Mineralogy and geochemistry of indium-bearing polymetallic veins in the Sarvlaxviken area, Lovisa, Finland

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ABSTRACT

A number of polymetallic vein mineralizations of different styles and metal associations, including base, alloy, noble and critical metals, have been discovered around the Sarvlaxviken bay in the westernmost parts of the Mesoproterozoic Wiborg Batholith, south-eastern Finland. The veins occur in two rapakivi granite varieties: coarse-grained wiborgite; and medium-grained Marviken granite. The veins are divided into five groups based on the dominant metal associations.

The Li–As–W–Zn–Mn, Pb–Zn and Cu–As–In associations are hosted by wiborgite, and are strongly controlled by a NNW-trending tectonic pattern that evolved in two main stages. The Li–As–W–Zn–Mn association (generation 1) formed in a typical greisen environment with Li-bearing mica in significant alteration halos around a narrow quartz vein. This greisenization was accompanied by silicification, followed by sericitization and chloritization. The Pb–Zn association occurs in a similar vein type but without typical high-temperature minerals and is considered to have formed at a higher crustal level. Generations 2a and 2b formed under more brittle conditions leading to fracturing, quartz veining and metal precipitation of ore minerals. This metal association is characterized by very high contents of Cu, As and up to 1490 ppm In but with ≤0.4% Zn, which leads to very high In/Zn ratios (up to 8400) enabling formation of abundant roquesite.

The As–Sn–Cu and Mo–Bi–Be associations are hosted by alteration zones without hydrothermal quartz in the Marviken granite. Mineralization with moderately high contents of As, Sn and Cu is associated with greisenization while mineralization with spectacular contents of Be as well as high contents of Mo and Bi is associated with sericitization, chloritization and berylification.

The internal age relations between the wiborgite-hosted, NNW-trending veins show a clear evolution from a typical greisen type environment (the Li–As–W–Zn–Mn and Pb–Zn associations of generation 1) to cooler and more brittle conditions governing quartz veining and precipitation of ore minerals belonging to the Cu–As–In association (generations 2a and 2b). The age relations between these wiborgite-hosted veins and the veins in the Marviken granite are more uncertain but the presence of a NS-trending granitic dyke on the eastern side of the Sarvlaxviken bay, with similar ore-fertile geochemical composition as the Marviken granite, indicates that the tectonically controlled veins formed simultaneously with the emplacement of the Marviken granite and associated hydrothermal activity.

The polymetallic veins in the Sarvlaxviken bay are unique for the Fennoscandian Shield, not the least for the locally high indium grades and spectacular roquesite grains. There is an obvious exploration potential for similar veins (and hence a number of base, alloy, noble and critical metals) also elsewhere in the entire Wiborg Batholith.

1. Introduction

Until relatively recently, A-type rapakivi granites were not considered particularly prospective for metals, even if the polymetallic skarn ores at Pitkäranta (Ladoga, Karelia) were earlier linked to the emplacement of rapakivi granites (Törnebohm, 1891; Trüstedt, 1907). Since then, numerous ore deposits, associated with rapakivi granites, have been recognized across the globe, including the giant Olympic Dam Cu–U–Au–Ag deposit, South Australia (e.g., Roberts and Hudson, 1983), Sn-bearing polymetallic deposits in Rondônia and Amazonas, Brazil (e.g., Bettencourt and Dall'Agnol, 1987), and at St. Francois Mountain, Missouri, USA (Kisvarsanyi and Kisvarsanyi, 1991) as well as minor deposits in Arizona (e.g., Anderson et al., 1955; Goodman, 1986), Ukraine (e.g., Dagelaysky, 1997) and southern Finland (e.g., Haapala, 1977a, 1988).

The metal concentrations in Finnish rapakivi granites have previously been studied by Haapala (1973, 1977b, 1988), mainly focusing on

elevated contents of Sn and Be and associated minerals (Haapala and Ojanperä, 1969, 1972), including several discoveries of greisen-type Sn–W–Be–Zn occurrences in the Eurajoki and Kymi stocks and the Ahvenisto Batholith (Haapala, 1974, 1977b, 1995, 1997).

Recent discoveries of new exploration targets in the 1.64 Ga Wiborg Batholith of southeastern Finland have extended the exploration potential in rapakivi granites to also include several other metals. Besides high contents of a number of base, alloy and noble metals, the significant amounts of In make them also attractive exploration targets for high-tech metals given the current supply and demand issues (British Geological Survey, 2012). Three ore types were recognized in the western parts of the Wiborg Batholith (Sundblad et al., 2008): compact In-bearing magnetite-sphalerite ore (Pahasaari and Getmossmalmen); Zn–Cu–Pb–Ag–In-bearing greisen veins (Jungfrubergen); and polymetallic veins (Sarvlaxviken), the latter area highlighted for the first time by Cook et al. (2011). In this study, more details are provided for the ore types around the Sarvlaxviken bay, including descriptions of field relationships, vein types, mineral paragenesis and geochemistry.

