intrusion, as represented by the talc-chlorite rocks, were highly magnetic. Topographically they were situated at the lowest level close to the banks of the Suukisjoki river.

The amphibole-gabbros contained hard, resistive, roundish olivine-gabbro nodules of varying sizes (diameters 0.2 m - 1.5 m). The nodules were covered by a 1-2 cm thick glassy surface. They were found both as loose, spherical boulders in the ravine and as tied firmly by the amphibole gabbro host rock. The strong remanent magnetization for nodules (ca. 13 A/m), and their high Q-ratios (6-7), are related to magnetite ribbons. These ribbons fill the cracks and fractures within the olivine crystals, indicating serpentinization of the olivines. In addition to magnetite and ilmenite, the optical studies of olivine gabbro showed also small amounts of iron

sulphides. It is possible, that the olivine-gabbro nodules are boulders transported in the solid state from the lower crust or upper mantle - xenoliths - captured from the country rock by the fierce upward flow of magma. Similar spherical xenolith boulders have been illustrated by Cox (1978). The possibility of magmatic pillow structures is excluded on the basis of the non-pillow shape of the nodules having no "neck", and the fact that they were surrounded on all sides by the glassy cover.

Structure of Suukisjoki gabbro-intrusion and remanence studies

The aerogeophysical and topographic data sets stress the main body of the Suukisjoki gabbro-intrusion to be located at and around the letter "K" in Figures 2-6, on the eastern side of Suukisjoki, but there is evidence of similar anomaly sources also between "P" (Porrastunturi) and "V" (Valkamajoki valley), aligning the Valkamajoki fault. Based on the exploration experiences at Hävityskuusikko, northern Finland (Turunen, P. op. cit.), the magnetite/ilmenite-bearing gabbro bodies there were distinguished from the serpentinized ultramafic rocks by their negative in-phase response. In accordance with those results, the gabbroic parts of the Suukisjoki intrusion are pointed out similarly, unlike the ultramafic parts which are associated with high remanences. The structure of the main gabbroic body was interpreted by integrated magnetic and gravity modelling of profiles across the body, in

varied orientations. By adapting the overall susceptibility of 0.05 SI calculated from the AEM in-phase data and the density contrast of about 100 kg/m³, the intrusion was interpreted as reaching to the depth of 3-6 km (Fig. 7). The upper surface at "K" is about 5 km wide, and the northern and eastern margins are more steep than the western or southwestern margins. The remanence direction of the present Earth's field (PEF) was favoured in the modelling.

One of the targets in this study was to determine the nature of remanence and its influence on the magnetic anomaly related to the Suukisjoki intrusion. However, oriented samples were hard to get due to the brittleness of the gabbros. Although sparse in number, the obtained samples represent the typical lithological and magnetic variations in the Suukisjoki formation. The gabbros are dominated by the induced magnetization carried by coarse magnetite grains. By contrast, the remanent magnetization and high Q-ratios were related particu-

larly to the ultramafic rocks, which were met mainly as boulders and nodules. The remanence in ultramafic samples is carried by the fine magnetite ribbons. If the relative proportion of ultramafic material compared with gabbros would be higher deeper in the crust, its remanence would affect the shape and intensity of the magnetic anomaly. The magnetite ribbons have been formed in connection with serpentinization, at temperatures below the Curie-point of magnetite (ca. 560 °C). This commonly produces a chemical remanence component (CRM), which is characterized by variable remanence directions. These tend to cancel each other out, and therefore the direction of PEF dominates the remanence. Furthermore, the normal polarity seems to be the natural choice, since the intrusion of Suukisjoki gabbros has been related to the 2.15-2.00 Ga old events (Korsman et al. 1997). This was between the reversed polarity periods in northern Fennoscandia, as they have occurred at ca. 2.4 Ga

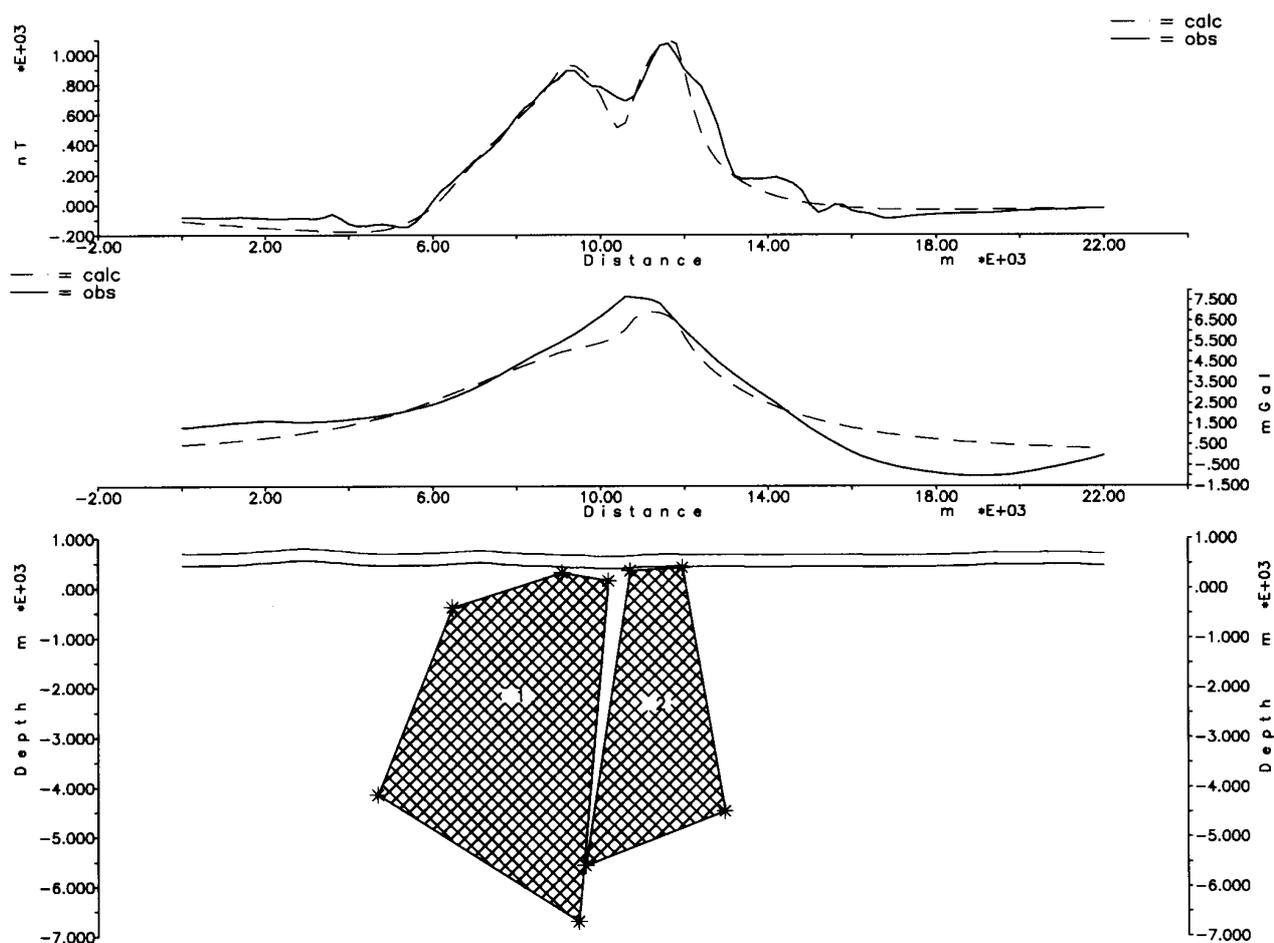


Fig. 7. Magnetic and gravimetric profiles across the intrusion from NW to SE. Regional trends removed. Magnetic profile: upward continued to 100 m from aerogeophysical survey of GTK. Gravimetric profile: Bouguer anomaly from Finnish Geodetic Institute's gravimetric measurements, having one anomalous station inside the intrusion. Solid line fitted to original measurements. Dashed line calculated using model parameters: magnetic susceptibility of 0.05 SI and density contrast of 100 kg/m³.

ago, at ca. 1.9 Ga ago and at 1.0 Ga ago (Mertanen & Pesonen 1994, Mertanen et al. 1994). The normal polarity characterized the period of Svecokarelian deformation, which was the last geological event, able to produce temperatures high enough to affect magnetite and the remanence in rocks.

Summary of tectonic analysis

Three lineament trends, namely NW-SE, NE-SW and N-S, predominate and control the geophysical and topographic image of the Suukisjoki gabbro-intrusion and its surroundings. These trends are met regularly all over northern Finland, and they emerge also in Finnmark, Norway (Olesen et al. 1992, Olesen & Sandstad 1993) and in Russian Karelia and the Kola peninsula (Petrov 1970; Berthelsen & Marker 1986; Smolkin 1996). On topographic maps the three trends are enhanced by Quaternary formations, waterways and glacial drift. There is evidence that the same weakness-zones have been active from the Paleoproterozoic to the post-glacial period (Olesen et al. 1992, Kakkuri 1997). A rhomboid overall structural pattern of bedrock is determined by the three rivers in the Pöyrisjärvi wildmark, namely the rivers Valkamajoki, Pöyrisjoki and Suukisjoki. It is manifested by NE-SW, NW-SE and N-S-trending fault zones in the magnetic data and by the orientations of rivers and ravines in the topographic data. Similar patterns are observed in the granitoid region on a smaller scale. The N-S directed fault and fold structures have been formed in connection of the N-S megashears according to Berthelsen and Marker (1986) at about 1.8 Ga ago. However, structures following this trend may form in connection with many tectonic events as conjugate direction simultaneously with the main NE-SW and NW-SE trends. It is suggested that the old weakness zones, that have formed during regional tectonic episodes and reactivated several times, have been enhanced by frost weathering. The same kind of rhomboid pattern is observed both in aeromagnetic, topographic and Bouguer-anomaly data of the Lapland granulite belt, thus supporting the idea of frost weathering.

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PHYSICAL PROPERTIES OF CARBONATE MARBLE SAMPLES FROM THE KISKO REGION, SOUTHERN FINLAND

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Introduction

The geological investigations of the Kisko carbonate marble deposit in southern Finland are in progress (Sarapää et al. 1999), and the main purpose of this study is to reveal petrophysical information on the carbonates from this region. These carbonate marble samples provided also an appropriate possibility to continue tests to clarify the abnormal behaviour of carbonate rocks observed in laboratory saturation and resistivity tests in the spring 1998. Dolomite rock samples from the Tervola (northern Finland) region had indicated a strange phenomenon: the resistivity values of the samples increased with the water immersion time (Kivekäs 1999). In this study both dolomite and calcite marble samples from the Kisko region, southern Finland, were tested. Besides the saturation and resistivity experiments, the physical properties: density, porosity, seismic P-wave velocity, magnetic susceptibility, natural remanent magnetization (NRM) and electric resistivity were measured at the petrophysical laboratory of the Geological Survey of Finland (GTK). The results of four dolomite and ten calcite marble samples are presented.

Samples

Drill core samples (20–30 cm) from different depths of drill hole R354/98 were cut for petrophysical measurements of four dolomite and ten calcite marble samples: length 48 mm, diameter 32 mm and volume 38 cm³. All the samples are very

dense (porosity 0.10 ± 0.03 %). Polished thin sections were prepared from both dolomite and calcite marble samples. The dolomite marble is fine-grained (0.1 - 0.5 mm), and composed of dolomite with some calcite, tremolite and quartz. There are also opaque minerals: pyrrhotite, chalcopyrite and pyrite (Fig. 1). The calcite marble is coarse-grained (2 - 5 mm), and in addition to calcite there is some tremolite, diopside and phlogopite (Fig. 2). A clear pyrrhotite filled microcrack is identified in the calcite marble sample from a core of depth 56.35 m.

Measurements

Bulk density was determined by weighing samples in air and water (Archimedes' principle). The weighing accuracy of the balance used in the computerized Petrophysics laboratory at GTK (Puranen et al. 1993) is 0.01 g. Maximum error of density values for the samples, with porosity 0.1% and volume 38 cm³, is 1 kg/m³. Porosity was deduced from the mass difference between the water-saturated and oven-dried (105°C) samples (Rasilainen et al. 1996). The accuracy of the balance used to measure the bulk mass of samples during saturation for mass difference curves was 0.001 g.

Seismic P-wave velocity was measured from water-saturated samples by the ultrasonic pulse-transmission method at atmospheric pressure and room temperature. Travel time was determined using two identical ultrasonic (66 kHz) P-wave transducers as transmitter and receiver.

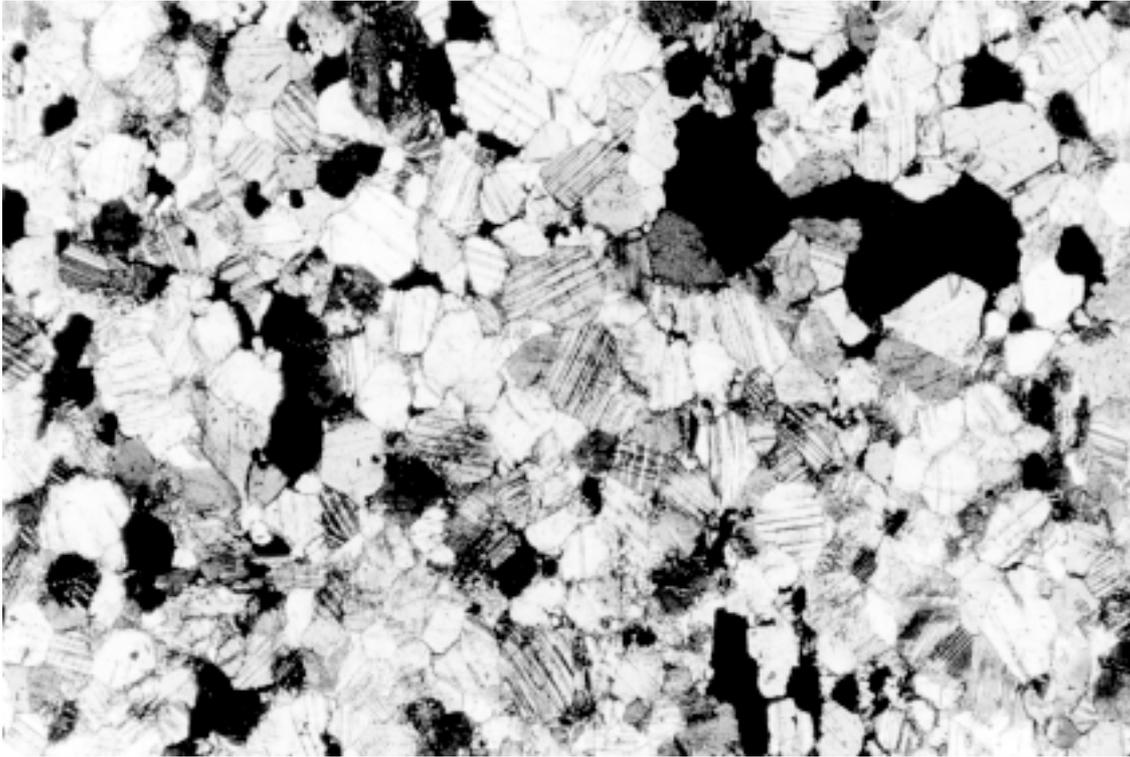


Fig. 1. Fine-grained dolomite marble R354/98-19.10m; from the Kisko region. Opaque minerals are mainly pyrrhotite. Transmitted light, crossed polarizers, field of view is 4mm wide. Photomicrograph by H. Appelqvist.

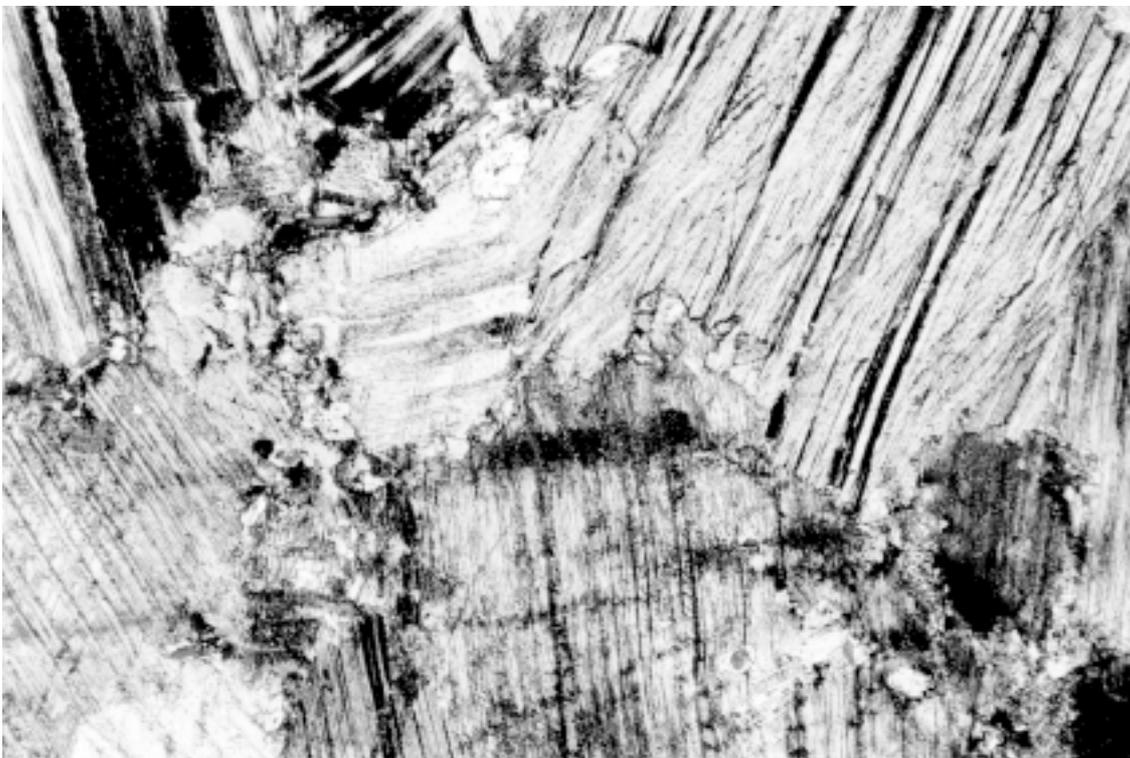


Fig. 2. Coarse-grained calcite marble R354/98-35.50m; from the Kisko region. Small fibrous or platy crystals on the grain boundaries of calcite are mainly tremolite. Transmitted light, crossed polarizers, field of view is 4mm wide. Photomicrograph by H. Appelqvist.