2. Geological setting

Finland occupies the central part of the Precambrian Fennoscandian Shield, and comprises Archaean 3.1–2.6 Ga crust in the east, and the 2.5–1.8 Ga Palaeoproterozoic Svecofennian Domain, which includes the remnants of magmatic and sedimentary components of ophiolites, island arcs, and active continental margins (Korsman et al., 1997). A number of Mesoproterozoic anorogenic granitic intrusions occur in southern Finland. The most significant are the 1.64–1.54 Ga rapakivi granites in the Vehmaa, Laitila, Wiborg and Åland areas, but several smaller bodies also occur (Rämö and Haapala, 2005) (Fig. 1).

The Wiborg Batholith is the largest rapakivi intrusion in Finland, with a diameter of 150 km and a surface area exceeding 18,000 km^2. The greater part of the Wiborg Batholith is located in southeastern Finland while a smaller part, including the type locality Wiborg, is located in Russia. The by far most common (80%) rock type in the Wiborg Batholith is wiborgite, which exhibits spectacular 1–3 cm-sized rounded orthoclase phenocrysts, mantled by a rim of plagioclase, within an even-grained groundmass of quartz, plagioclase, orthoclase, biotite and occasional hornblende (Simonen and Vorma, 1969). Other rock types in the Wiborg Batholith are pyterlite (6%), dark even-grained rapakivi granite (e.g., tirilite) (3%), porphyritic rapakivi granite (1%), and various biotite granites (8%). Collectively, this rock suite represents the products of several igneous phases between 1.65 and 1.63 Ga (Vaasjoki et al., 1991).

Rapakivi granites are geochemically within-plate granites (WPG) and have characteristics of A-type granites. Rapakivi batholiths commonly consist of various types of granites, thus implying several different intrusive phases that cross-cut older ones. The differences between these phases are mainly in the proportions and speciation of mafic minerals; earlier stages have hornblende, Fe-rich biotite as well as fayalite, whereas the later phases only have Fe-rich biotite. In general, the rapakivi granites are rich in light rare earth elements (LREE) with negative Eu anomalies, but the later (topaz-bearing) granites, have fairly flat chondrite-normalized REE fractionation trends and display pronounced negative Eu anomalies (Rämö and Haapala, 2005). LREE depletion and relative enrichment in heavy rare earth elements (HREE) have also been proposed to relate to processes of greisenization (Öhlander et al., 1989).

The study area (Fig. 2) is located in the south-western part of the Wiborg Batholith, around the Sarvlaxviken bay (forming part of the Gulf of Finland), where the contact between 1839 Ma Late Svecofennian potassium-rich anatectic granites (Kurhila et al., 2011) and 1645 Ma wiborgitic rapakivi granites is indicated on the bedrock map sheet of the Geological Survey of Finland (Laitala, 1964). This map has no indications of any metallic mineralization in the region and it was not until the discovery of roquesite and associated sulphide minerals in a quartz vein at Korsvik (Cook et al., 2008, 2011) that this area came into focus for metallogenetic studies. The Fennoscandian region was subject to glacial erosion at repeated intervals during the Quaternary, with the latest glacial maximum at 30–13 ka BP (Räsänen et al., 2015), causing significant transport and redeposition of rock debris from the bedrock surface along the ice transport directions. Based on ice striae in the bedrock surface, the most powerful and oldest advances of the continental ice sheet in the Sarvlaxviken area was from the northwest (320–330°) while a younger ice movement was from 350 to 360° (Punakivi et al., 1977).

3. Material and methods

The bedrock geology of the Sarvlaxviken area was re-examined by carefully visiting all outcrops with respect to rock types, structures as well as any expression of alteration and mineralization. Structure measurements were made with a standard compass but all strike directions have been recalculated from magnetic north to the north direction of zone III in the national grid system. Vein samples from the eastern side of the Sarvlaxviken bay were collected with the help of a diamond saw to create 25–40 cm-long rock slabs along the strike directions of the veins. The samples were split into two pieces, from which one was used to prepare polished thin and thick sections, polished sections and rock powders for whole rock geochemistry. The second piece was preserved for further studies. Vein samples from the western side of the bay were collected with the help of a hammer and were further cut in the laboratory. In total, 31 polished sections, 20 polished thin sections and 10 thick sections were prepared. Petrographic observations were made by using a combination of reflected and transmitted light microscopy.