Magnetic susceptibility was measured with an AC bridge apparatus at low frequency (1025 Hz). For isotropic, weakly magnetic (susceptibility < 1000 μ SI) samples the standard error of repeated measurements stays generally below 20 μ SI (Puranen et al. 1993). For strongly magnetic and anisotropic samples the results measured in different directions can vary by more than 20 %. The values reported here were measured in the direction of the core axis. The intensity of natural remanent magnetization (NRM) was determined with a fluxgate magnetometer inside magnetic shielding. The standard error of repeated remanence measurements is about 10 mA/m. Highly magnetic samples may show variations of more than 10 %.

Before measurements of electric resistivity, the samples are saturated in tap water for at least 2 days, usually for 3 - 5 days. Resistivities were determined at the frequencies of 10 and 500 Hz using a two-electrode system with wet electrodes. If the saturating of a sample and drying of its surface before measurement are repeated as similarly as possible, then variation of results can be kept below 10 %. Four dolomite and ten calcite marble samples from the Kisko carbonate deposit were measured using these methods and results are presented in this paper (Table 1).

Porosity, density and P-wave velocity

The porosity determination of calcite marble samples was difficult because the samples started to dissolve in water. The samples were saturated with water for four days. The saturation curves (Fig.3) were necessary for porosity estimation. Porosities are calculated from the highest measured mass value of each sample during water saturation. This point was reached one to four hours after the samples were placed in water. Since that time the dissolving mass of calcite samples was bigger than the amount of water the samples could absorb. The time and quantity of full saturation was impossible to determine exactly, but full saturation was probably reached near the lowest resistivity point (between 2-10 hours, see Fig. 4). The calculated porosities are thus under-estimated. The dissolution of dolomite marbles was considerably weaker. The porosity estimates of the Kisko carbonates, for dolomite marble 0.12 ± 0.06 % and calcite marble 0.09 ± 0.02 %, are so low that their grain density, wet bulk density and dry bulk density are very close to each other (Kivekäs 1993), and only the dry bulk density is presented (Table 1). Density values of the dolomite marble samples 2872 ± 7 kg/m³ and calcite marble samples 2733 ± 6 kg/m³ are typical for

Table 1. Petrophysical properties of carbonate marbles from the Kisko region, southern Finland, drill hole R354/98: porosity [P], dry bulk density [D_d], P-wave velocity [V_p], magnetic susceptibility [K], natural remanent magnetization [NRM] and electric resistivity [R_{10Hz}]. Resistivity data are based on measurements after three days saturation in tap water [$R_w = 55 \Omega m$], * marked samples in deionised water [$R_w = 120 \Omega m$]. See text and Figures 4 and 7 for details.

Sample depth m	Volume cm ³	Carbonate marbles	P %	D_d kg/m ³	V_p m/s	K μ SI	NRM mA/m	R_{10Hz} Ωm
19.00	38.88	Dolomite*	0.204	2879	6850	34560	1260	16800
19.05	38.66	Dolomite	0.112	2863	6750	13880	820	19100
19.10	37.27	Dolomite*	0.069	2874	6730	22500	1150	32400
19.15	37.35	Dolomite	0.081	2874	6850	10800	570	64600
24.70	38.16	Calcite	0.068	2731	6390	130	250	121000
24.75	37.91	Calcite	0.093	2727	6360	50	180	85300
35.40	37.79	Calcite*	0.101	2730	6230	10	160	73000
35.45	37.76	Calcite	0.066	2730	6400	20	140	122000
35.50	38.24	Calcite*	0.082	2730	6200	20	170	101000
35.55	37.92	Calcite	0.087	2726	6210	20	170	90900
56.25	37.97	Calcite	0.116	2737	6330	130	250	57000
56.30	37.79	Calcite	0.125	2731	6140	70	190	58200
56.35	37.44	Calcite	0.107	2743	6120	430	330	34000
56.40	38.14	Calcite	0.105	2745	6300	120	240	48300
Mean	N = 4	Dolomite	0.117	2872	6800	20440	950	33200
St Dev			0.061	7	60	10640	310	22000
Mean	N = 10	Calcite	0.095	2733	6270	100	210	79100
St Dev			0.019	6	100	130	60	30200

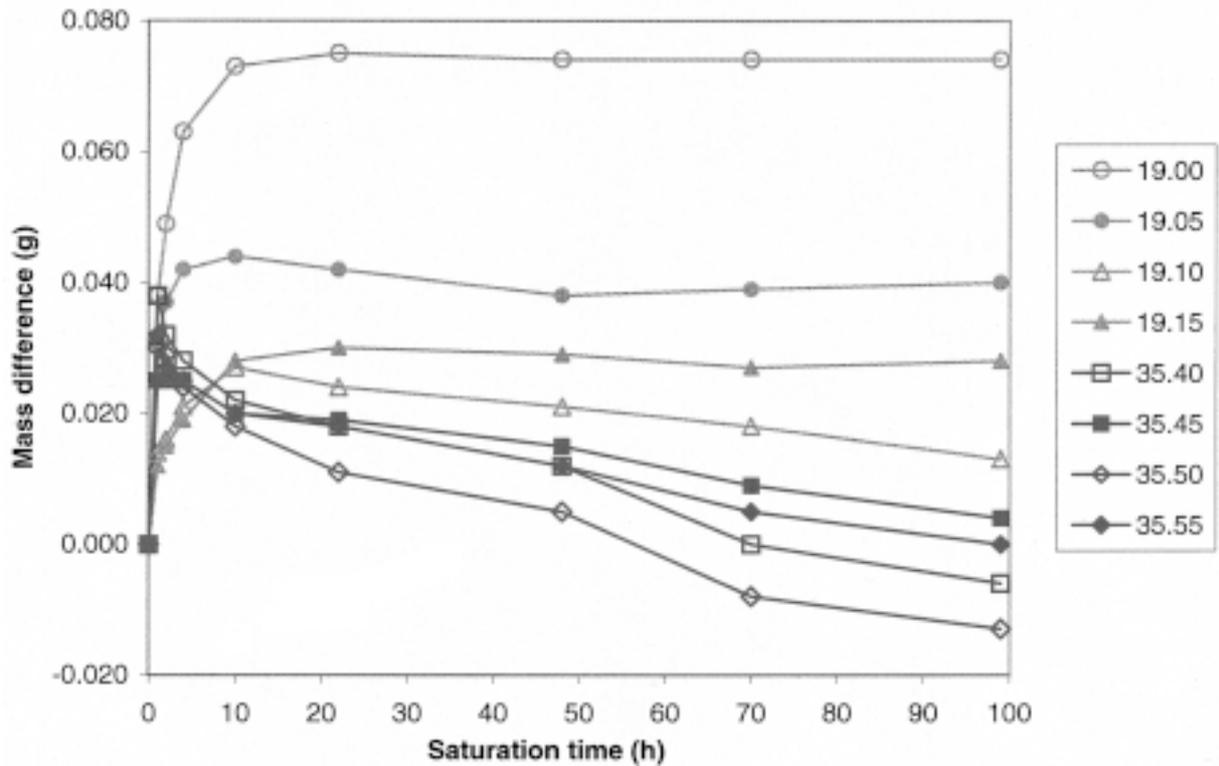


Fig. 3. Mass difference (saturation and dissolving) of Kisko carbonate samples during water saturation.
 Blue curves = dolomite marble samples from the core depths of 19.00 - 19.15 m
 Red curves = calcite marble samples from the core depths of 35.40 - 35.55 m
 Open symbols = samples were saturated in deionised water
 Solid symbols = samples were saturated in tap water

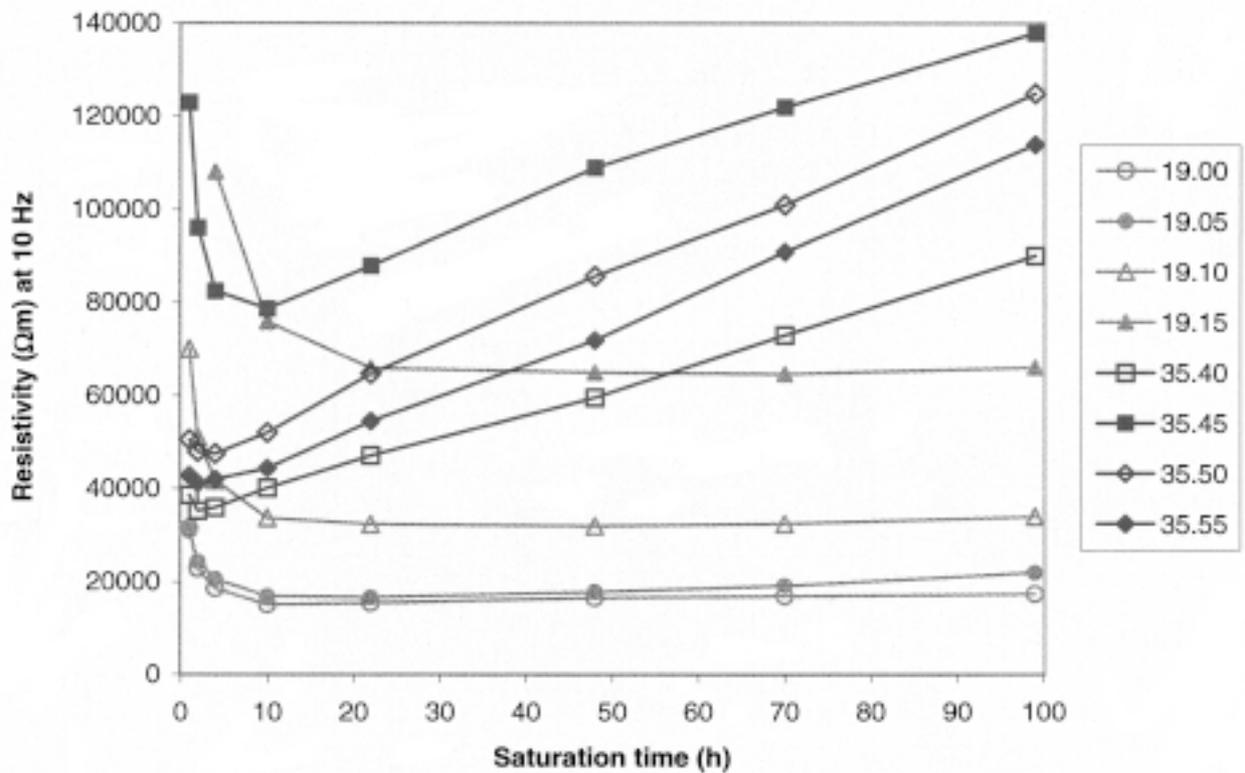


Fig. 4. Resistivity at frequency 10 Hz of Kisko carbonate samples versus saturation time .
 Blue curves = dolomite marble samples from the core depths of 19.00 - 19.15 m
 Red curves = calcite marble samples from the core depths of 35.40 - 35.55 m
 Open symbols = samples were saturated in deionised water
 Solid symbols = samples were saturated in tap water.

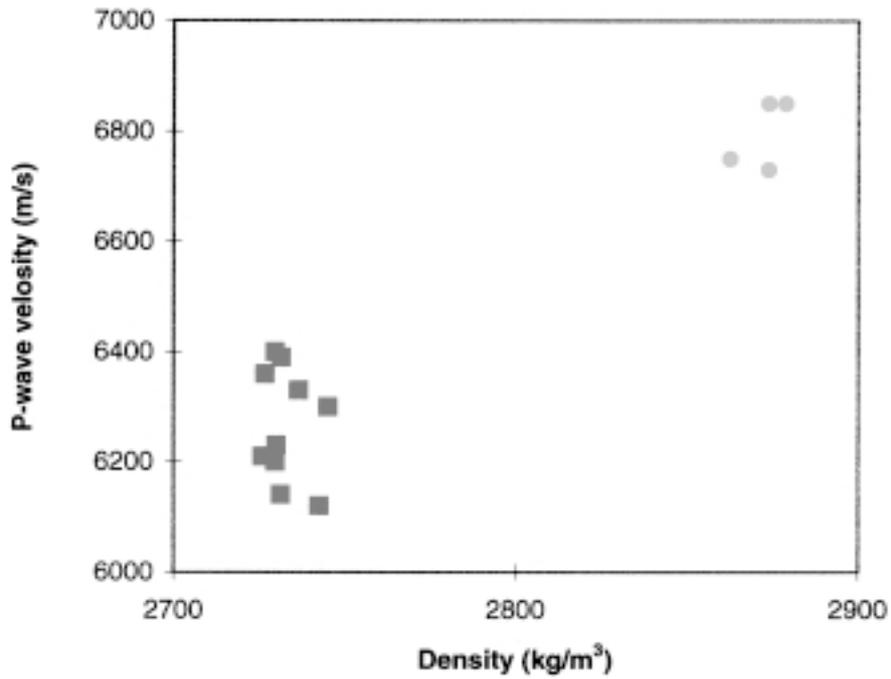


Fig. 5. P-wave velocity - density plot of dolomite (blue circles) and calcite (red squares) marbles from the Kisko region.

dolomites and calcites. The low values of standard deviations indicate homogeneity. Seismic P-wave velocity of dolomite marble samples is 6800 ± 60 m/s and calcite marble samples 6270 ± 100 m/s. These values correlate positively with density values (Fig. 5).

Magnetic properties

The magnetic characters of dolomite and calcite marbles differ strongly from each other. In the susceptibility - density plot (Fig. 6) dolomite and calcite marble samples form clearly their own

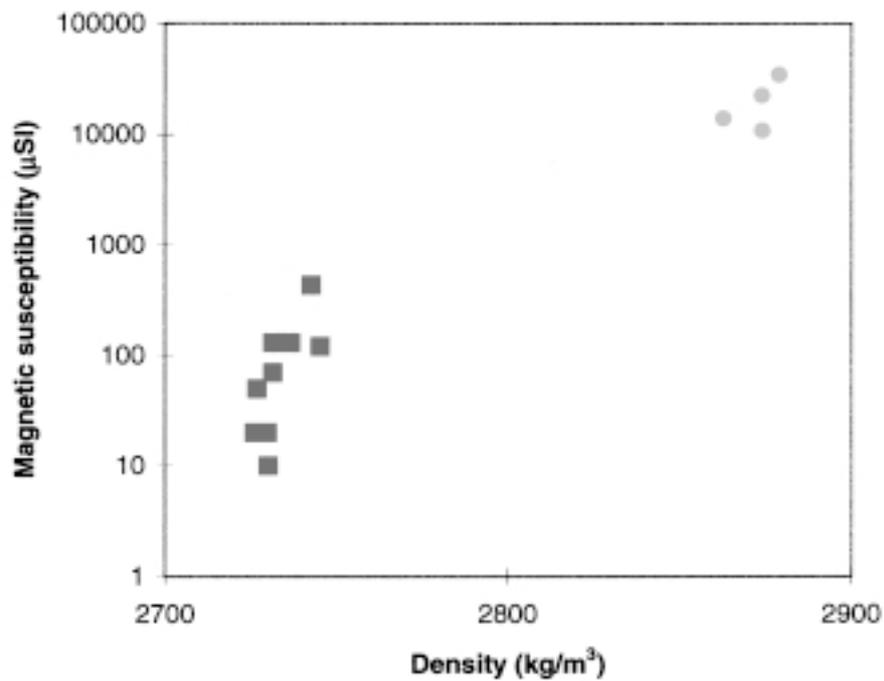


Fig. 6. Susceptibility - density plot of dolomite (blue circles) and calcite (red squares) marbles from the Kisko region.

groups, which reflect differences in the amount of magnetic minerals. The dolomite marble samples are ferrimagnetic, the susceptibility is $20440 \pm 10640 \mu\text{SI}$ and the intensity of natural remanent magnetization (NRM) is $950 \pm 310 \text{ mA/m}$. The standard deviations are quite large due to the variation of pyrrhotite content. Pyrrhotite is visible in the thin sections of dolomite marble (Fig. 2).

The magnetic parameters of the calcite marble samples show much lower values, the susceptibility is $100 \pm 130 \mu\text{SI}$ and the remanent magnetization is $210 \pm 60 \text{ mA/m}$. Especially the remanent magnetization suggests that some ferrimagnetic accessories are present. Pyrrhotite is visible in a filled microcrack of the calcite marble sample (56.35), which shows the highest susceptibility value and remanent magnetization of calcite marble samples (Table 1).

Electric resistivity

The resistivity of four dolomite and four calcite marble samples from the depths of 19.00 - 19.15 m and 35.40 - 35.55 m were first monitored during their saturation (Figs.3 and 4) in an attempt to explain the behaviour of water-carbonate interactions. Half of the samples were saturated in tap water and the other half in deionised water. There was 1.25 dm^3 of water in both cases and the combined total volume of the four samples was 152 cm^3 .

The changes in the properties of saturating waters were recorded. The pH value of deionised water increased in two hours from 5.44 to 8.69 and then remained at a level of 8.16 ± 0.66 . No significant changes were observed in the tap water during the four days of saturation and the pH value was all the time 8.02 ± 0.07 . The temperature of the water was $22.5 \pm 0.6^\circ\text{C}$ in both cases. The resistivity of the deionised water decreased during the saturation process from 8550 to $83 \Omega\text{m}$ (Fig. 7) and the resistivity of tap water from 66 to $51 \Omega\text{m}$. The use of tap water is thus the best way to saturate samples for resistivity measurements.