A scanning electron microscope (SEM) was used to investigate smaller mineral grains and textures. Two different instruments were used; HITACHI S-3600 N equipped with Energy Dispersive X-ray
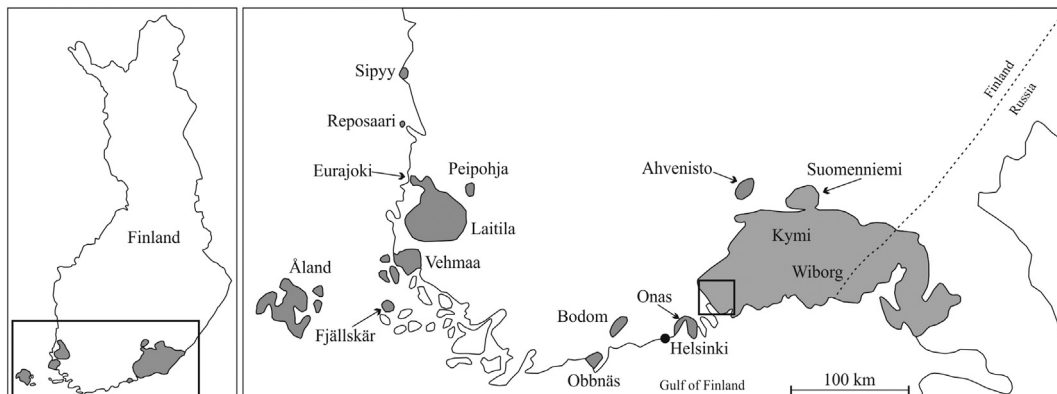

Fig. 1. Distribution of the anorogenic rapakivi granites in Finland and adjacent areas.
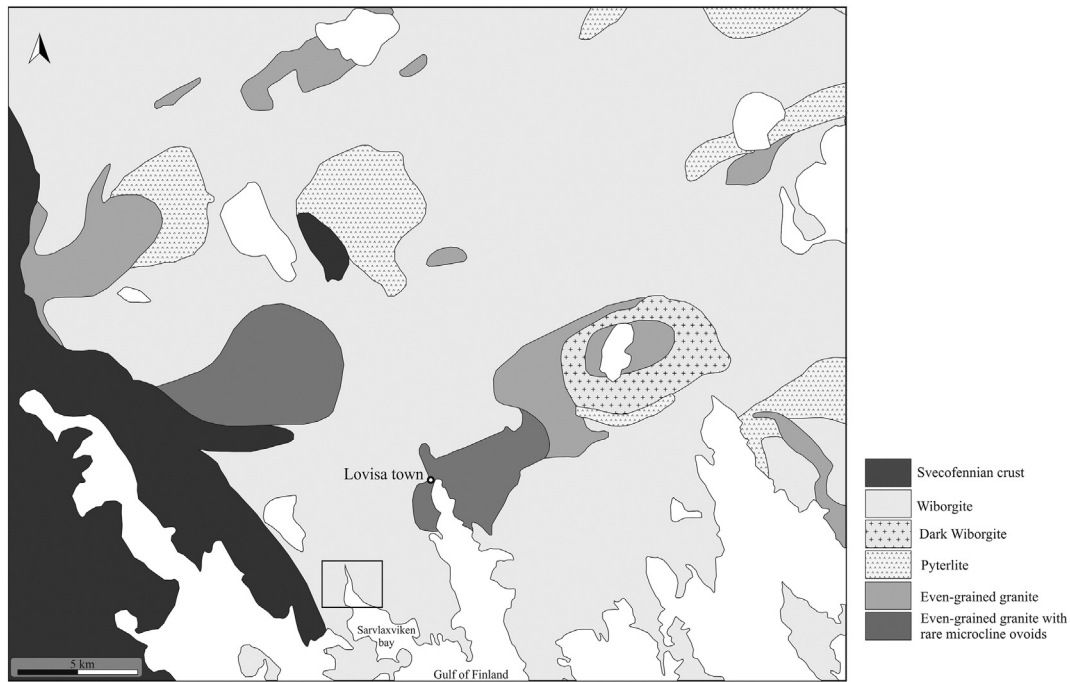
Fig. 2. Geological map of the southwestern part of Wiborg rapakivi Batholith.

Spectroscopy (EDS) and Back-scattered Electron detector (BSE) at the Natural History Museum, University of Oslo, and a JEOL JSM 5900 LV with Oxford EDS-spectrometer and BSE-detector at the Geological Survey of Finland, Espoo.

Forty rock powders were prepared by crushing the veins with a jaw crusher after having removed the wall rocks from the vein by a diamond saw. The gravel-sized fragments were then ground with a swing-grinder to rock powders, which were analysed with the Ultratrace-3 analytical package by Activation laboratory (Ancaster, Canada). Element concentrations were determined by a combination of instrumental neutron activation analysis (INAA), multi-acid digestion inductively coupled plasma (ICP) and inductively-coupled plasma emission mass spectrometry (ICP-MS) techniques. The ICP-MS equipment used for this package was a Perkin Elmer-SCIEX ELAN 6000. Standards, measurement conditions and detection limits are described in Ultratrace 3-Total Digestion report (Actlab Ltd., 2015).

Visible near infrared and shortwave infrared reflectance (VNIR-SWIR, 350 to 2500 nm) spectroscopic data were used to confirm the identities of some of the alteration minerals in the veins. VNIR-SWIR spectroscopic data were measured with an ASD TerraSpec® spectrometer and spectral processing and mineral identification were carried out using TSG (The Spectral Geologist) software at Åbo Akademi University, Turku. The spectra were measured from the flat surface of the cut sample piece.
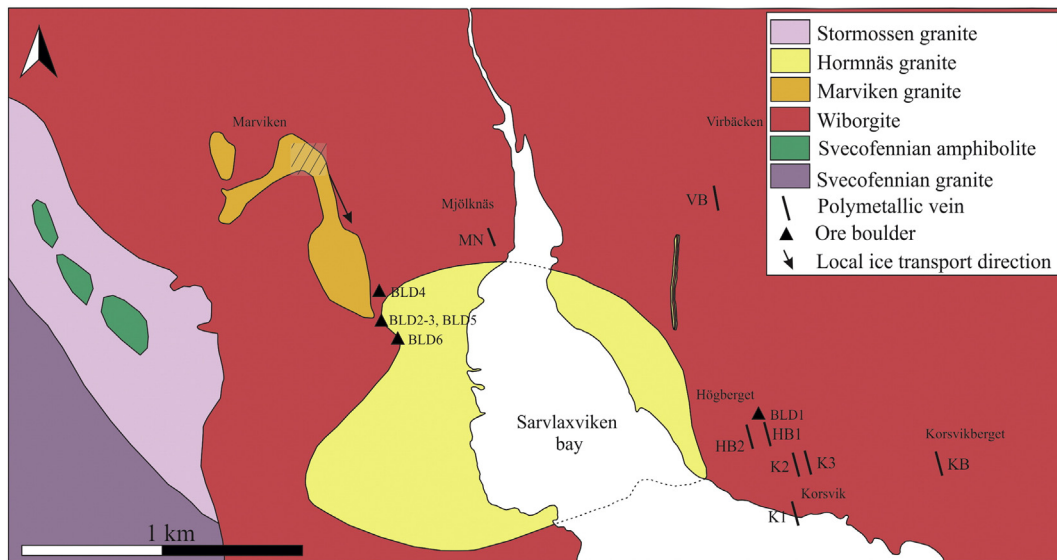

Fig. 3. Bedrock map of the Sarvlaxviken area with locations of polymetallic veins (K1 = Korsvik-1, K2 = Korsvik-2, K3 = Korsvik-3, HB1 = Högberget-1, HB2 = Högberget-2, VB = Virbäcken, KB = Korsvikberget, MN = Mjölknäs) and ore boulders = BLD. The hatched pattern in the northeastern part of the Marviken granite represents the assumed source area for ore boulders 2–6.

Table 1
Geochemical summary of the polymetallic veins (K1 = Korsvik-1, K2 = Korsvik-2, K3 = Korsvik-3, HB1 = Högberget-1, HB2 = Högberget-2, VB = Virbäcken, KB = Korsvikberget, MN = Mjölknäs) and ore boulders = BLD in the Sarvlaxviken area.