Any significant differences between the resistivity results of the samples depending on the two different saturation conditions were not noticed, although the resistivities of saturating waters differed strongly from each other (Fig.7). Calcite marble samples dissolved in deionised water slightly more strongly than in tap water (Fig. 3). At first the deionised water was acid (pH = 5.44), but already after one hour of soaking samples the pH-value increased to 7.40. Any calculations or analyses of anions and cations of dissolved salts have not been done yet. Ions in aqueous solution are affected by the presence of each other. Even apparently simple processes, such as the rate at which calcite (CaCO_3) dissolves, have recently been shown to be highly complicated (Bland & Rolls 1998).

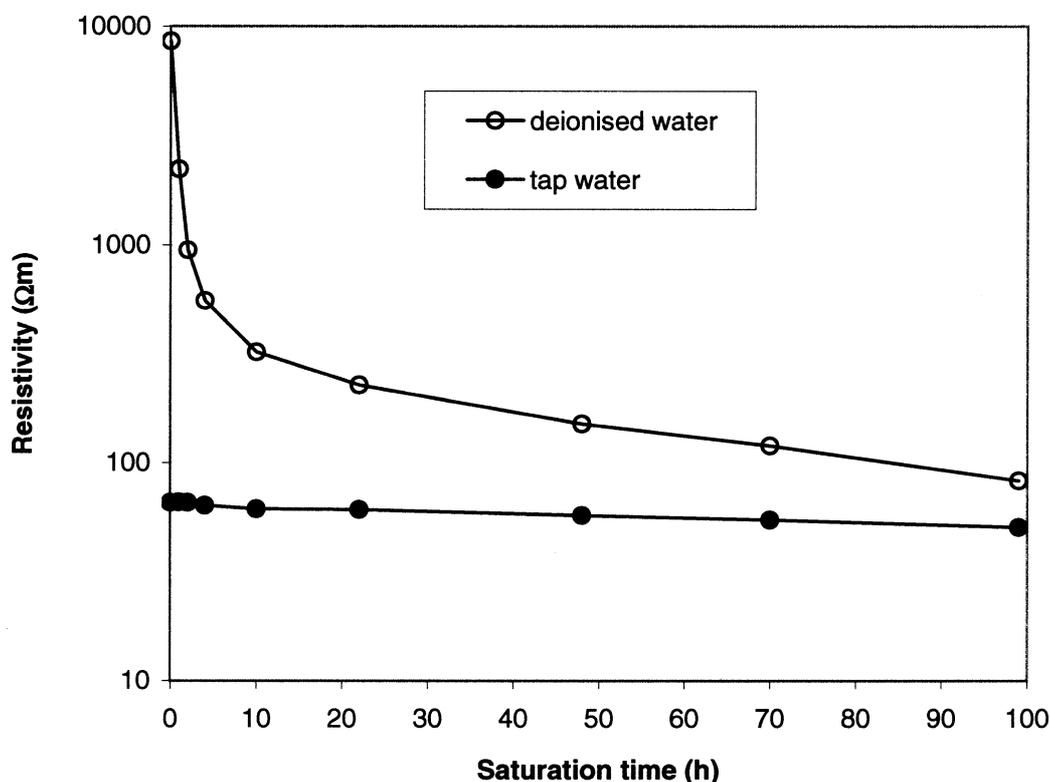


Fig. 7. Resistivity of saturating waters versus saturation time of carbonate marble samples.

Table 2. Porosity estimates [P] and minimum resistivity values [$R_{10\text{Hz}}$] during water saturation of calcite marble samples from the Kisko region, southern Finland, drill hole R354/98. Samples 35.40 and 35.50 were saturated in deionised water ($R_w = 945\Omega\text{m}$), others in tap water ($R_w = 64\Omega\text{m}$). See text and Figures 4 and 7 for details.

Depth m	P %	$R_{10\text{Hz}}$ Ωm
24.70	0.068	80400
24.75	0.093	56300
35.40	0.101	35200
35.45	0.066	78700
35.50	0.082	47900
35.55	0.087	42000
56.25	0.116	30400
56.30	0.125	27500
56.35	0.107	29200
56.40	0.105	34500
Mean	0.095	46200
St Dev	0.019	19700

The resistivity values at the frequency of 10 Hz in Table 1 have been taken from the data measured after three days of saturation, which is the normal saturation time in routine measurements at GTK.

For dolomite samples these resistivity values are correct, but for calcite marble samples the situation is complicated due to their abnormal behaviour during saturation (Fig. 4). Their resistivity values are doubled in three days of saturation from the minimum values (Table 2) between two and ten hours of saturation.

The matrix of dolomite and calcite rocks is practically an insulator having resistivity of about $10^{13} \Omega \text{ m}$. The conductivity of samples depends thus on the electrical properties of pore water in the interconnected pores, microcracks and at mineral boundaries. Anions and cations can also contribute to the conductivity of rocks by electrochemical interaction with the solid matrix at the fluid-solid interface. The interface acts both as a conductor and capacitor (Schön 1996). Although the porosity range of calcite marble samples is very low and narrow (0.066 - 0.125 %), the cross-correlation plot between the porosity estimates and the lowest measured resistivities (Table 2) indicates a good correlation with the coefficient $r = -0.954$ (Fig. 8). The included Archie's equation

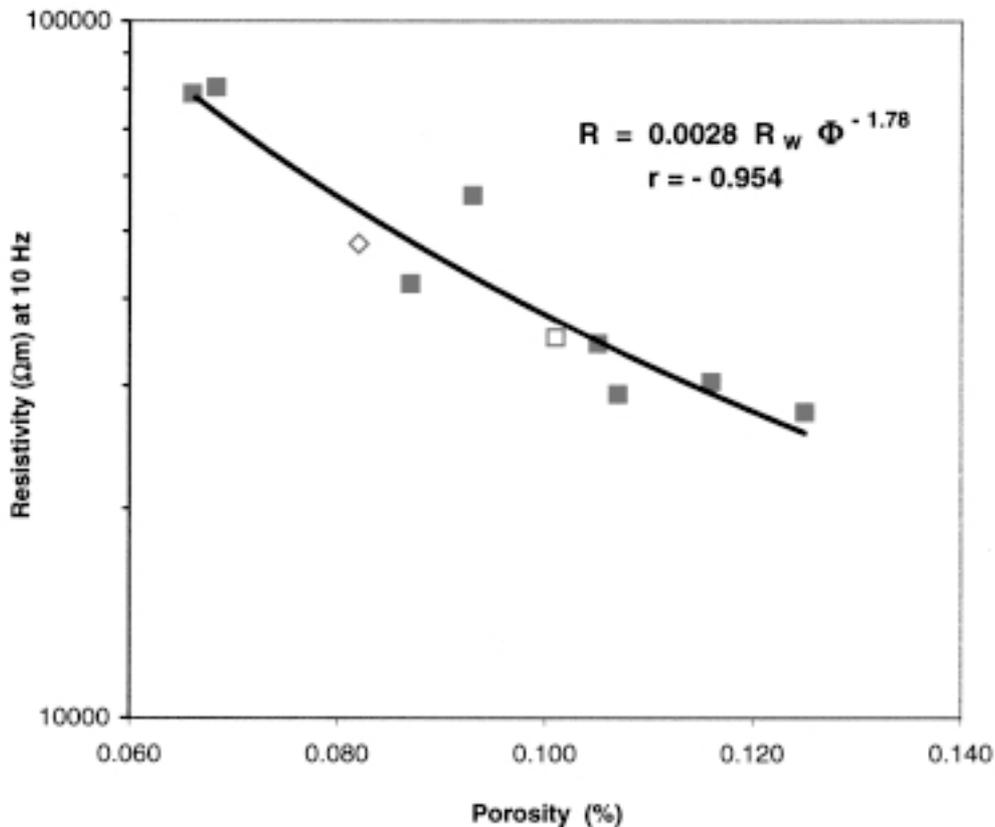


Fig. 8. Relationship between resistivity and porosity of calcite marble samples. A least-squares fit of Archie's law $R = a R_w \Phi^{-m}$ is included, where a and m are empirical coefficients, R_w = resistivity of pore water, Φ = porosity as a fraction and r = coefficient of correlation. The formula of the fitted curve is based on the values of samples saturated in tap water ($R_w=64\Omega\text{m}$). The open symbols are values of samples saturated in deionised water ($R_w=945\Omega\text{m}$), if this resistivity value of saturating water were applied to formula, the points of samples 35.40 and 35.50 were out of this figure ($R=569000\Omega\text{m}$ and $842000\Omega\text{m}$). See text, Table 2 and Figures 4 and 7 for details.

is relevant only for the rocks with pure electrolytic conductivity. The conditions of pores and electrolytes in the voids were probably changing during the saturation process by the dissolving of calcite, precipitation and recrystallization.

Discussion and conclusions

The samples of this study are from only one drill hole (R354/98) of the Kisko carbonate marble deposit, and dolomite marble samples from only a very narrow depth interval (19.00 - 19.15 m). So the number of samples is quite small for general conclusions of the physical parameters of this region.

The magnetic characters of the studied dolomite and calcite marbles differ strongly from each other. In the susceptibility - density plot (Fig. 6) dolomite and calcite marble samples clearly form their own groups, which reflect differences in the amount of magnetic minerals. The dolomite samples contain visible amounts of pyrrhotite (Fig. 2). Both dolomite and calcite marbles from the drill hole are very dense, porosities are low (0.10 ± 0.03 %) and electric resistivities high (dolomite marble samples $33200 \pm 22000 \Omega\text{m}$ and calcite marble samples $46200 \pm 19700 \Omega\text{m}$). The density ($2872 \pm 7 \text{ kg/m}^3$ and $2733 \pm 6 \text{ kg/m}^3$) and seismic P-wave velocity ($6800 \pm 60 \text{ m/s}$ and $6270 \pm 100 \text{ m/s}$) values are at the upper level of typical values for dolomites and calcites.

In the saturation and resistivity tests (Fig. 4) the dolomite marble samples of the Kisko region behaved normally, as their resistivity decreased by water saturation and stabilised at the resistivity level of full saturation. By contrast, the resistivity values of calcite marble samples started to increase during saturation and the values were doubled or tripled in about four days. In the repeated tests the dolomite samples gave the same results. The calcite samples, instead, did not revert to their former resistivity level but increased and exceeded the measuring range of our equipment (maximum measurable values are 100 000 - 200 000 Ωm depending on the dimensions of samples). Studies to verify and interpret this abnormal behaviour of carbonate rocks is underway. Suggestions of changes in electrolytes, their paths on mineral boundaries, chemical reactions and carbonate precipitation is under investigation. A key to the solution might be discovered from Davis and Kent's (1990) description of carbonate minerals in aqueous processes. They explain that cation uptake occurs in two steps. A relatively rapid initial step, which reaches completion within one day, is followed by a slow step,

whereby the uptake rate appears to be constant over a long period of time (at least several days). The rapid step results from sorption onto a hydrated CaCO_3 layer. The slow step can be interpreted as resulting from recrystallization.

A probable explanation for the abnormal behaviour of calcite samples in these laboratory saturation and resistivity tests might be that the paths of electrolytes and electric current can be obstructed. Cooperation between geophysicists, chemists and geologists is necessary to fully understand the physico-chemical conditions in water-carbonate interactions.

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AIRBORNE ELECTROMAGNETIC SURVEYS OF CLAY AREAS IN FINLAND

by

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Introduction

On the aerelectromagnetic (AEM) maps produced by the Geological Survey of Finland (GTK) the most significant anomalies are related to clay areas. Proper interpretation of these anomalies is difficult, because information is scarce on the electric conductivity structure of clays, and so the AEM maps have been little used in studies of clay areas. However, elsewhere in the world electromagnetic methods are quite commonly applied in various clay investigations. AEM surveys have been used in Austria to locate prospective clay deposits (Hübl et al. 1996) and in the USA for planning of irrigation canals (Gamey et al. 1996). Clay areas can also become salinized, which is detrimental to agriculture and the environment. The salinization process can be electrically monitored due to the increased conductivity of saline soils (Rhoades & Ingvoldson 1971). Saline soils have been mapped by EM methods from the ground surface e.g., in Australia (Williams & Baker 1982), in Canada (Cannon et al. 1994), in Pakistan (Hendrickx et al. 1992) and in the USA (Vaughan et al. 1995). In Australia a national dryland salinity research program was established in 1993, during which various AEM methods are being tested (see Coppa et al. 1998).

Alkaline and neutral saline soils are formed mainly in arid climates, whereas acid sulphate (AS) soils harmful to the environment can be also formed in the temperate climate of Finland by oxidation of drained Littorina clays (Purokoski 1959). AS soils are characterized by high electric conductivity (Erviö

1975) so that electric methods should be suited to their investigation. However, the use of electric methods has been minor, although the delineation of sulphide sediment areas using AEM maps has been tested in one study (Åström 1996). At an early stage of their development the AS soils generate sulphuric acid, which besides causing hazards to the environment (see Palko 1994) is a danger to concrete and steel structures (Hyypä 1977, Dent & Dawson 1999). It is thus important to know where the actual and potential AS soils occur when land use or construction projects are planned. Potential AS soils are sulphide sediments that are now below the groundwater table, but may be exposed to oxidation as a result of drainage or excavation. If the electric conductivity of the sulphide-bearing sediments differs sufficiently from the conductivity of their surroundings, then the AEM method would be ideal for mapping of potential AS soils.

This paper reports some results of conductivity probing performed in various clay types and different areas of Finland. These data define the conductivity structures of clay deposits so that proper methods can be selected for the AEM interpretation of different clay areas. The usefulness of AEM maps in the delineation of AS soils and sulphide clays and for the classification and thickness mapping of clay deposits is examined with the aid of case studies.

Measuring equipment

The various aerogeophysical systems used by GTK in the low-altitude measurements have been

described by e.g. Peltoniemi (1982) and Poikonen et al. (1998). Survey flights started in 1972 using a McDonnell Douglas DC-3 aircraft, but from 1980 the surveys have been carried out with a DHC-6 Twin-Otter aircraft, including the areas interpreted here. The survey speed is about 50 m/s, nominal flight altitude 30-40 m and line spacing 200 m. Besides the AEM equipment the aerogeophysical system comprises two cesium magnetometers, a gamma spectrometer and a DGPS navigation unit. The magnetic and AEM measurements are registered 4 times per second corresponding to about 12.5 m spacing. The transmitter and receiver coils of the AEM system are mounted rigidly on the wingtips of the aircraft. The coil configuration is vertical-coplanar with a coil spacing of 21.4 m and a measuring frequency of 3.1 kHz. In 1995 the AEM system was enhanced by installing to the wingtips another pair of vertical-coplanar coils for measurements at a higher frequency (14.4 kHz). The measurement results can be obtained as computer files including the position data, flight altitudes and the real (RE) and imaginary (IM) components of the AEM anomalies. In this study we examine only low-frequency AEM data, because no high-frequency data were available from the investigation areas.

The variations in electric conductivity of clay areas were measured on site with a conductivity probe (Puranen et al. 1997) weighing 1.2 kg. Its sensor is pressed into the ground with the extension rods of a peat sampler. The present depth range of the probe is 12 m, as determined by the length of the Kevlar-braided cable between the sensor and the electronics unit. The conductivity sensor is formed by a small (4.5 cm long) Wenner electrode array, operated at a frequency of 500 Hz in order to avoid electrode polarization. The conductivity measured by the probe mainly reflects the material which is in front of the sensor within a half-sphere with a radius of 5 cm. The probe is calibrated by measuring electrolytes of known conductivity. The error of calibration is less than 5% in the conductivity range 2-200 mS/m and less than 10% in the range 200-500 mS/m. Conductivity probing repeated in the same place gives results varying generally less than 10%. As it is difficult to push the probe into the hard dry crust of clays, a separate surface sensor (also called conductivity fork) was constructed, which can be connected to the electronics unit of the probe. The conductivity fork is formed by a broader Wenner electrode array (48 cm long), and its electrode spikes (11 cm long) can be easily pressed into the dry crust, so that a conductivity estimate for the uppermost, driest layer of the overburden is obtained,

mainly for a depth range of 0-30 cm.

Geological setting

The stratigraphic sequence in the clay deposits varies regionally (Fig. 1), reflecting the postglacial history of the Baltic, which may be divided into four stages (see Eronen 1992): the Baltic Ice Lake 11000-10300 years ago, the Yoldia Sea 10300-9600 years ago, the Ancylus Lake 9600-7500 years ago and the Littorina Sea during the last 7500 years. The Baltic Ice Lake, the Ancylus Lake and even the Yoldia Sea were mainly freshwater stages. However, the Littorina Sea was brackish, and therefore different electric conductivities can be expected in clay deposits from these stages. The clay deposits within the Salpausselkä zone (Fig. 1) are dominated by varved glacial clays of the Baltic Ice Lake, which were deposited near the ice margin in fairly shallow water. These varved clays are overlain by stratified sediments of the Yoldia Sea (Niemelä 1971). Finer clay-sized particles, transported further from the ice margin into deeper water, were deposited in the foreland of the Salpausselkä ridges in the form of homogeneous Yoldia clay overlying the varved sediments so that the Yoldia sediments form the bulk of the clay deposits in this area (Fig. 1).