Element			Fe	Mn	Sn	W	Mo	Cu	Zn	Pb	Ag	In	As	Bi	Co	Cd	S	Au	Ba	Be	Ga	Li	Ni	Te	U	In/Zn
Unit			wt.%	ppm	ppm	ppm	ppm	wt.%	wt.%	ppm	ppm	ppm	wt.%	ppm	ppm	ppm	wt.%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Limit			0.01	1	1	1	1	0.00002	0.00005	0.5	0.05	0.2	0.00005	0.1	0.1	0.1	0.01	0.002	1	0.1	0.1	0.5	0.5	0.1	0.1	
Wiborgite hosted veins																										
Average wiborgite			2.4	400	10.77	4	<2	0.0009	0.01	31	0.6	<0.2	0.0	2	3	<0.5	0.001	-	1063	5	21	-	6	-	7	20
Li–As–W–Zn–Mn association (generation 1)																										
Sample ID		Coordinates																								
SWAS 161	HB1	3455355 6700511	12.4	2400	162	1	30	0.35	1.19	6180	17.1	24	6.3	27	53	84.7	4.1	<0.002	166	15	50	2390	4	0.2	8	20
SWAS 162	HB1	3455355 6700511	14.0	2120	157	2470	38	0.91	0.15	2740	33.6	14	7.7	56	78	11.3	5.1	0.023	153	13	41	1840	6	0.1	7	93
SWAS 163	HB1	3455355 6700511	15.2	1940	175	3690	62	0.60	0.67	315	31.0	45	13.2	55	74	54.2	6.7	<0.002	35	12	36	1840	5	0.1	5	67
SWAS 164	HB1	3455355 6700511	13.4	2170	193	152	37	0.99	1.70	520	33.3	107	7.2	50	61	115.0	5.8	<0.002	233	17	45	2400	4	0.1	5	63
SWAS 249	HB1	3455355 6700511	2.4	1190	76	10	6	<0.01	0.02	136	3.0	1	<0.01	9	1	30.2	0.0	0.009	740	10	32	778	3	0.1	4	63
EN 1329	HB2	3455287 6700453	5.8	1790	90	825	10	<0.01	0.02	125	7.4	2	0.4	79	7	0.9	0.0	<0.002	488	8	27	1460	2	<0.1	6	125
SWAS 204	BLD1	3455343 6700500	5.5	869	68	36	7	0.01	0.03	42	0.6	2	0.5	14	5	0.7	0.2	<0.002	472	57	40	2200	3	0.2	10	56
Pb–Zn association (generation 1)																										
SWAS 205	MN	3454314 6701301	4.5	4470	59	14	3	0.01	0.43	1540	3.6	3	<0.01	4	4	22.9	0.2	<0.002	975	3	27	76	3	0.3	6	7
SWAS 206 A	MN	3454314 6701301	2.5	1310	85	5	7	0.34	0.10	1150	24.7	3	<0.01	10	4	1.0	0.5	<0.002	481	2	20	53	3	0.3	20	28
SWAS 206 B	MN	3454314 6701301	3.4	2910	63	1	7	0.09	0.84	18400	32.5	2	<0.01	8	3	51.4	0.7	0.029	167	2	13	81	8	0.2	4	2
Cu–As–In association (generation 2a)																										
Sample ID		Coordinates																								
SWAS 165	VB	3455182 6701334	5.7	509	140	19	22	0.99	0.02	153	87.6	41	0.1	1290	2	2.9	1.0	<0.002	309	60	31	835	5	0.1	4	2010
SWAS 166	VB	3455182 6701334	8.3	555	157	40	21	3.25	0.04	218	119.0	84	0.2	2120	5	6.8	2.9	<0.002	81	2090	37	1090	4	0.2	5	2398
SWAS 167	VB	3455182 6701334	10.0	583	154	28	7	4.36	0.03	159	120.0	146	0.3	998	8	0.9	4.0	0.017	116	1320	40	1060	5	0.2	3	4220
SWAS 168	VB	3455182 6701334	6.5	459	123	140	10	2.10	0.03	162	62.8	58	0.2	865	3	4.7	2.2	0.016	181	980	33	660	5	0.1	3	2304
Cu-As-In association (generation 2b)																										
KS0801	K1	3455444 6700200	12.4	599	7080	414	4	6.45	0.25	455	13.2	1050	4.1	498	10	28.4	8.7	<0.002	68	4	15	224	8	0.2	3	4268

Table 1 (*continued*)

Element				Fe	Mn	Sn	W	Mo	Cu	Zn	Pb	Ag	In	As	Bi	Co	Cd	S	Au	Ba	Be	Ga	Li	Ni	Te	U	In/Zn
Unit				wt.%	ppm	ppm	ppm	ppm	wt.%	wt.%	ppm	ppm	ppm	wt.%	ppm	ppm	ppm	wt.%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	
Detection Limit				0.01	1	1	1	1	0.00002	0.00005	0.5	0.05	0.2	0.00005	0.1	0.1	0.1	0.01	0.002	1	0.1	0.1	0.5	0.5	0.1	0.1	
SWAS 153	K1	3455444	6700200	13.8	228	5400	1	4	7.68	0.30	7	7.5	989	7.2	121	23	37.3	9.6	<0.002	13	1	4	38	3	0.1	0	3297
SWAS 154	K1	3455444	6700200	13.4	861	7100	9230	3	8.55	0.20	15	14.1	995	6.0	331	23	27.0	10.2	<0.002	27	1	7	69	5	0.1	1	5103
SWAS 155	K1	3455444	6700200	11.2	1510	12600	35800	3	9.15	0.40	8	12.8	1160	3.8	158	14	53.2	10.5	<0.002	14	1	4	38	12	0.1	1	2937
SWAS 156	K1	3455444	6700200	10.4	512	4600	3700	3	5.71	0.22	7	10.5	777	5.5	240	22	29.0	8.4	<0.002	40	2	7	68	6	0.1	1	3564
SWAS 146	K2	3455455	6700392	12.2	1050	33	1	15	7.46	0.09	17	46.0	564	0.1	598	12	7.7	4.2	<0.002	33	5	32	134	6	0.2	3	6573
SWAS 147	K2	3455455	6700392	12.2	893	179	1	22	8.16	0.13	10	14.6	1100	0.3	273	19	16.1	6.1	<0.002	27	4	26	130	4	0.1	4	8397
SWAS 148	K2	3455455	6700392	12.1	1170	76	1	48	4.45	0.10	14	17.4	631	0.4	565	15	9.1	3.1	<0.002	54	5	32	171	5	0.4	7	6310
SWAS 149	K2	3455455	6700392	10.7	1010	65	1	16	5.61	0.07	11	14.1	589	1.2	453	16	6.7	4.6	<0.002	27	3	24	134	4	0.2	4	8512
SWAS 150	K2	3455455	6700392	10.8	808	60	1	7	6.42	0.09	10	15.0	778	0.9	728	12	9.4	5.6	<0.002	29	3	22	118	5	0.3	4	8366
SWAS 157	K3	3455458	6700397	17.6	1040	68	1	20	1.43	0.07	40	7.2	197	7.8	140	38	1.9	5.2	0.051	40	6	34	222	3	0.3	2	2736
SWAS 158	K3	3455458	6700397	13.4	599	174	1	7	6.78	0.14	19	6.6	775	2.7	87	18	15.5	7.0	<0.002	35	4	18	100	4	0.2	3	5382
SWAS 159	K3	3455458	6700397	18.6	609	12600	37	8	12.30	0.31	24	7.9	1490	3.1	156	34	35.8	11.8	<0.002	29	3	17	122	4	0.2	2	4822
SWAS 160	K3	3455458	6700397	17.6	806	15300	36	9	11.40	0.28	26	8.0	1470	2.0	90	30	32.9	9.9	<0.002	28	5	23	148	2	0.2	2	5231
SWAS 169	KB	3455950	6700380	14.2	226	1500	1	5	0.04	<0.01	15	14.0	6	15.3	119	28	0.4	7.0	<0.002	33	7	19	34	4	0.3	4	1751
SWAS 170	KB	3455950	6700380	16.0	170	1300	1	6	0.01	<0.01	18	15.1	5	17.3	121	33	0.3	8.3	<0.002	36	5	17	23	6	0.3	5	1956
SWAS 171	KB	3455950	6700380	11.6	143	144	1	5	0.04	<0.01	16	12.2	5	9.5	81	22	0.2	5.7	0.016	40	5	14	21	4	0.2	5	1122
SWAS 172	KB	3455950	6700380	12.9	196	1300	1	5	0.03	<0.01	17	16.1	5	13.2	119	32	0.3	6.3	<0.002	32	4	19	29	5	0.1	5	1420
SWAS 173	KB	3455950	6700380	10.6	291	2000	1	3	0.46	<0.01	18	11.3	29	6.2	57	19	3.0	4.8	0.017	69	4	22	38	5	0.1	4	1212

Marviken granite hosted veins

				Fe	Mn	Sn	W	Mo	Cu	Zn	Pb	Ag	In	As	Bi	Co	Cd	S	Au	Ba	Be	Ga	Li	Ni	Te	U	In/Zn
Average Marviken granite				1.9	209	30	10	3	0.0003	0.0	47	1.6	<0.2	<0.01	3	1	<0.5	0.01	-	264	13	30	-	3	-	17	26

As-Sn-Cu association (generation x)