After deglaciation the climate became warmer and the salinity of the sea increased, which led to intense biological activity (see Eronen 1992). Organic material was deposited along with clay, forming gyttja clays in the Littorina Sea. In the clay deposits on the west coast of Finland (Fig. 1) the Littorina clays are uppermost and commonly predominant (Gardemeister 1973, Ignatius et al. 1980). In the northern parts of the coastal area only Ancylus sediments are found under the Littorina clay, while in more southern areas Yoldia clay is also found at the base of the deposits. The Littorina clays may be several metres thick in river deltas and low-lying river basins. In areas of higher elevation and strong erosion the Littorina clays may, however, become so thin that the Ancylus or Yoldia sediments form the bulk of the clay deposit. Most of the sulphide clays and sulphur-rich soils of Finland were deposited during the Littorina Sea stage (Purokoski 1959, Erviö 1975). A high sulphur content is typical of gyttja clays containing abundant organic material, and below the groundwater table the sulphur occurs commonly in the form of black ferrous monosulphide. As the soft sulphide clays gradually emerge from the sea, they are exposed to wave and current erosion, which ex-

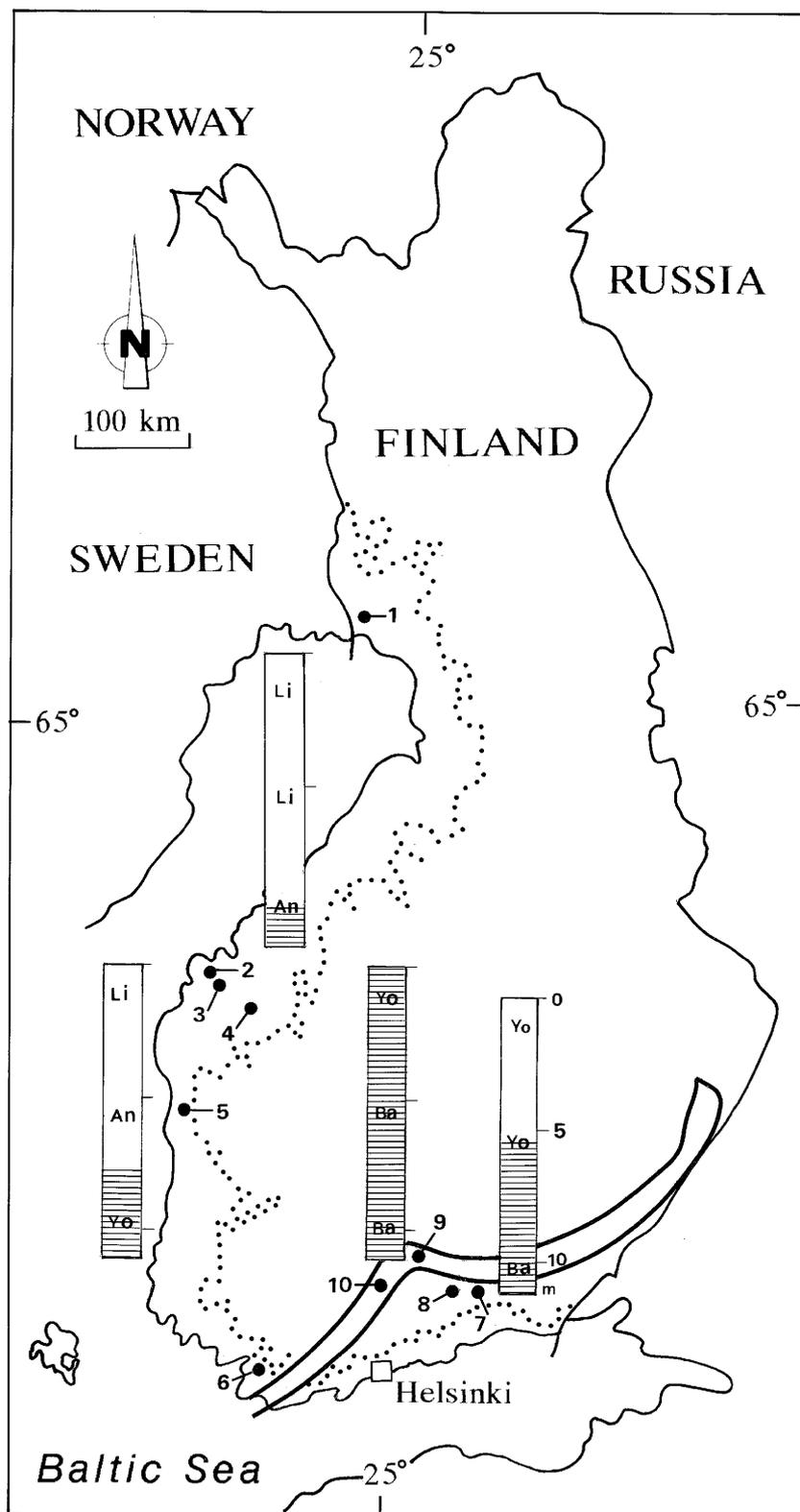


Fig. 1. Investigation localities and geological setting. The Salpausselkä zone (thick line) and the highest shore of Littorina Sea (dotted line) are drawn according to Eronen (1992). The stratigraphic columns of clay deposits are outlined for the Salpausselkä zone and its foreland based on Niemelä (1971) and for the coastal region of western Finland according to Ignatius et al. (1980) and Fromm (1965). In the columns the varved or stratified sediments are marked with ruling. Clay types: Li=Littorina, An=Ancylus, Yo=Yoldia and Ba= Baltic Ice Lake sediments. Localities (and their altitudes in metres above sea level): 1=Tornio (5-10), 2=Koivulahti (0-5), 3=Vähäkyrö (10-15), 4= Nurmo (35-40), 5=Storsjö (34-37), 6=Perniö (14-17), 7=Koria (40-60), 8=Sääskjärvi (50-60), 9=Paimela (80-85) and 10=Ryttylä (80-85).

plains their patchy occurrence in depressions and hollows of the terrain (Purokoski 1959).

The thickness of clay deposits ranges mostly between 5 and 10 m in inland areas while near the coast the average thickness is about 10 m. In SW Finland clay deposits up to 30-50 m thick may be found (Gardemeister 1975). Finnish clays contain less than 10% quartz, less than 10% feldspars and small amounts of amphibole group minerals. The bulk of clays is composed of micaceous minerals, of which the most important are illite and chlorite (Soveri 1956, Gardemeister 1975). For this reason the cation exchange capacity (CEC) of Finnish clays is quite low (10-30 meq/100 g), although in the dry crust where vermiculite also occurs (Soveri 1956), the CEC is somewhat higher (100-150 meq/100 g). Because of the low CEC the electric conductivity of Finnish clays is largely controlled by their water content (porosity) and the salinity of pore water, which in turn are related to the clay and humus contents. The ranges of averages calculated for various clay types are for porosity 59-71%, for salinity 0.04-0.33%, for clay content 34-40% and for humus content 0.6-3.9% (Gardemeister 1975). Water content and especially salinity are clearly the highest in Littorina clays and lowest in the varved sediments of the Baltic Ice Lake.

Electric conductivities

The in situ variations of electric conductivity in the clay deposits were studied by conductivity probing in several areas (Fig. 1). The major part of probing work was carried out in the coastal area of western Finland in order to provide a basis for electric mapping of sulphide clays (i.e. potential AS soils) in this area. During the conductivity probing the presence of sulphide clays was indicated by the black monosulphide stuck to the probe. In most cases the conductivities measured for the sulphide-bearing Littorina clays (Fig. 2) exceed the value 100 mS/m at a depth of 0.5-1.5 m and may even increase to a value of 500 mS/m deeper down. The high conductivity of the Littorina clays is not caused by sulphide particles but is explained by the high electrolyte content of the clays (Erviö 1975). As for its electric conductivity, the dry crust of the Littorina clays (0-1 m) does not noticeably differ from that of other clays. This is seen when comparing the topmost points of conductivity profiles determined by probing in various areas (Figs. 2-3). This was also verified in many areas by mapping the electric conductivity of the dry crust surface with the new conductivity fork. Regardless of area the dry crust

conductivities varied mostly in the range 5-25 mS/m. It is thus difficult to distinguish electrically the AS soils developing in the aerobic surface layer of sulphide clays from the dry crust of clays in general.

Close to the sulphide-bearing probing sites in the coastal area, approximately at the same altitude above sea level, we also found less conductive clay deposits (Fig. 2), in which no black monosulphide was encountered during probing. Littorina clay may be lacking from the surface of these deposits, or it may occur as a thin, dry and washed layer, the electric conductivity of which does not differ from that of the less saline *Ancylus* or *Yoldia* clays occurring below the groundwater table. The conductivity of the latter clays (40-80 mS/m) is clearly lower than that of the sulphide-bearing Littorina clays. In the foreland of the Salpausselkä ridges (Fig. 1) the surface part of clay deposits is dominated by homogeneous, fat *Yoldia* clays, in which the conductivities determined by probing are mostly in the range 30-70 mS/m (Fig. 3A). The varved and stratified sediments within the Salpausselkä zone have the lowest clay and water contents, and thus they could not be penetrated by the conductivity probe. However, the conductivities measured from the surficial parts of the deposits (Fig. 3B) using the probe and the fork, and those interpreted from the AEM maps define consistently the electric conductivity range 5-25 mS/m for these sediments.

To summarise the probing data, the most typical range of in-situ conductivity is 100-500 mS/m for the sulphide-bearing Littorina clays, 30-80 mS/m for the *Ancylus* and *Yoldia* clays and 5-25 mS/m for the sediments of the Baltic Ice Lake. These ranges are consistent with the conductivities of clays determined at various times by DC resistivity soundings (cf. Saraoja 1946, Peltoniemi 1982, Pernu 1991). The results are also in harmony with Archie's law (see e.g. McNeill 1989), according to which the electric conductivity of a water-saturated sediment increases with its porosity (water content) and the conductivity (salinity) of pore water. In addition, a clay fraction with a high cation exchange capacity (CEC) increases the conductivity of the sediment especially if the salinity of pore water is low. The Finnish clays have a low CEC, which thus cannot explain the variations in the electric conductivity of clays. The high conductivity of the Littorina clays (Fig. 2) compared with that of the Baltic Ice Lake sediments (Fig. 3B) is due to the high salinity and water content of the former sediments as compared with the latter. In the dry crust, no significant differences in conductivities (5-25 mS/m) were observed between the clay types.

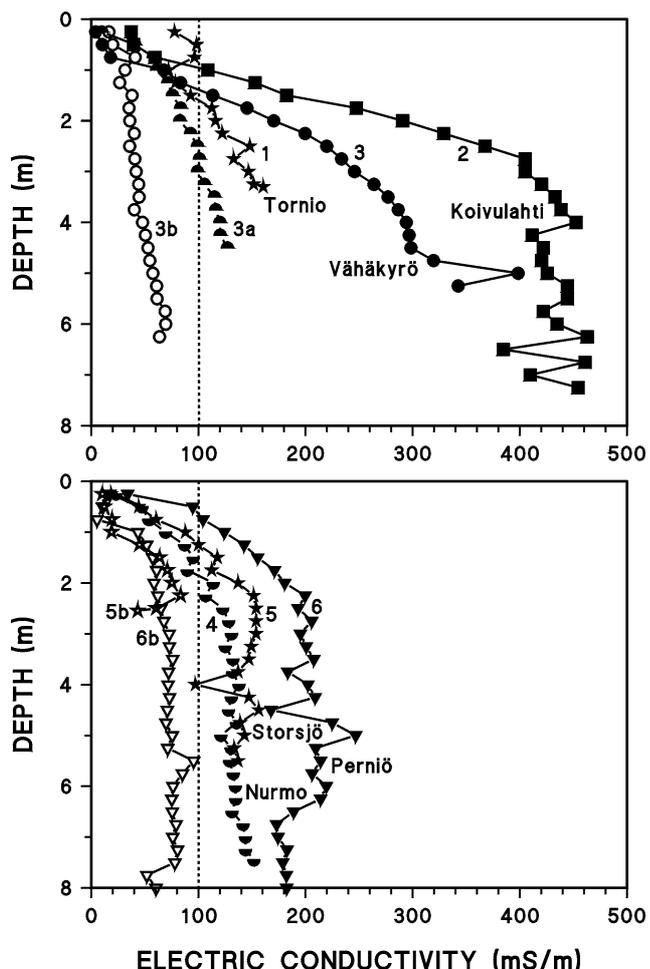


Fig. 2. Vertical conductivity profiles of clay deposits in the coastal region. Profiles dominated by monosulphide-bearing Littorina clays are presented using solid black symbols. Conductivity probing localities shown in Figure 1.

The probing data outline the vertical and horizontal conductivity variations or the conductivity structures of different clay deposits. The sharp minima observed in some conductivity profiles are often related to coarser sediment layers. The electric conductivity is generally at its highest in the intermediate layers of clay deposits, from where the conductivity decreases towards the surface and sometimes also towards the base of the deposit. Near the surface this is due to decreasing pore water content and increased leaching of the surface layers. Near the base of clay deposit the salinity and water content may also decrease, especially if sediments of the Baltic Ice Lake are present at the base (cf. Gardemeister 1975). In the coastal sulphide clays the electric conductivity may show a systematic tenfold increase from the surface downwards over a distance of a few metres. The whole deposit cannot then be described accurately with one conductivity value in the AEM interpretations. Below the surface

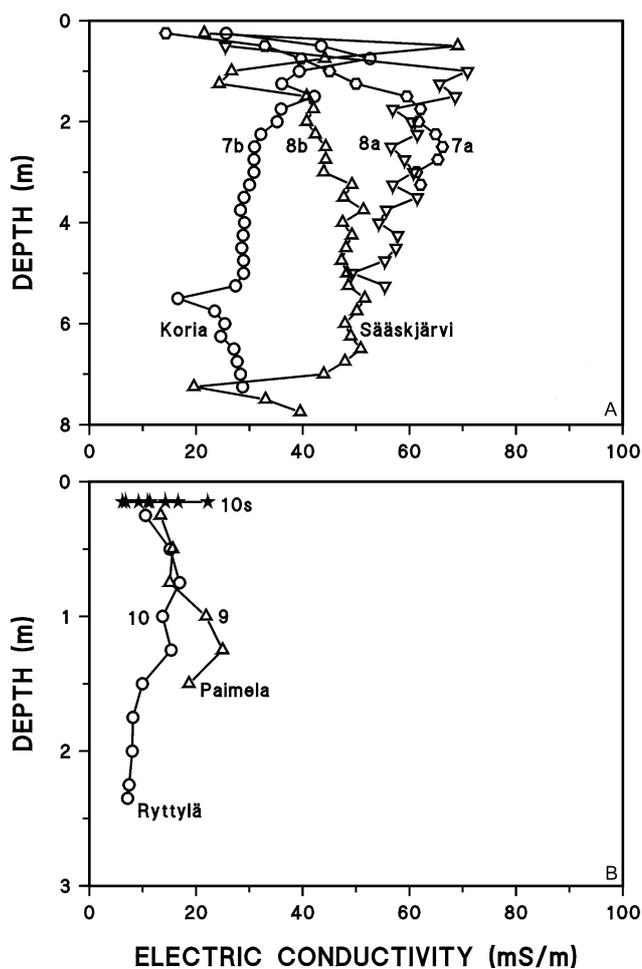


Fig. 3. Vertical conductivity profiles of clay deposits A) in the foreland of Salpausselkä ridges and B) in the Salpausselkä zone. The results measured at the surface using the conductivity fork are marked with stars. Conductivity probing localities shown in Figure 1.

layer the vertical conductivity variation is often smaller and more sporadic, particularly in the inland clay areas so that average or maximum conductivity values may be used in their thickness interpretations.

Interpretation methods

The clay deposit and its substratum can be described with horizontal layer models, the theoretic AEM anomalies of which are calculated below using a computer program based on the works of Sinha (1977) and Peltoniemi (1982). A one-dimensional two-layer model may be used as the first approximation of many clay deposits, if the poorly conducting surface layer of the deposit is treated by increasing the flight altitude in the model correspondingly. The top layer of the model with a high conductivity represents the clay deposit and the basal layer represents the substratum (till, bedrock), which is

assumed to be resistive (0.2 mS/m) and semi-infinite. The response of the AEM system to the two-layer model at typical clay conductivities (25-250 mS/m) is illustrated by the curves in Figure 4, which show the real-imaginary (RE/IM) ratio of the AEM response vs. the conductivity-thickness product (σZ) of the top layer. The response is characterized by using the RE/IM ratio that combines the measured data in a way which is rather insensitive to minor measuring errors and small changes in the flight altitude.

The response curves of Figure 4 define three different regions, which should be considered in the AEM interpretations of clay deposits. The response regions are the thin layer, the thick layer and the half-space region. In the region of electrically thin layers, where the RE/IM ratio is less than 0.5 and the product σZ less than 1000 mS, the response curves for different conductivities coincide defining a σZ -equivalency. Within this equivalency a 2-m-thick layer of sulphide clay ($\sigma=250$ mS/m) cannot be distinguished, for example, from a 10-m-thick layer of Yoldia clay ($\sigma=50$ mS/m) or a 20-m-thick layer of Baltic Ice Lake sediments ($\sigma=25$ mS/m). As the clay thickness increases, the AEM response attains 95% of the half-space response at different points on the σZ -axis depending on the conductivity of clay (see Fig. 4). The thickness estimates at these points ($Z=70$ -23 m) characterize the penetration depth of the AEM system when surveying deposits in the conductivity range 25-250 mS/m. The estimated half-space response limits are so high that Finland's clay deposits can be seldom described accurately with a half-space model as the AEM surveys are interpreted. However, in countries with thicker sedimentary deposits the half-space model can be valid in large areas, and then the RE/IM values reflect directly the regional conductivity variations of the deposits.