Sample ID		Coordinates		Fe	Mn	Sn	W	Mo	Cu	Zn	Pb	Ag	In	As	Bi	Co	Cd	S	Au	Ba	Be	Ga	Li	Ni	Te	U	In/Zn
SWAS 258	BLD2	3453980	6700895	2.7	511	55	38	2	0.12	0.09	277	24.1	12	0.4	77	1	6.5	0.4	<0.002	116	6	29	274	4	0.1	33	129
SWAS 259 A	BLD3	3453980	6700895	3.0	409	83	38	6	0.30	0.07	65	24.4	15	0.3	63	1	5.5	0.6	<0.002	101	6	30	230	4	0.1	55	211
SWAS 259 B	BLD3	3453980	6700895	4.0	428	57	127	4	0.18	0.04	150	12.6	10	1.0	36	2	2.8	0.7	<0.002	41	5	31	265	4	0.1	60	239
SWAS 259 C	BLD3	3453980	6700895	2.9	391	59	33	4	0.12	0.17	318	9.2	12	0.7	24	2	11.9	0.5	<0.002	125	6	33	298	4	0.1	48	75
SWAS 247	BLD4	3453991	6700985	3.9	510	>1000	53	19	0.33	0.02	46	0.6	8	1.1	41	2	1.6	0.9	<0.002	76	125	31	261	5	0.2	20	338
SWAS 2	BLD4	3453991	6700985	3.3	424	15400	288	3	0.12	0.02	148	1.1	6	0.7	15	1	1.2	0.4	<0.002	126	8	25	143	4	0.1	8	350
SWAS 250	BLD5	3453980	6700895	2.3	378	46	21	3	0.08	0.06	79	5.1	6	0.2	12	1	4.1	0.2	<0.002	144	5	24	233	5	0.2	28	93

Mo–Bi–Be association (generation x)

				Fe	Mn	Sn	W	Mo	Cu	Zn	Pb	Ag	In	As	Bi	Co	Cd	S	Au	Ba	Be	Ga	Li	Ni	Te	U	In/Zn
SWAS 248 A	BLD6	3454055	6700810	2.2	279	33	14	1550	<0.01	0.01	53	0.8	1	<0.01	489	1	0.1	0.1	0.045	45	3014	39	158	7	2.2	31	54
SWAS 248 B	BLD6	3454055	6700810	1.3	210	21	14	3510	0.01	0.01	112	3.7	3	<0.01	848	1	0.1	0.2	0.068	9	30720	46	191	4	7.0	16	264

Footnote: Average granite data compiled from Lammi (2008); Nygård (in preparation) and Penttinen (in preparation). The wiborgite average data was compiled from 13 samples and even-grained, Marviken granite from six samples, collected around the study area.

4. Results

4.1. Common rock types

As a result of the fieldwork, a more accurate geological map of the Sarvlaxviken area is now available (Fig. 3) in which four different rapakivi units and two Svecofennian units are recognized. The main rock type is, as for other parts of the Wiborg Batholith, the coarse-grained wiborgite, representing the oldest intrusive phase. In addition, three other rapakivi granite varieties (the Marviken, Hormnäs and Stormossen granites) have been recognized for the first time and are briefly described below. All granitic units show typical within-plate, A-type geochemical patterns. The most evolved components are the Marviken granite and the porphyritic dyke east of the Sarvlaxviken bay (Nygård, in preparation). A more comprehensive study of these granite units is currently carried out as a M.Sc. study (Nygård, in preparation).

The wiborgite is a coarse-grained porphyric granite with quartz, plagioclase, orthoclase and biotite, organized in the very particular rapakivi texture. The groundmass is composed of 2–5 mm-sized grains of quartz and biotite and 5–10 mm-sized orthoclase and plagioclase with 3–4 cm diameter rounded orthoclase phenocrysts mantled by 1–3 mm thick plagioclase rims. The average contents of selected elements in 13 wiborgite samples are shown in Table 1.

The Marviken granite constitutes a horseshoe-shaped, <1 km² body of even-grained granite on the western side of the Sarvlaxviken bay. It is dominated by 2–5 mm-sized grains of quartz and biotite and 5–10 mm-sized grains of orthoclase and plagioclase with a petrographic character reminiscent of the groundmass in the wiborgite. The contact between the Marviken granite and the wiborgite is not sharp (Fig. 4), suggesting that these two rapakivi units are actually co-magmatic, and that the Marviken granite may have been formed from the cooling wiborgite via some kind of filter pressing. The average contents of selected elements in 6 samples of the Marviken granite are shown in Table 1.

The Hormnäs granite occurs on both sides of the Sarvlaxviken bay and forms a km-sized stock with an even-grained assemblage of 2–5 mm-sized grains of quartz, orthoclase, plagioclase and biotite, thus slightly more fine-grained than the Marviken granite. Crosscutting relations with the wiborgite suggest that the Hormnäs granite is the youngest intrusive phase in the area.

The Stormossen granite is located along the western margin of the Wiborg Batholith and is dominated by even-grained 2–5 mm-sized grains of orthoclase, plagioclase, high-temperature quartz and biotite. The numerous xenoliths of wiborgites, as well as Svecofennian amphibolites and Late Svecofennian granites in all sizes from a few to many tens of m³, indicate that the Stormossen granite melt must have been heavily influenced by partial melting of both Svecofennian and wiborgitic components.