In the thick layer response region, located between the half-space and thin layer regions (Fig. 4), the response curves can be used to estimate the minimum conductivity of clay layer and if the conductivity is known the thickness of clay layer from the measured RE/IM values. The sulphide clays on the west coast of Finland have been identified from the AEM maps using the RE/IM value 1 (Åström 1996), which is a quite certain criterion for localising sulphide clays (cf. Fig. 4). On the other hand, the areas delineated using an easier condition $RE/IM > 0.5$ also include sulphide-bearing Littorina clays at high probability. This condition corresponding to the σZ -value of 1000 mS (Fig. 4) can be fulfilled by a clay layer with a

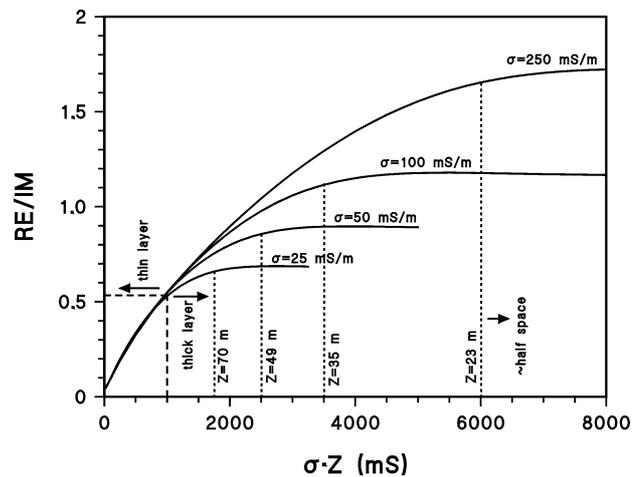


Fig. 4. Real-imaginary ratio (RE/IM) of AEM response vs. conductivity-thickness product (σZ) of the clay layer in a one-dimensional two-layer model of clay deposits. Response curves are presented for typical conductivities ($\sigma=25$ -250 mS/m) of clay layer. The substratum of clay is assumed to be resistive (0.2 mS/m) and semi-infinite, the flight altitude is 35 m and the measuring frequency is 3.1 kHz as used in the AEM system of GTK. The region of thin layer response is outlined by a dashed line. The lower σZ -limit (dotted line) and corresponding minimum thickness (Z) of the half-space response is indicated for each curve. The thick-layer behaviour characterizes the response curves between the dashed and dotted lines.

thickness in the range 4-10 m and a conductivity in the range 250-100 mS/m, respectively, which are typical values for sulphide clays (cf. Fig. 2). The sulphide-poor clays of the west coast generally have a σZ -value lower than 800 mS, because their conductivity is mostly under 80 mS/m (Fig. 2) and their average thickness should not exceed 10 m (Gardemeister, 1975). It is obvious that sulphide-poor clays and minor pockets of sulphide-bearing clays cannot be distinguished from each other based on the values of RE/IM ratio or σZ product.

The AEM interpretations of clay areas should be started by eliminating the AEM anomalies of conductive bedrock sources, although such sources occur only in limited areas (<10 %) of Finland. Bedrock sources can be usually identified on the basis of their magnetic anomalies and the distinctly banded shape of their AEM anomalies. In the following case histories the bedrock is magnetically tranquil and no conductive bedrock zones (e.g. black schists) occur in the areas so that the AEM anomalies are caused by conductivity and thickness variations of the clay deposits. The electric conductivity of clay (5-25 mS/m) even in the thin and dry marginal parts of clay areas is clearly higher than the typical conductivities of underlying bedrock (0.2 mS/m) and surrounding overburden (<1 mS/m). For this reason the margins of clay areas can be defined quite accurately by the low-frequency AEM sur-

veys, in which particularly the IM component is sensitive even to thin conductive layers and small conductivity variations. When a clay layer ($\delta=25$ mS/m) thins out to 1 metre, i.e. to its limit thickness in the mapping of Quaternary deposits, the IM anomaly of the clay layer is 348 ppm as computed by the two-layer model using a flight altitude of 35 m. By comparing the IM anomaly maps and the maps of Quaternary deposits we have found that the 400 ppm contour seems to outline the clay areas quite precisely.

In many areas the clay thickness is known from sporadic drilling sites, for which the average conductivity of clay can be estimated using the measured RE/IM ratio and the response curves of Figure 4. If the conductivities estimated for various sites differ significantly, then the clay composition (salinity, water and clay content) is variable, which hampers AEM mapping of clay thickness. In case the conductivities of the clay area remain reasonably constant, the clay thickness variations may be estimated from the AEM data. For individual points the thickness estimates are obtained by using the curves in Figure 4. For automatic profiling of clay thickness we wrote a computer program performing two-layer model-based inversion of the AEM data. As initial values the program requires the conductivity estimates of the clay layer and its substratum along with the thickness of a possible dry crust. The dry crust is assumed to be so poorly conducting that it can be handled by increasing correspondingly the flight altitude in the model. On the basis of the AEM data (RE value, IM value, flight altitude) and the initial model values the program solves iteratively for the clay thickness at each measuring point by using the Levenberg-Marquardt method. The quality of thickness profiling can be estimated by comparing the measured AEM data with the modelled RE and IM values computed by the program.

Apparent conductivity maps based on the half-space model are also processed from the AEM data. In the process the computer determines for each measuring point a half-space that would produce the measured anomaly by its apparent conductivity and the distance of its upper surface. The bedrock sources of AEM anomalies may approach electrically a half-space, and then the apparent conductivity maps reflect the true conductivity of bedrock. However, typical clay deposits of Finland (thickness 5-20 m) are electrically thinner than a half-space (cf. Fig. 4) so that the apparent conductivity maps of clay areas are almost always affected by the underlying resistive bedrock. Correspondingly, the apparent conductivities of clay areas are lower than

the true conductivities of clay deposits. Nevertheless, the apparent conductivity maps qualitatively reflect the regional variation in the conductivity-thickness product of clay deposits, so that by using these maps clay areas may be distinguished and classified. The apparent conductivity maps also make it possible to compare and combine the data measured by the different AEM systems of GTK (DC3 and Twin Otter system).

Vähäkylä clay area

The Quaternary deposits of the Vähäkylä area have been described by Lindroos et al. (1989). The river Kyröjoki flows across this area and the river surface is only 6-12 metres above sea level. About half of the area is covered by fine-grained sediments, i.e. clay and silt. Based on drilling results the thickness of these deposits is 4-10 m in general and 15-20 m at the most. Two thirds of the cultivated fields consist of gyttja clay formed during the Littorina Sea stage, and about one fourth is silty clay, which is found especially in the south-eastern part of the area. The cultivated fields in the central parts are underlain by several metres of soft gyttja clay with low bearing capacity, which makes this area problematic for construction. In addition, almost the entire area of cultivated fields in Vähäkylä has been troubled by AS soils (Erviö 1975). The conductivity of sulphide clays decreases markedly towards their surface (Fig. 2) so that their AEM anomalies are not caused by the oxidised surface layer of the clays, i.e. the possible AS soils. The anomalies are mainly due to deeper layers of sulphide clays, which are highly conducting because of the high salinity of Littorina clays (Erviö 1975).

The maps of RE/IM ratio and apparent conductivity (Fig. 5) compiled from the AEM data of Vähäkylä area reflect the regional variations in the conductivity-thickness product (σZ) of overburden. The lowest conductivities characterize the forested till areas and the minor areas of exposed bedrock and bogs (green on the maps), which show low IM anomaly values (<400 ppm). The thin and poorly conducting marginal areas of clay deposits are seen on the maps as white areas with apparent conductivities lower than 25 mS/m and RE/IM values lower than 0.5. These areas are located at the edges of the Kyröjoki river valley, where Littorina clay occurs, if at all, as a thin layer overlying the Ancylus sediments (silty clays, silts). Clay deposits characterized by higher conductivity and greater thickness are shown in grey-tones, the darkness increasing with the σZ -value. In the light grey areas the

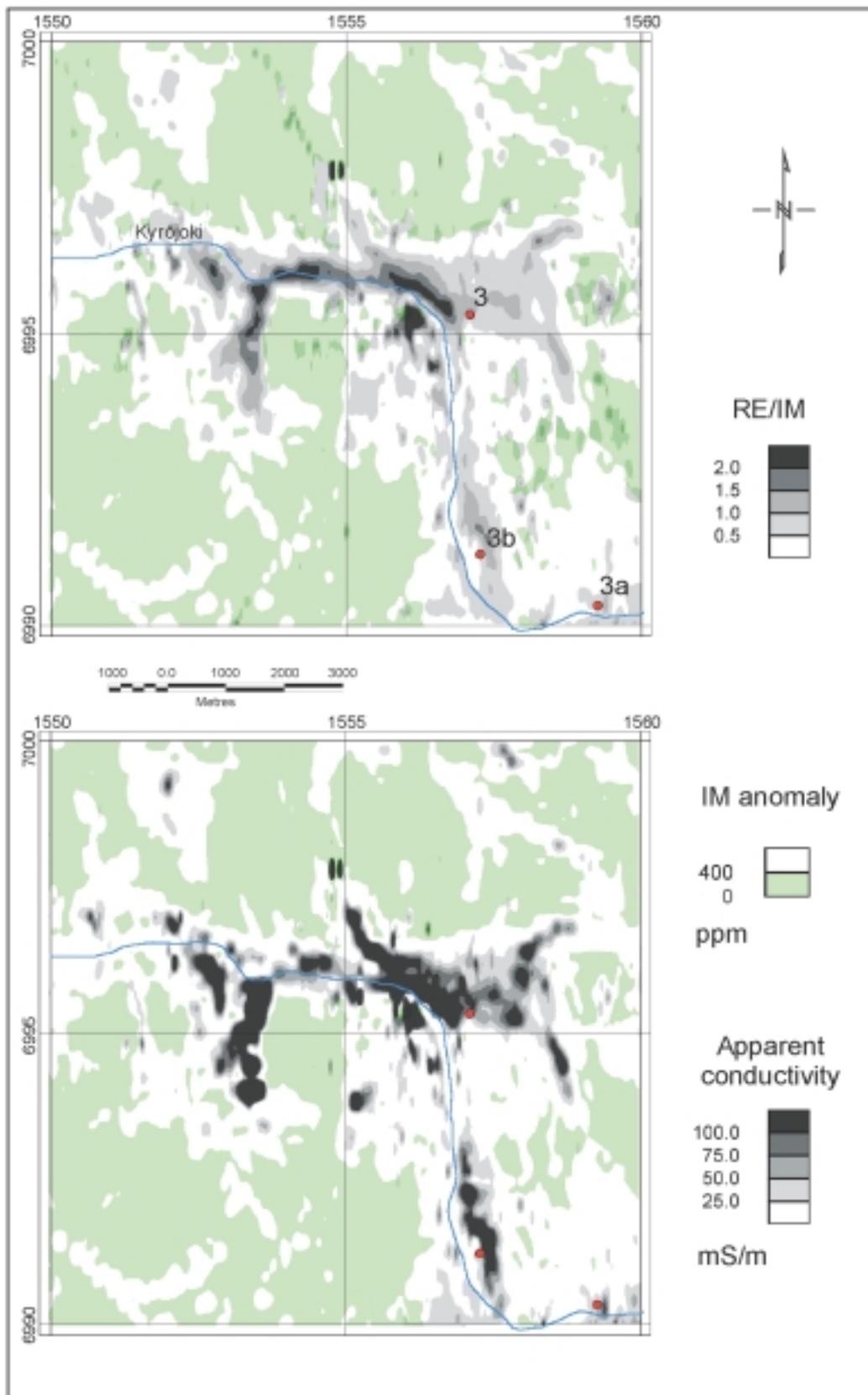


Fig. 5. Grey tone maps of the RE/IM anomaly ratio and the apparent conductivity based on the AEM data of Vähäkylä area. The IM anomalies (green<math>< 400 \text{ ppm}</math>) are shown in the background. Conductivity probing sites (3-3b) are marked with red dots.

RE/IM ratio is over 0.5 and thus the σZ -value is over 1000 mS (see Fig. 4), which can be caused, for example, by 10 metres of Littorina clay with a conductivity of 100 mS/m or 4 metres of sulphide-bearing gyttja clay with a conductivity of 250 mS/m. On the apparent conductivity maps the limiting value 100 mS/m of sulphide-bearing clays is exceeded in large areas, and so the true conductivity of the clays in these black areas is clearly higher than the limiting value, which is consistent with the conductivity probing data of site 3 (Fig. 2). The sulphide-bearing gyttja clay pockets showing the highest σZ -values appear on the RE/IM maps as dark grey and black areas where the RE/IM ratio is over 1 and even over 2, which then indicates that the clay conductivity is at least 250 mS/m (cf. Fig. 4).

Both the half-space and the two-layer model describe quite roughly sulphide clay deposits, which are thinner than 20 m and which show conductivities that increase strongly downwards (Fig. 2). Thus the apparent conductivities based on the half-space model are minimum estimates and even the interpretations based on the RE/IM ratio of two-layer model are only approximations. However, the AEM surveys cover the Vähäkylä clay area by over 10,000 data points, and so the area is reflected by the data in considerable detail. The AEM interpretation maps (Fig. 5) show that the most highly conducting gyttja clays, which have low bearing capacity and usually contain the most sulphides, occur as patches and pockets mainly in the depressions of the central areas. These areas are most problematic as regards construction works and potential formation of AS soils. Verification of this interpretation, based on AEM surveys, requires geological sampling and chemical analyses.

Koria clay area

The Quaternary deposits of the Koria area, which is located in the foreland of the Salpausselkä ridges, have been described by Rainio et al. (1989), according to whom the thickness of clay deposits in the area is often 15-20 m. Because of the altitude of the area (40-60 metres above sea level) the topmost layer of clay deposits is typically homogeneous Yoldia clay, underlain by varved Yoldia clay and Baltic Ice Lake sediments (Niemelä 1971, Rainio 1993). In these sediments the water content and especially the salinity are clearly lower than in the Littorina clays of the coastal areas. It is thus natural that in the clays of Koria area both the measured and the apparent conductivities (Figs. 3A and 6) are

distinctly lower than in the Littorina clays of Vähäkylä (Figs. 2 and 5). At Koria the apparent conductivity exceeds the value 75 mS/m only at scattered points, whereas in the Littorina clays of Vähäkylä the conductivity exceeds 100 mS/m in considerable areas. In addition, the vertical conductivity variations are smaller in the clays of Koria than in the Littorina clays of the coastal area, and so the Koria area is better suited for AEM mapping of clay thickness based on two-layer model.

The limits of the clay areas on the map of Quaternary deposits (Rainio et al. 1989) are fairly compatible with the 400 ppm contour of IM anomalies on the interpretation maps of AEM data (Fig. 6). The resistive till and bedrock areas (green) form a rather small part of the Koria area (28%). The thin and poorly conducting marginal parts of the clay deposits, the apparent conductivity of which is under 12.5 mS/m, are shown on the maps as white areas. In the light grey areas the RE/IM ratio is over 0.25, i.e. the conductivity-thickness product is over 500 mS (Fig. 4), which requires for example, 10 metres of clay with a conductivity of 50 mS/m. In the medium grey areas the apparent conductivity is over 25 mS/m and the RE/IM ratio over 0.5, which can be caused by 15 metres of clay with a conductivity of 60 mS/m. The dark grey and black areas at the western margin of the Koria area (Fig. 6) are characterized by the highest values of the apparent conductivity (>75 mS/m) and the RE/IM ratio (>0.75), which require for their explanation at least 20 metres of clay with a conductivity of 75 mS/m (Fig. 4). In the Yoldia clays no high salinities or great variations in salinity have been reported, and so probably the elevated conductivity of the western margin is mainly due to higher water content of the clay. Since the Yoldia clays with a higher water content are generally richer in clay fraction (fatter), the AEM interpretation maps evidently localise the fattest clays in the area, which are also the most suitable for production of expanded clay aggregates (see Hatakka 1997).

In the central part of the Koria area the AEM interpretation maps of clay deposits are characterized by smooth variations (Fig. 6). In this area the deposits may be described with a two-layer model, in which we assume that the clay conductivity is (reasonably) constant, the dry crust is thin and the substratum is resistive (0.2 mS/m). The conductivities determined by probing from the Koria clays were in the range 30-60 mS/m (Fig. 3A). The automatic thickness mapping of the central clay area was carried out with the computer program described above, which performs two-layer model-

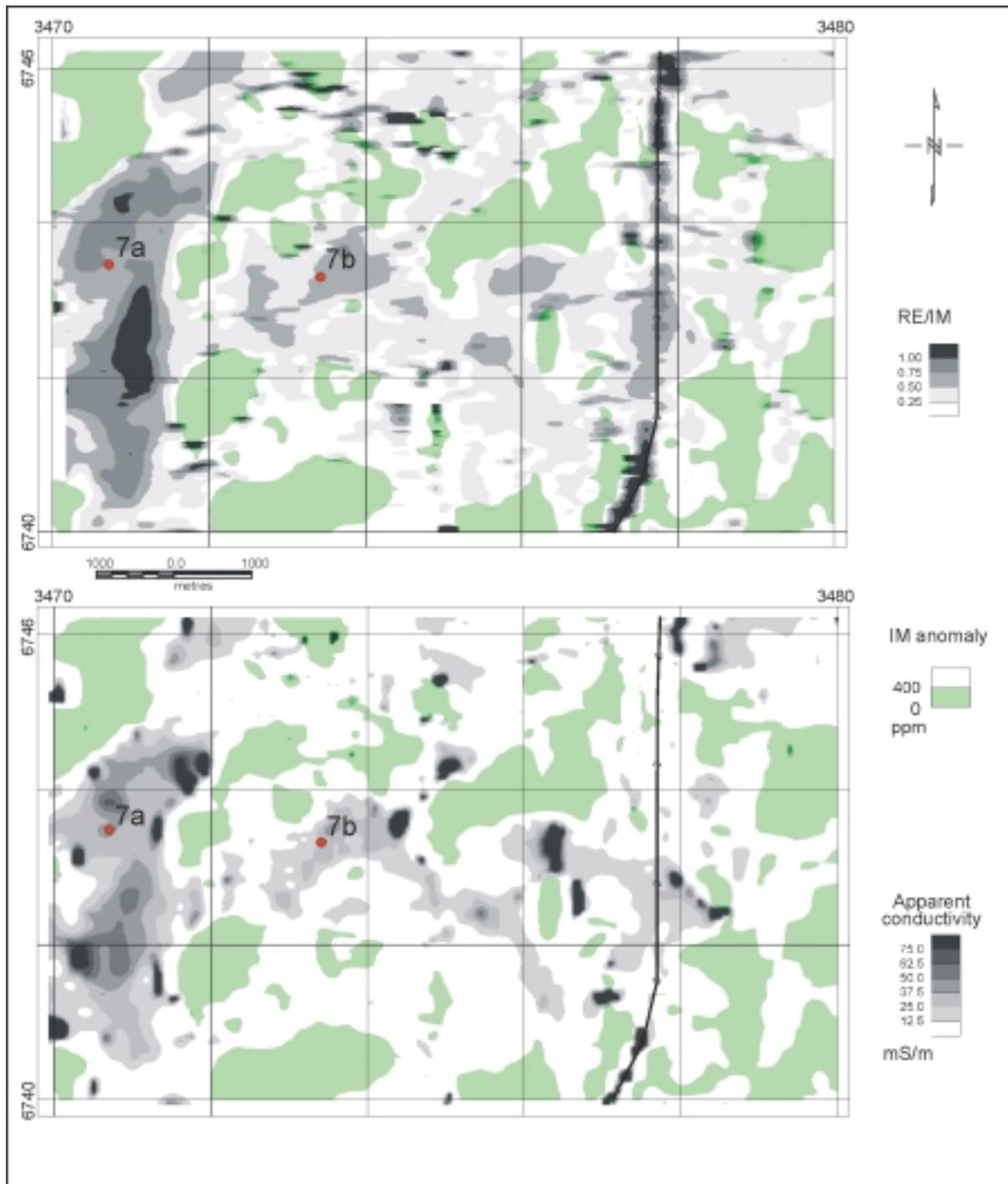


Fig. 6. Grey tone maps of the RE/IM anomaly ratio and the apparent conductivity based on the AEM data of Korja area. The IM anomalies (green < 400 ppm) are presented in the background. Conductivity probing sites (7a-7b) are marked with red dots. The electric power line causing the long and narrow RE/IM anomaly is shown with a Z-line.

based inversion of the AEM data. In the inversion we used the maximum conductivity estimate (60 mS/m), which led to minimum estimates of clay thickness. Based on the inversion results we compiled a clay thickness map for the central area (Fig. 7), which is in reasonable accord with the few thickness estimates obtained earlier by drilling. The conductivity determined by probing from the central area (site 7b) is 30 mS/m (Fig. 3A). If this lower

conductivity value is used in the inversion, the thickness estimates are nearly doubled in disagreement with the drilling results. This demonstrates that the reliability of clay thickness mapping by inversion of AEM data must be always verified by drilling and conductivity probing from several sites of the study area.

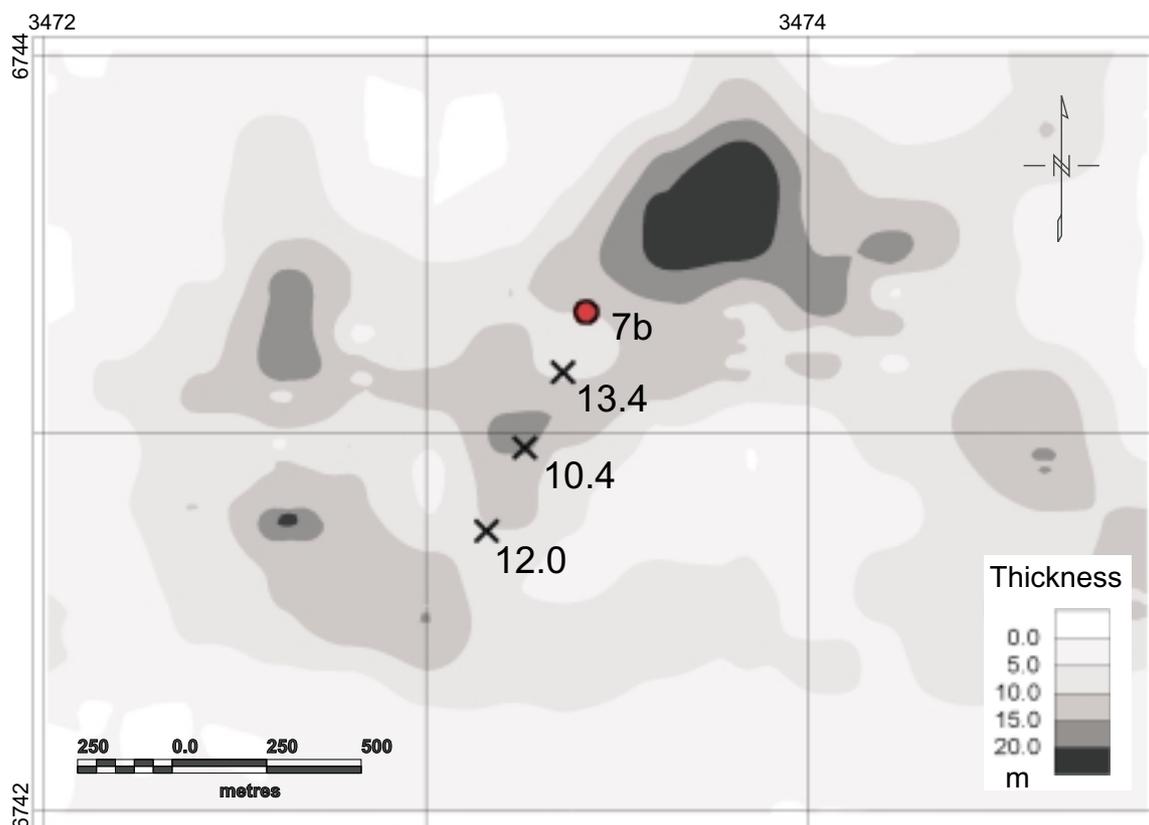


Fig. 7. Clay thickness map of the central Koria area computed by automatic model-based inversion of AEM data. In the inversion the clay deposit is described with a two-layer model, and the conductivity 60 mS/m is assumed for the clay layer and 0.2 mS/m for its substratum. The conductivity probing point (7b) is marked with a red dot. The clay thickness estimates (in metres) based on drilling results are indicated for three sites (crosses).

Conclusions

As a summary of the conductivity probing data from different areas of Finland (Figs. 1-3), the following characteristic ranges can be presented for the in situ conductivities of various clay types. The range is 100-500 mS/m for the sulphide-bearing Littorina clays, 30-80 mS/m for the Ancyclus and Yoldia clays and 5-25 mS/m for the Baltic Ice Lake sediments. The especially high conductivity of the Littorina clays is caused by their high water content and salinity. The Baltic Ice Lake sediments again have the lowest water content and salinity, and correspondingly the lowest electric conductivity. In most cases the conductivity of clay deposits decreases towards their surface due to decreasing pore water content and increased leaching of the surface layers. No significant differences between clay types were found in the conductivity of dry crust (5-25 mS/m). Hence, it is difficult to identify electrically the AS soils that develop in the dry surface layers of clay deposits. On the other hand, even the dry crust of clays is clearly more conductive than the dry surface layer of other sediments (<1 mS/m), from which even thin and dry clay layers can be

electrically distinguished.

The vertical and horizontal variation of electric conductivity is so strong in the Littorina clays of the coastal region that these clays cannot be accurately described with a two-layer model, which is rather more suited for representation of the inland clays with lower and less variable conductivities. The top layer of one-dimensional two-layer model is formed by conductive clay (25-250 mS/m) while the basal layer of the model (till, bedrock) is assumed to be resistive (0.2 mS/m) and semi-infinite. As the AEM data of clay deposits are interpreted with the two-layer model, three different cases may be distinguished: thin layer, thick layer and half-space (Fig. 4). In the case of thin layer, for which the RE/IM ratio is less than 0.5 and the conductivity-thickness product (σZ) less than 1000 mS, only the σZ -value of clay layer can be solved from the AEM data. In the case of thick layer, the minimum conductivity of the clay layer and its σZ -value can be estimated from the RE/IM ratio. Finally, in the case of half-space the RE/IM values determine directly the conductivity of clay deposit so that conductivity variations of thick sedimentary piles may be mapped by AEM measurements. In sediments with a con-

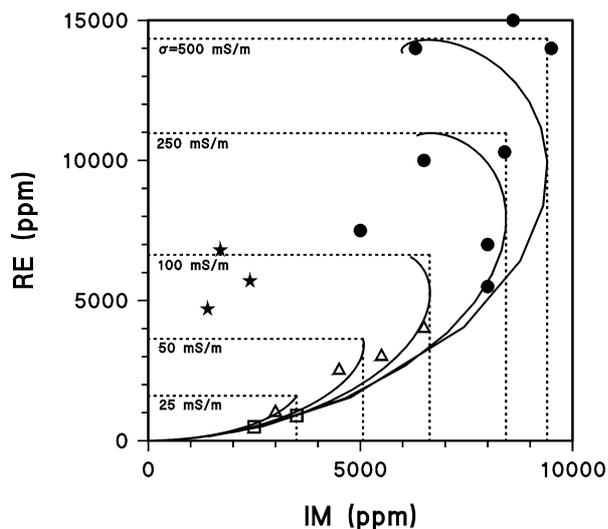


Fig. 8. Typical AEM anomalies of the example clay deposits compared with each other, with theoretical anomaly curves of two-layer model and with AEM anomalies of black schists. The black schist anomalies (area 1) are marked with stars, the clay anomalies from the west coast of Finland (areas 1-6) with circles, the anomalies of Salpausselkä foreland (areas 7-8) with triangles and the anomalies of Salpausselkä zone (areas 9-10) with squares. For location of areas, see Figure 1. The model curves were computed for typical conductivities (25-500 mS/m) of clay deposits, the thickness of which increases along the curves from 0 m (origin) to 30 m (upper end of each curve). In modelling we assumed a resistive substratum (0.2 mS/m) for the clay layer, flight altitude of 35 m and measuring frequency of 3.1 kHz (the AEM system of GTK).

ductivity of 25 mS/m (or 250 mS/m), the electric half-space is attained at a layer thickness of 70 m (or 23 m), which also characterizes the penetration depth of the AEM system (of GTK) into such deposits.

Regional σ Z-variations of clay deposits may be estimated from the RE/IM ratio maps based on two-layer model or from the apparent conductivity maps based on half-space model. For delineation of the potentially harmful sulphide-bearing Littorina clay pockets we may use the limiting minimum value 100 mS/m for the apparent conductivity and 1 for the RE/IM ratio. If the conductivity of clay deposit is known and remains fairly constant (two-layer model), the thickness variation of the deposit can be estimated from the AEM data by using nomograms (e.g. Fig. 4) or computer programs written for automatic thickness profiling. A comparison of typical AEM anomalies of the example clay deposits (Fig. 8) illustrates how the intensity of anomalies increases from the stratified sediments of the Salpausselkä area to the Littorina clays of the coastal region. Further, the AEM anomalies of clays and black schists clearly differ from each other and from the theoretical anomaly curves of the two-layer model (Fig. 8). The divergence of the measured AEM data from the computed model curves is caused by variations in the flight altitude and differences between the geo-

logical reality and the two-layer model.

Due to their high electric conductivity the largest pockets of the humus-rich and sulphide-bearing gyttja clays deposited in the Littorina Sea can be clearly distinguished on the AEM interpretation maps. This is important, because the Littorina clays are problematic for several reasons (see Palko 1994, Dent & Dawson 1999). The Littorina clays may be oxidised into AS soils when they emerge from under the groundwater table as a consequence of isostatic uplift or artificial drainage. In the oxidation processes sulphuric acid is formed and elevated concentrations of toxic metals may be released into the soils, which can be harmful to cultivation, hazardous to the environment and the acid generated may also corrode steel and concrete structures. In addition, the gyttja clays with high humus and water content are soft and of low bearing capacity (Kauranne et al. 1972), which makes them unstable as foundations for buildings or roads. The Littorina clays are also unsuitable for production of expanded clay aggregates (Hatakka 1997) due to the high humus content. On the other hand, because of their high content of organic material the Littorina clays are significant carbon stores, which can be mapped by AEM measurements and should be included in the carbon budget calculations of sediments (cf. Pajunen & Kortelainen 1998).

For production of expanded clay aggregates the most suitable clays are fat and homogeneous, containing sufficiently iron and water of crystallisation and the right amount of organic material (see Hatakka 1997). The Yoldia clays of southern Finland often fill these requirements, while the Littorina clays contain too much humus and the varved sediments of the Baltic Ice Lake are too varied as to their grain-size distribution. Because the clay deposits dominated by Littorina clays or Baltic Ice Lake sediments can be identified from the AEM maps, the deposits least suitable for production of expanded clay aggregates may be excluded. Within the promising deposits it may be possible to locate the areas with the highest clay content (water content), which should be characterized by high conductivities on the AEM interpretation maps (e.g. the western margin of the Koria area). Finally, with AEM measurements we can delineate clays even below other sediments and estimate clay thickness variations, which may be helpful in various construction projects. The AEM maps can thus help to solve many problems in environmental and engineering geology of clay deposits, but the AEM anomalies of clays may also mask the anomalies of some interesting bedrock sources (e.g. ore deposits).

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PRELIMINARY MAGNETIC AND GRAVITY ANOMALY MAPS OF THE FENNOSCANDIAN SHIELD 1:10 000 000

by

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Introduction

The main geological formations of the Fennoscandian Shield were evolved and stabilized in the Palaeo-Mesoproterozoic. Less than 20 per cent of the bedrock area originates in the Neoproterozoic and was affected by the Palaeoproterozoic Svecofennian Orogeny. Neoproterozoic mafic and Phanerozoic alkaline magmatism added minor masses to the uppermost part of the shield. The Precambrian crystalline rocks of the shield continue below the Vendian-Phanerozoic sediments of the East European craton, establishing the Fennosarmatian Shield. It is not known what factors caused the Precambrian rocks of the Fennoscandian Shield to be exposed in the upper surface of the crust, in contrast to the covered rocks of contemporary origin in the platform area. Thus the question is what is the history of the updoming of the shield?

Another problem is the correlation of geological formations across shield subareas covered by water and separated by national borders. The geological nomenclature, definitions of formations and theories of evolution of rocks differ from country to country. The main emphasis of the geological studies has been on the regional geology and the main mineral potential areas inside each country. Describing the geology of the whole shield has been the responsibility of individual geologists.

The Fennoscandian map project

To see the Fennoscandian Shield geologically as a whole the Geological Surveys of Finland, Norway and Sweden, the Northwest Regional Geological Centre of Russia with its subsidiary companies, the Finnish Geodetic Institute, the National Land Survey of Sweden and the Norwegian Mapping

Authority started joint work to collect numerical geological, geophysical and petrophysical information on a scale of 1:1 million in 1997. The practical aim was to compile an overall presentation of the geological structure and evolution of the shield area by the end of 2000. The main geophysical goals include compiling uniform magnetic and gravity data sets and maps, defining the petrophysical properties of the geological formations, using them to trace exposed geological formations at depth, identifying unexposed sources of magnetic and gravity anomalies and geologically interpreting the sources of major anomalies. All the geophysical information is to be used in geological correlation and creating a geological evolution model of the area.

In the first two years of the project preliminary magnetic and gravity data were collected, petrophysical data collection was started and a preliminary base map was compiled. In the next two years the final digital maps will be compiled, interpretations made and map explanations written.

Magnetic anomaly map

Most of the data originates from airborne surveys that have been presented as regional magnetic maps previously. Gaps in the coverage are patched by ground and seaborne magnetic measurements. Tielines are used to bring the data sets to the same level. In Sweden 23 000 km and in Finland 7000 km of tielines were measured in connection with the SVEKALAPKO BEAR-project in summer 1998 (BEAR & Korja 1998, Byström et al. 1999, Korhonen et al. 1999). Russia measured 2000 km of tielines in March 1999 (Ludmila Zhdanova, pers. comm.).

The participating organizations will make data reductions to the DGRF-65 anomaly level and provide magnetic information of their area as 1 km x 1 km subgrids. The data will be completed by an Estonian magnetic grid outside the shield (Rein Vaher and Tarmo All pers. comm.). The grids will be joined together in a Gauss-Krueger projection (central meridian 21° E: false easting 1500 km) and in WGS-84 datum.

Based on readily available data sets a preliminary compilation (map version 0.3) was made (Korhonen et al. 1997). The data was completed and an interim magnetic 2 km x 2 km grid and a magnetic map on a scale of 1:4 mill (map version 0.5) were compiled (Korhonen et al. 1998). A magnetic anomaly map (version 0.54) on a scale of 1:10 mill is shown in Figure 1 (Appendix 1).

The mean DGRF65-anomaly of the map area is

+15 nT, mode -25 nT and standard deviation 241 nT.

The central part of the shield is characterized by a lower magnetic level and smoother variation than at its periphery. The shield boundaries are not visible in the anomaly picture.

Gravity anomaly map

The gravity data consists mainly of national gravity nets that have been published as gravity anomaly maps by participating organizations. It is completed by gravity stations measured for regional studies and prospecting and by sea gravimetry as well as by an Estonian gravity grid outside the shield (e.g. Raukas & Teedumae 1997, copyright by Geological Institute of Tallinn). The IGSN71-system and a Bouguer density of 2670 kg/m³ were applied. The Russian grid was calculated from Russian system 71 to IGSN71 system using GRS80 normal gravity formula. The reduction principles of the original data have been described, e.g., in the explanation of the Bouguer anomaly map of Finland 1:1 mill (Kääriäinen, J. & Mäkinen, J., 1997). No atmospheric correction was included. The data set is planned to be further completed by 18 000 line km of airborne gravity measurements, to be made jointly by Sweden, Baltic Countries, Denmark, Finland and Norway (Joint Nordic-Baltic airborne gravity survey in Baltic Sea) in 1999.

The national grids will be joined together in the same projection and area as for the magnetic map. The final cell size of the Bouguer anomaly grid will be 2.5 km x 2.5 km. As first approach a 5 km x 5 km grid and a Bouguer anomaly map on a scale of 1:4 mill (map version 0.5) was compiled (Korhonen et al. 1998). A completed version (0.54) on a scale of 1:10 mill, is shown in Figure 2 (Appendix 1).

The average Bouguer anomaly of the area is -18 mGal, mode -20 mGal and standard deviation 30 mGal. The minimum and maximum values are -143 mGal and +150 mGal respectively.

The Caledonian mountain area corresponds to a long gravity minimum less than -50 mGal. The Bouguer-anomaly field of the land uplift area forms another elongated minimum of -20 mGal of width 600 km and length of 2000 km in the central part of the shield (Elo 1997).

Petrophysics and interpretation

To correlate the magnetic and gravity anomalies with geological formations and to separate

shallow and deep seated anomaly sources from each other, the available bulk density and magnetic susceptibility data of the area (c. 330 000 samples), intensity of remanence (c. 170 000 samples) and direction of remanence (c. 7000 samples) are planned to be used to compile density and magnetic characteristics of geological formations of the shield and further to calculate 5 km x 5 km geologically weighted density and magnetization grids. The goals include interpreting the depth extent of major surficial geological formations from geophysical anomalies and petrophysical properties, and identifying previously unknown geophysical anomaly sources at depth (Korhonen et al. 1997). This information will contribute to the understanding of the 3-D structure and evolution of the Precambrian rocks.

Where applicable, the magnetic and gravity interpretation will be done jointly. The petrophysical data provides information to what extent the magnetic and gravity sources are located in the same geological formations. The distribution and geological correlation of crustal magnetic masses may be calculated by first integrating the magnetic field to become a pseudogravimetric anomaly and then applying similar techniques as for gravity interpretation.

The working group reports an observation that the average magnetic anomaly field of the central part of the shield is low (-120 nT) and increases outwards to an average value of +120 nT at a radius of 500 km, rapidly dropping near zero outside. This circular symmetry is roughly concentric with the postglacial Fennoscandian land uplift and is more pronounced on the western and northern parts of the shield. The positive magnetic anomalies are associated with Neoproterozoic-Mesoproterozoic igneous rocks, mainly acid in composition. Part of the anomalies is caused by unexposed magnetic sources. The main part of the circular structure was born or reactivated in the Svecofennian orogeny. Studies are going on to determine what the causes of the structure are and what connections, if any, exist between the structure and the appearance of the Shield and land uplift in the same area. The Shield outside the structure consists of accreted Precambrian terrains of the Kola, Sveconorwegian and Lofoten areas. These terrains are characterized by higher magnetization in their central parts than in border areas, thus differing in nature from the central part of the Shield.

Products of the project

The preliminary grids were interpolated and maps compiled by Geosoft Oasis Montaj 4.2 and by minimum curvature interpolation.

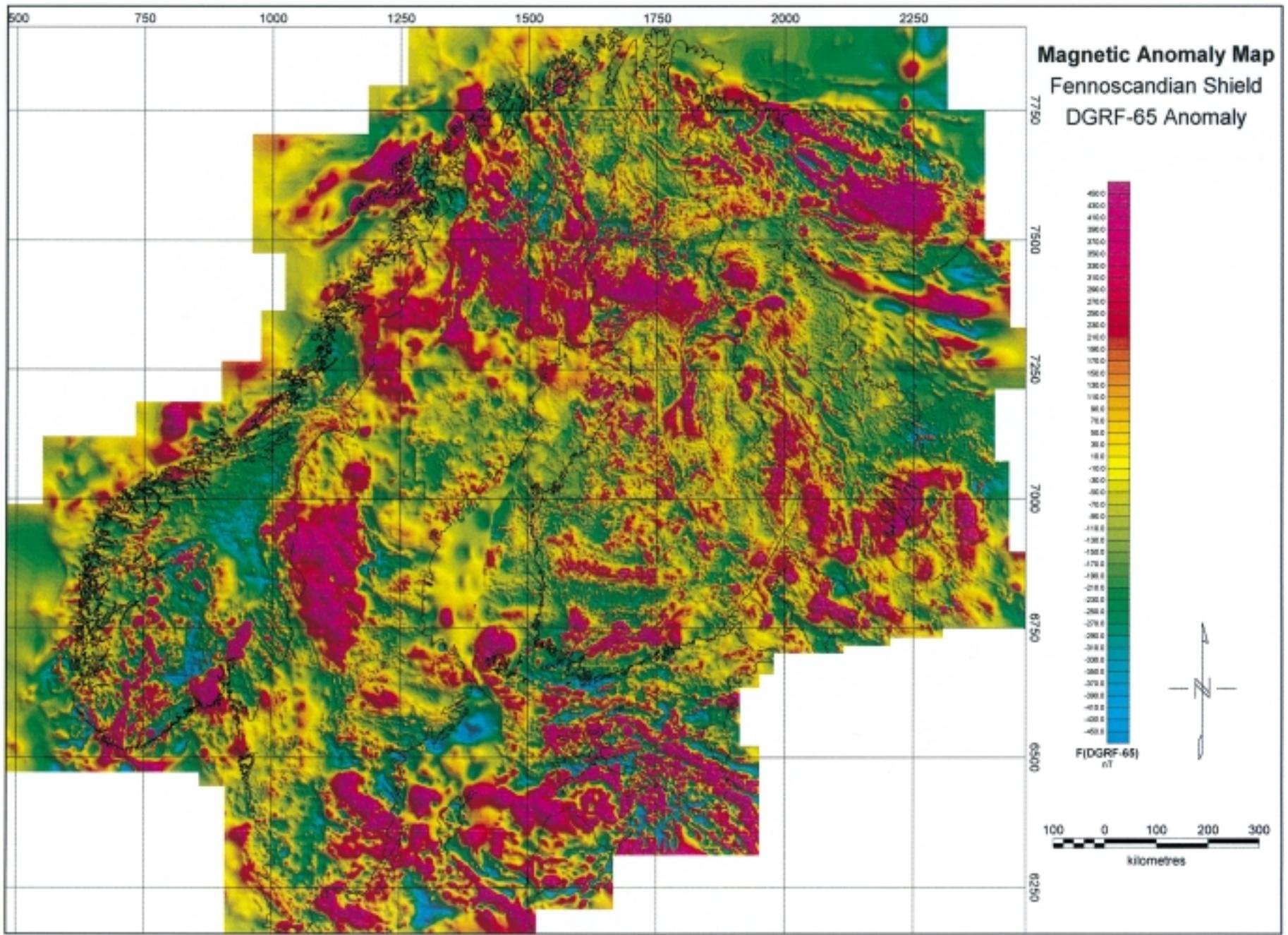
The final geophysical grids are planned to be ready by the end of 1999. Digital maps, together with the geological map will be printed and distributed on CD in the beginning of 2001. The maps will be digitally prepared for a scale of 1:1 million and this will be the scale for the CD-maps as well. The base map consists of a combination of the Nordic Map Database for the western part and a corresponding geological base map for the eastern part. The digital maps will be presented in ArcInfo-format. The printed maps will be available on a scale of 1:2 million.

The grids will be shared by the participating organizations for scientific work. A CD of small scale maps will be available at a modest price. The results are planned to be available on the Internet as well.

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APPENDIX 1. Fig.1, Part A



Magnetic Anomaly Map of the Fennoscandian Shield

1 : 10 000 000

Version 0.54

**Magnetic Total Field Anomaly
Absolute Field Reduced to the Epoch 1965.0
DGRF 65 Normal Field Subtracted**

Organizations:

The map is compiled in a framework of the Project for Geological Map and Geophysical Maps of the Fennoscandian Shield 1 : 1 000 000 between the Geological Surveys of Finland, Sweden and Norway, Northwest Regional Geological Centre of Russia, Petersburg Geophysical Expedition, SC Mineral, and with contribution of the Geological Institute of Tallinn, Geological Survey of Estonia and Finnish Meteorological Institute.

Coordinator:

Juha V. Korhonen

Working Group Members:

Sven Aaro, Tarmo All, Anatoli Chepik, Heikki Nevanlinna, Jan Reidar Skilbrei, Heikki Säätuvuori, Rein Vaher and Ludmila Zhdanova

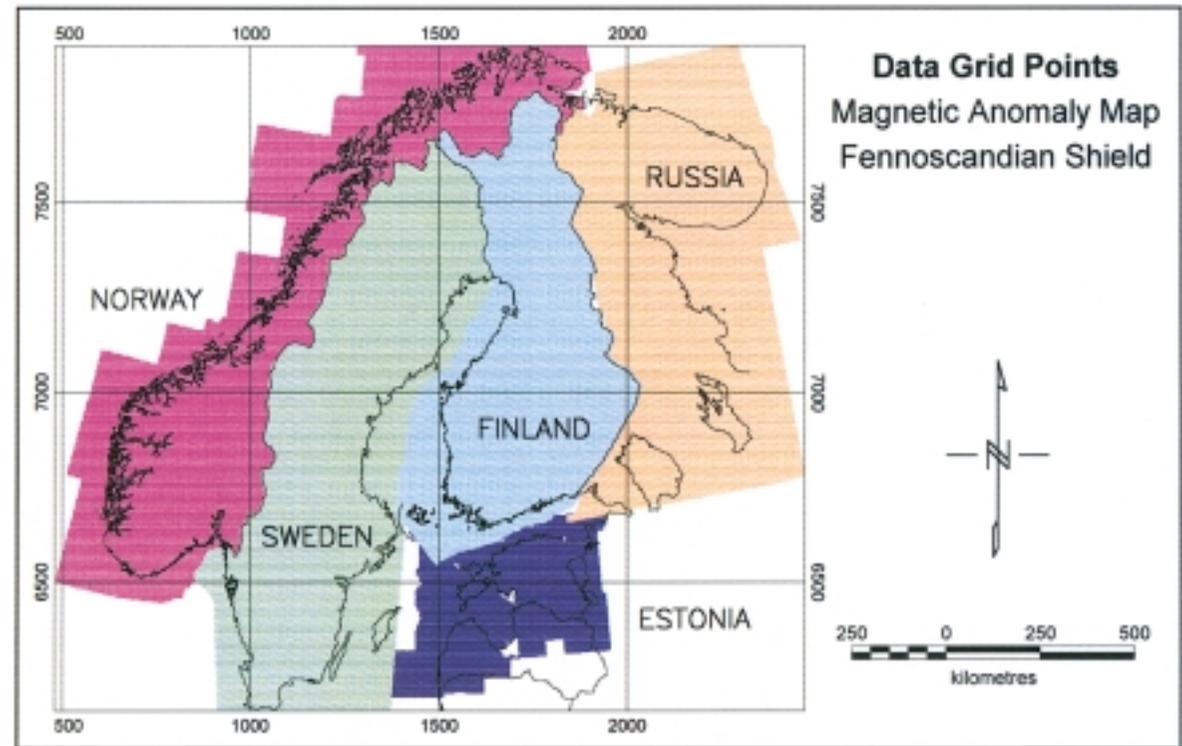


Fig. 1. Magnetic Anomaly Map of the Fennoscandian Shield on a scale of 1 : 10 000 000 (version 0.54, part A) with data index map on 1 : 20 000 000.

Colour Scale:

Class interval 20 nT in a range from -470 nT to +470 nT

Illumination:

D = N 45° E, I = H 45° Z, vertical scale 1 nT : 0.2 km

Map Drafting:

Geosoft Oasis 4.2 / Windows 98 / Tectronix Phaser 560 F

Datum:

WGS84

Projection:

Gauss-Krueger, the Central Meridian 21° E

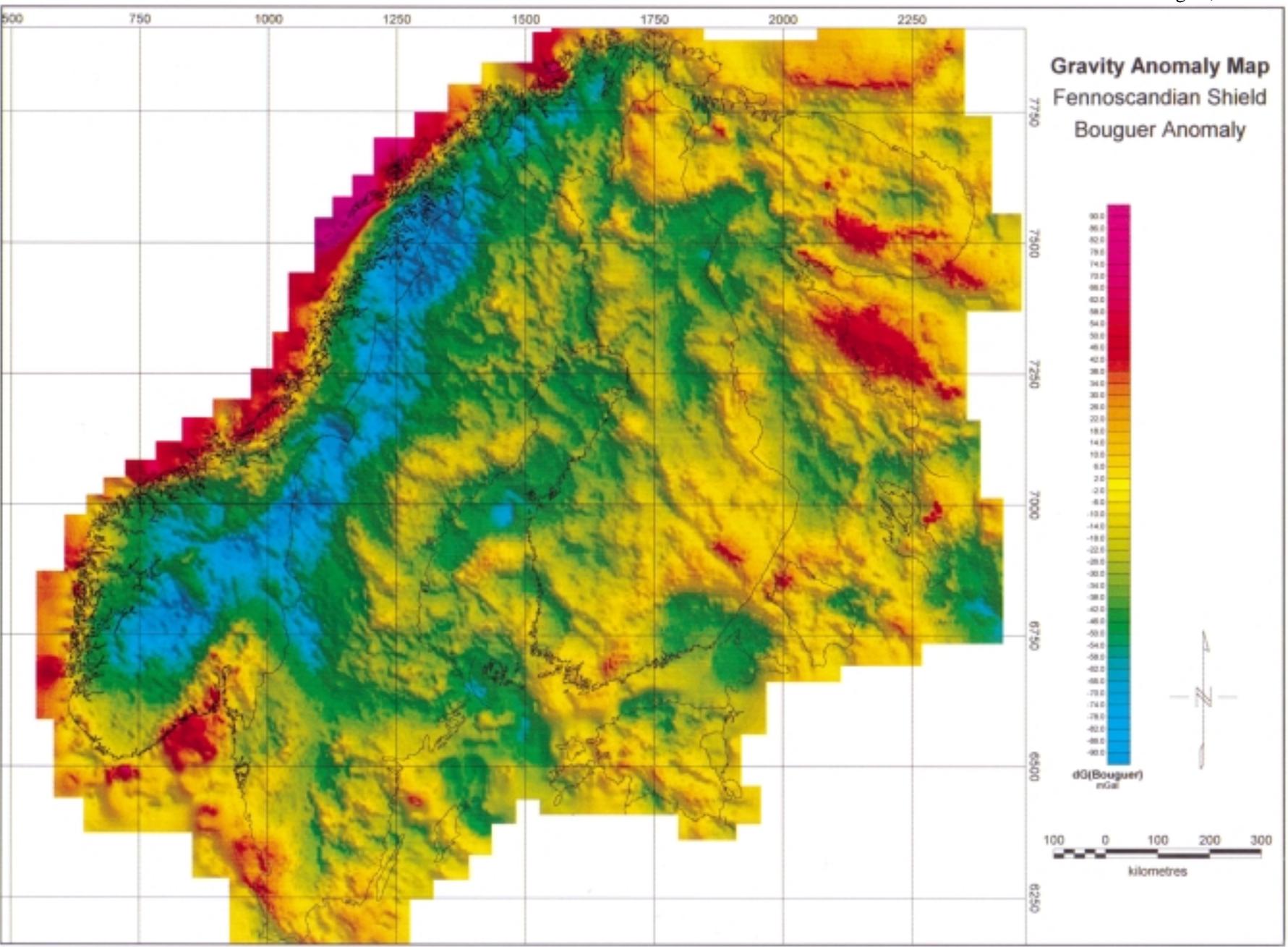
False Easting:

1500 km

Base Map:

Compiled by joining the Nordic Map Database 1 : 2 000 000 and the Base Map of the Geological Map of the Russian Part of the Fennoscandian Shield 1 : 1 000 000

APPENDIX 1. Fig. 2, Part A.



Gravity Anomaly Map of the Fennoscandian Shield

1 : 10 000 000

Version 0.54

Bouguer Anomaly
Density 2670 kg/m³
IGSN71 Gravity System
Terrain correction applied

Organizations:

The map is compiled in a framework of the Project for Geological Map and Geophysical Maps of the Fennoscandian Shield 1 : 1 000 000 between the Geological Surveys of Finland, Sweden and Norway, Northwest Regional Geological Centre of Russia, Petersburg Geophysical Expedition, SC Mineral, Finnish Geodetic Institute, National Land Survey of Sweden and Norwegian Mapping Authority, and with contribution of the Geological Institute of Tallinn, Geological Survey of Estonia and Estonian Land Board.

Coordinator:

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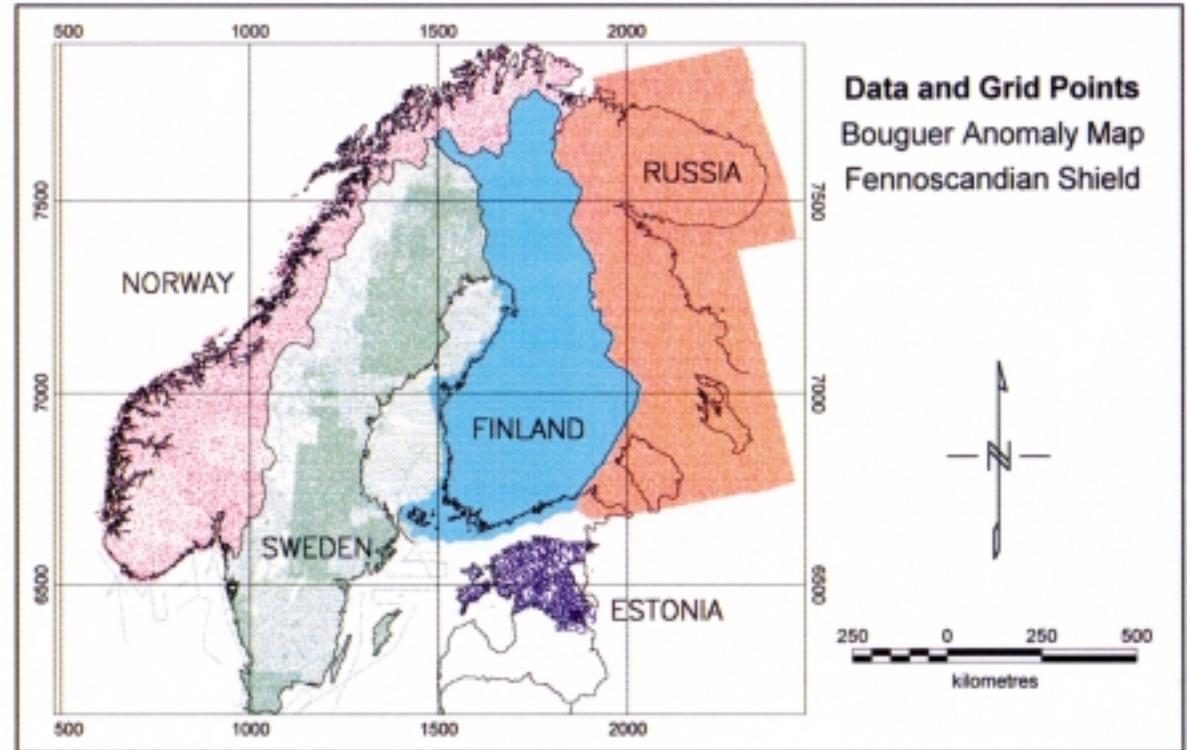


Fig. 1. Gravity Anomaly Map of the Fennoscandian Shield on a scale of 1 : 10 000 000 (version 0.54, part A) with data index map on 1 : 20 000 000.

Colour Scale: Class interval 4 mGal in a range from -94 mGal to +94 mGal
Illumination: D = N 45° E, I = H 45° Z, vertical scale 1 mGal : 2 km
Map Drafting: Geosoft Oasis 4.2 / Windows 98 / Tectronix Phaser 560 F
Datum: WGS84
Projection: Gauss-Krueger, the Central Meridian 21°E
False Easting: 1500 km

Base Map:

Compiled by joining the Nordic Map Database 1 : 2 000 000 and the Base Map of the Geological Map of the Russian Part of the Fennoscandian Shield 1 : 1 000 000

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compiled by Lahja Voutilainen

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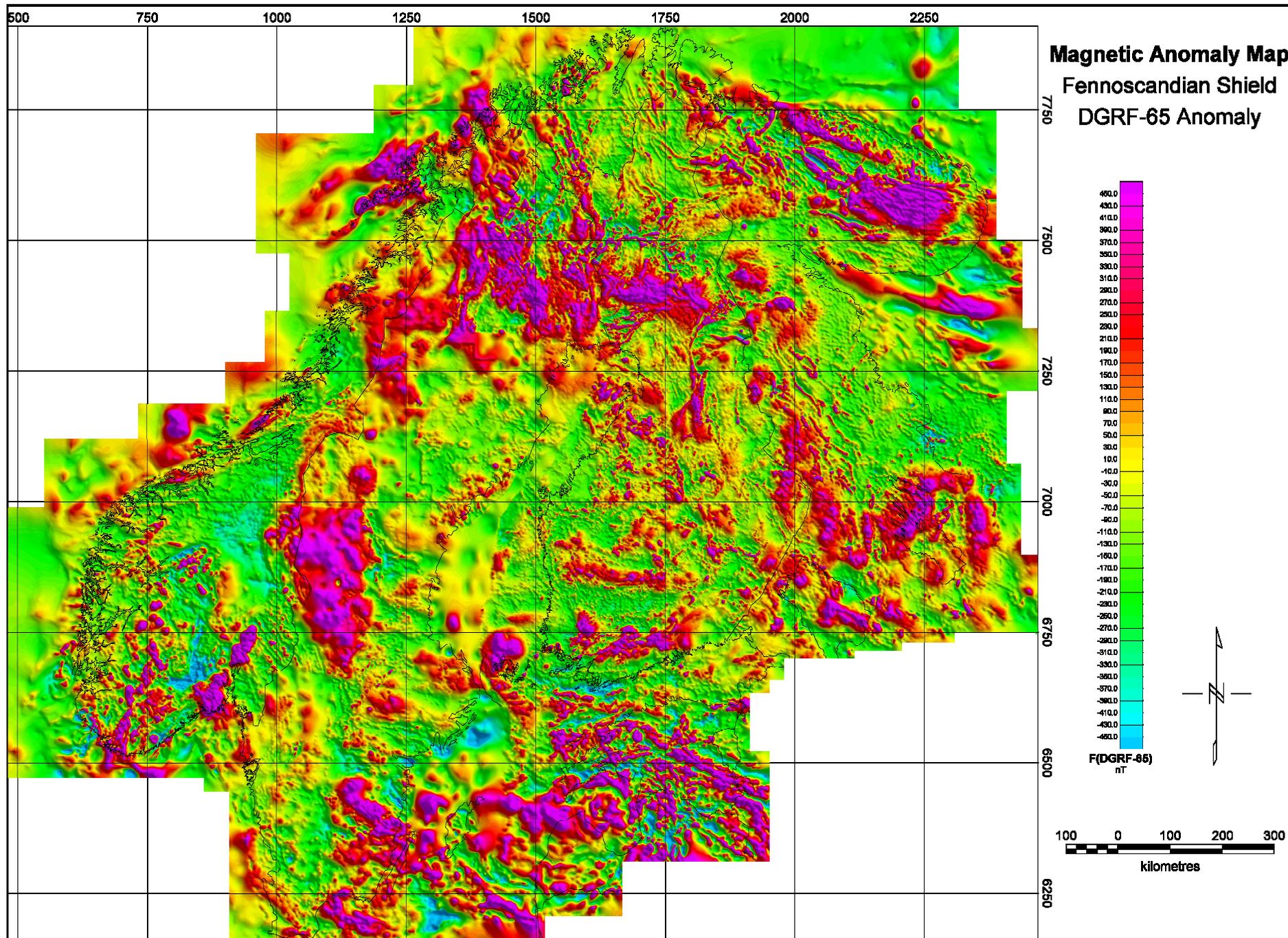
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Magnetic Anomaly Map of the Fennoscandian Shield

1 : 10 000 000

Version 0.54

Magnetic Total Field Anomaly
Absolute Field Reduced to the Epoch 1965.0
DGRF 65 Normal Field Subtracted

Organizations:

The map is compiled in a framework of the Project for Geological Map and Geophysical Maps of the Fennoscandian Shield 1 : 1 000 000 between the Geological Surveys of Finland, Sweden and Norway, Northwest Regional Geological Centre of Russia, Petersburg Geophysical Expedition, SC Mineral, and with contribution of the Geological Institute of Tallinn, Geological Survey of Estonia and Finnish Meteorological Institute.

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Juha V. Korhonen

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Sven Aaro, Tarmo All, Anatoli Chepik, Heikki Nevanlinna, Jan Reidar Skilbrei, Heikki Säävuori, Rein Vaher and Ludmila Zhdanova

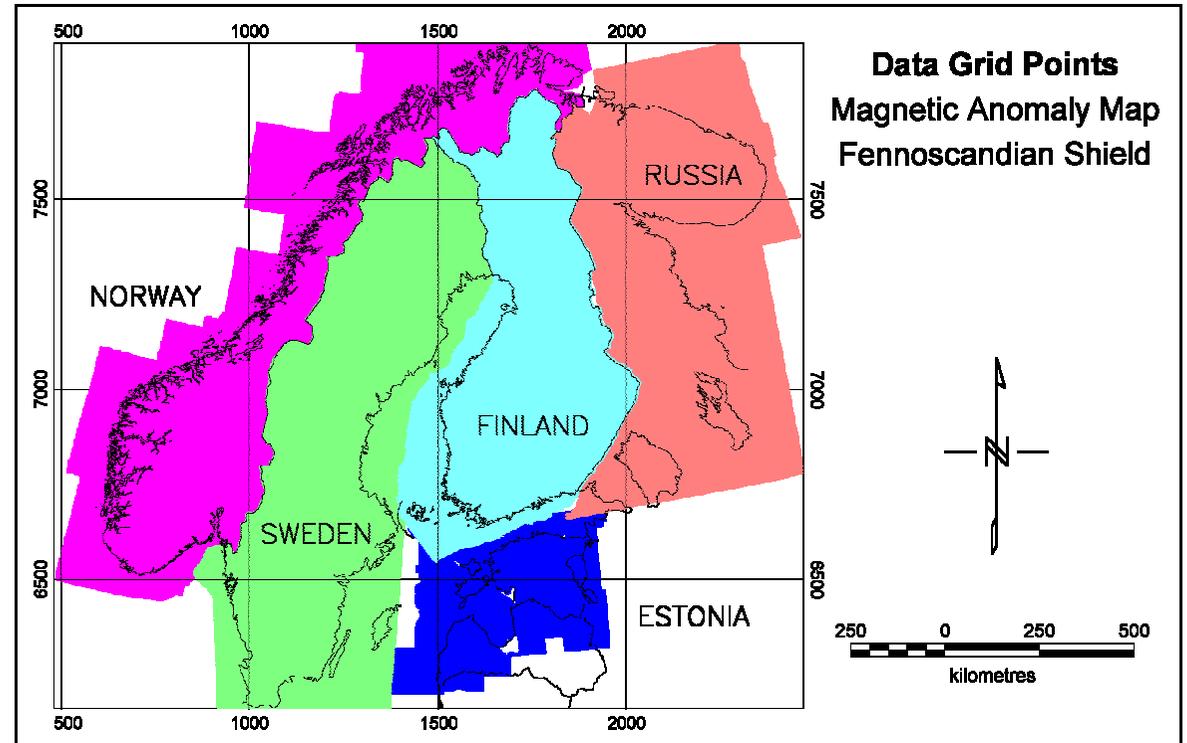
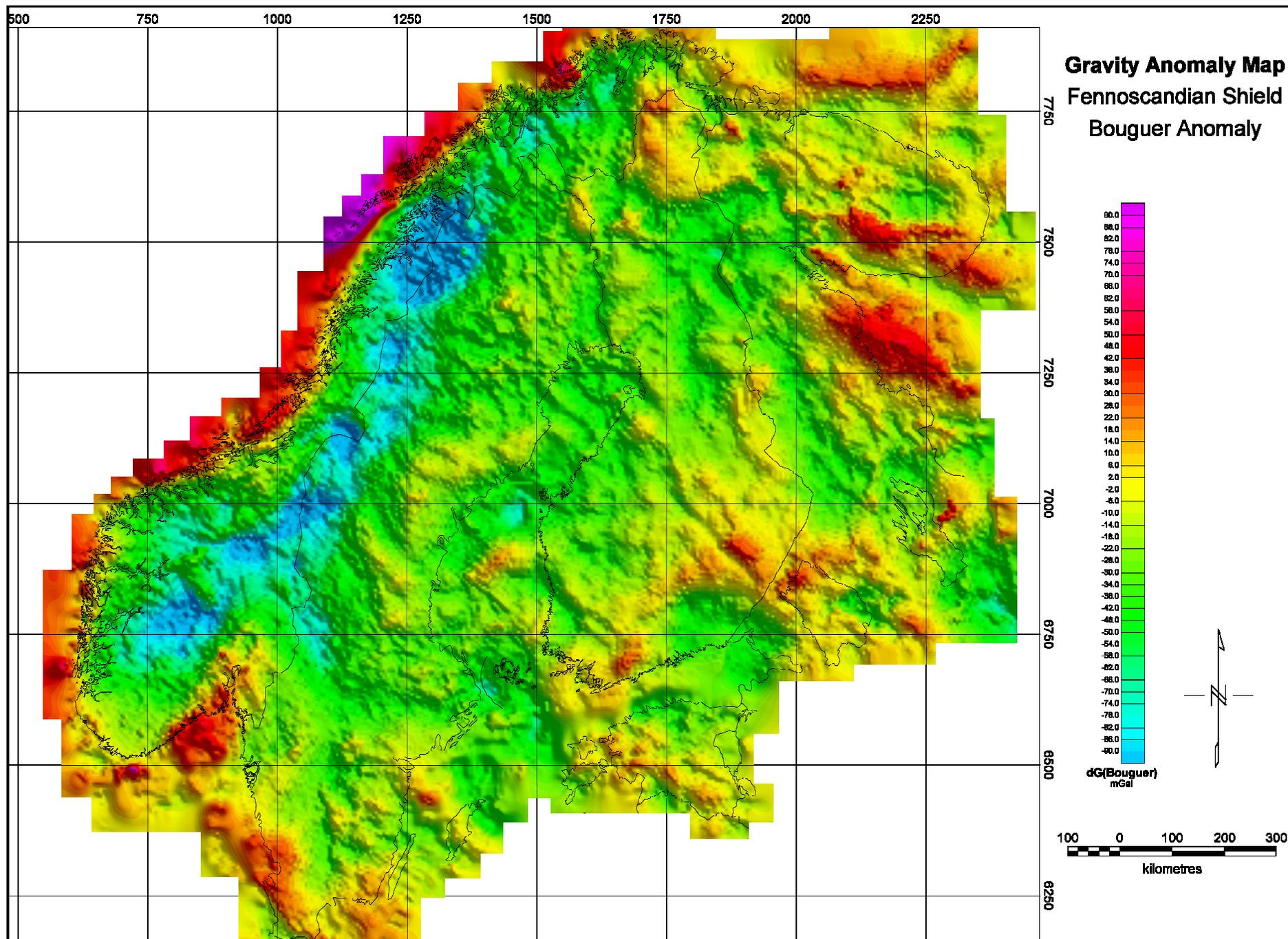


Fig. 1. Magnetic Anomaly Map of the Fennoscandian Shield on a scale of 1 : 10 000 000 (version 0.54, part A) with data index map on 1 : 20 000 000.

Colour Scale: Class interval 20 nT in a range from -470 nT to +470 nT
Illumination: D = N 45° E, I = H 45° Z, vertical scale 1 nT : 0.2 km
Map Drafting: Geosoft Oasis 4.2 / Windows 98 / Tectronix Phaser 560 F

Datum: WGS84
Projection: Gauss-Krueger, the Central Meridian 21° E
False Easting: 1500 km

Base Map: Compiled by joining the Nordic Map Database 1 : 2 000 000 and the Base Map of the Geological Map of the Russian Part of the Fennoscandian Shield 1 : 1 000 000



Gravity Anomaly Map of the Fennoscandian Shield

1 : 10 000 000

Version 0.54

Bouguer Anomaly
Density 2670 kg/m³
IGSN71 Gravity System
Terrain correction applied

Organizations:

The map is compiled in a framework of the Project for Geological Map and Geophysical Maps of the Fennoscandian Shield 1 : 1 000 000 between the Geological Surveys of Finland, Sweden and Norway, Northwest Regional Geological Centre of Russia, Petersburg Geophysical Expedition, SC Mineral, Finnish Geodetic Institute, National Land Survey of Sweden and Norwegian Mapping Authority, and with contribution of the Geological Institute of Tallinn, Geological Survey of Estonia and Estonian Land Board.

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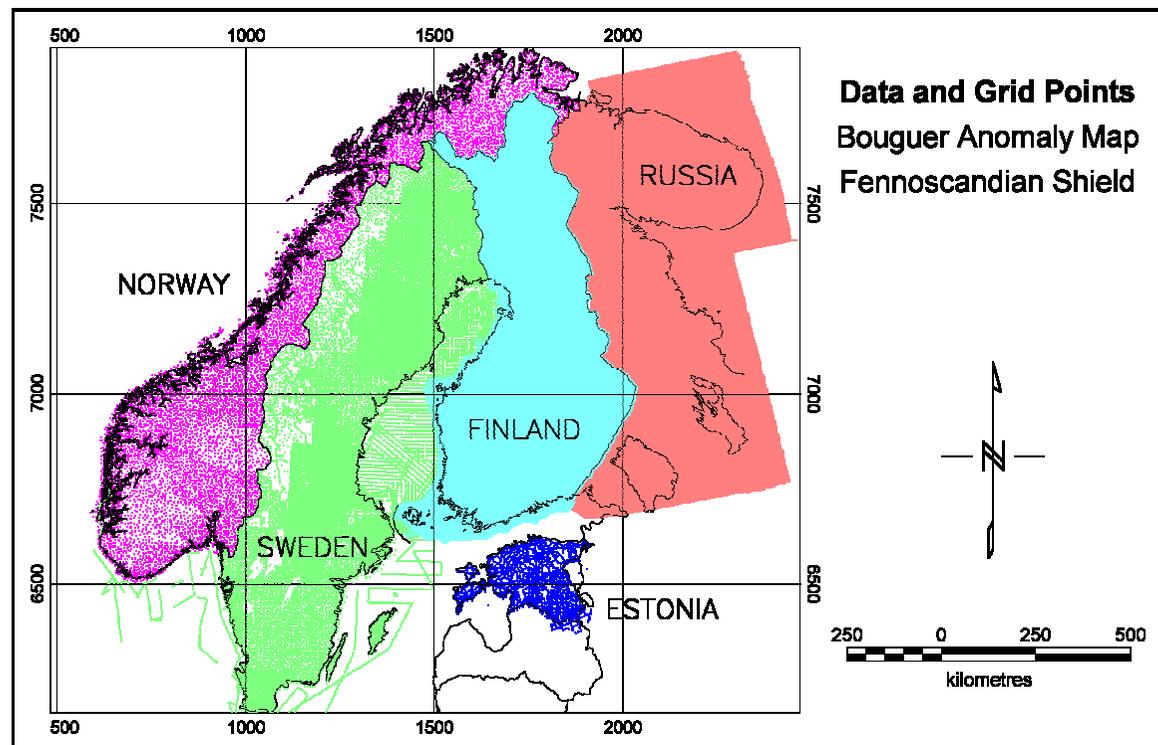


Fig. 2. Gravity Anomaly Map of the Fennoscandian Shield on a scale of 1 : 10 000 000 (version 0.54, part A) with data index map on 1 : 20 000 000.

Colour Scale:
Illumination:
Map Drafting:

Class interval 4 mGal in a range from -94 mGal to +94 mGal
D = N 45° E, I = H 45° Z, vertical scale 1 mGal : 2 km
Geosoft Oasis 4.2 / Windows 98 / Tectronix Phaser 560 F

Datum:
Projection:
False Easting:

WGS84
Gauss-Krueger, the Central Meridian 21° E
1500 km

Base Map:

Compiled by joining the Nordic Map Database 1 : 2 000 000 and the Base Map of the Geological Map of the Russian Part of the Fennoscandian Shield 1 : 1 000 000



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