Two NS-trending granitic dykes cut the wiborgite on the eastern side of Sarvlaxviken, some 200 m N of the Hormnäs granite. One of these dykes has the same mineral assemblage, texture and geochemical composition as the Hormnäs granite, and is evidently an offshoot of the Hormnäs granite. The other dyke has a porphyritic texture and an evolved geochemical character reminiscent of the Marviken granite (Nygård, in preparation).

4.2. Ore-bearing veins

Several types of ore-bearing veins have been recognized in the Sarvlaxviken area, partly in outcrop, and partly in locally derived ore boulders. The veins are either dominated by quartz or dark alteration minerals (or a combination of the two), and are occasionally host to polymetallic sulphide minerals. The polymetallic veins can be divided by their host rock (Wiborgite and the Marviken granite), and further subdivided according to structural patterns and the dominant metal association. Cutting relations between some of the vein types have provided the base for a temporal control of at least a part of the ore forming system. The metal contents of the veins are summarized in Table 1. Arsenic, Cu, Fe, S, Sn and Zn are expressed in wt.% while concentration data for all other elements are given in ppm.

4.2.1. Wiborgite-hosted polymetallic veins

A number of sulphide-bearing veins, hosted by wiborgitic rapakivi granites, can be followed in a km-wide NNW-trending zone on both sides of the Sarvlaxviken bay. The most heavily mineralized zone runs for a distance of more than one km from Korsvik, along the Sarvlaxviken shoreline, over the Högberget hill to Virbäcken. Although the veins commonly are barren, they are occasionally heavily (locally completely) mineralized with sulphide minerals (Fig. 5A-G). Three vein generations can be recognized, with the most significant time break between the first two generations; the three generations will hence be referred to as 1, 2a and 2b, respectively.

4.2.1.1. Generation 1 (the Li–As–W–Zn–Mn and Pb–Zn associations).
The Li–As–W–Zn–Mn association belongs to the oldest mineralization event and has been observed along the western side of the Högberget hill where quartz veins with significant wall rock alteration and occasional sulphide mineralization are seen.

The Högberget-1 vein consists of a 5 cm-wide dark alteration zone with a core of a 0.3–0.5 cm-wide quartz vein (Fig. 5A). The Högberget-1 vein can be followed for 60 m along strike (344°) and is further revealed by soil geochemistry for another 50 m towards the NNW. The vein is only rarely observed to contain visible ore minerals, but when it does (samples SWAS 161–164, all with >4% S), it is with high grades of a number of elements (Table 1): up to 15.2 wt.% Fe, up to 2390 ppm Li, up to 50 ppm Ga, up to 2400 ppm Mn, up to 6180 ppm Pb, up to 3690 ppm W, up to 1.7 wt.% Zn, up to 196 ppm Sn, up to 13.2 wt.% As, and up to 0.99 wt.% Cu. The In contents are moderately high (up to 107 ppm), while the Bi, Cd, Cu and U contents are low when compared to the other vein groups. At most other parts along the well-exposed Högberget-1 vein, the opaque minerals are less abundant and the contents of metals and sulphur are significantly lower (e.g., in sample SWAS 249, collected 30 m north of the sulphide-rich part of the vein). Nevertheless, also that sample is significantly enriched in metals like Mn, Sn, W, Pb and Li when compared to the background wiborgite.

The Högberget-2 vein is located c. 100 m to the west of, and sub-parallel to, the Högberget-1 vein and can be followed in outcrop for c. 20 m along strike. The Högberget-2 vein is more discontinuous compared to the Högberget-1 vein and is cut and sinistrally faulted over a distance of c. 1 m by a brittle fracture filled with a 2 cm-thick quartz vein belonging to vein generation 2b. Only weak signs of metal concentrations have been recorded in the Högberget-2 vein but it has a
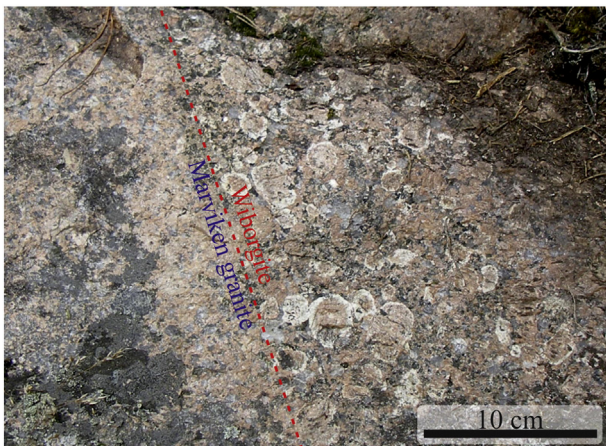

Fig. 4. The contact between the Marviken granite (left) and the Wiborgite (right). North-facing photography of a vertical outcrop surface at 3453880E, 6701200 N.
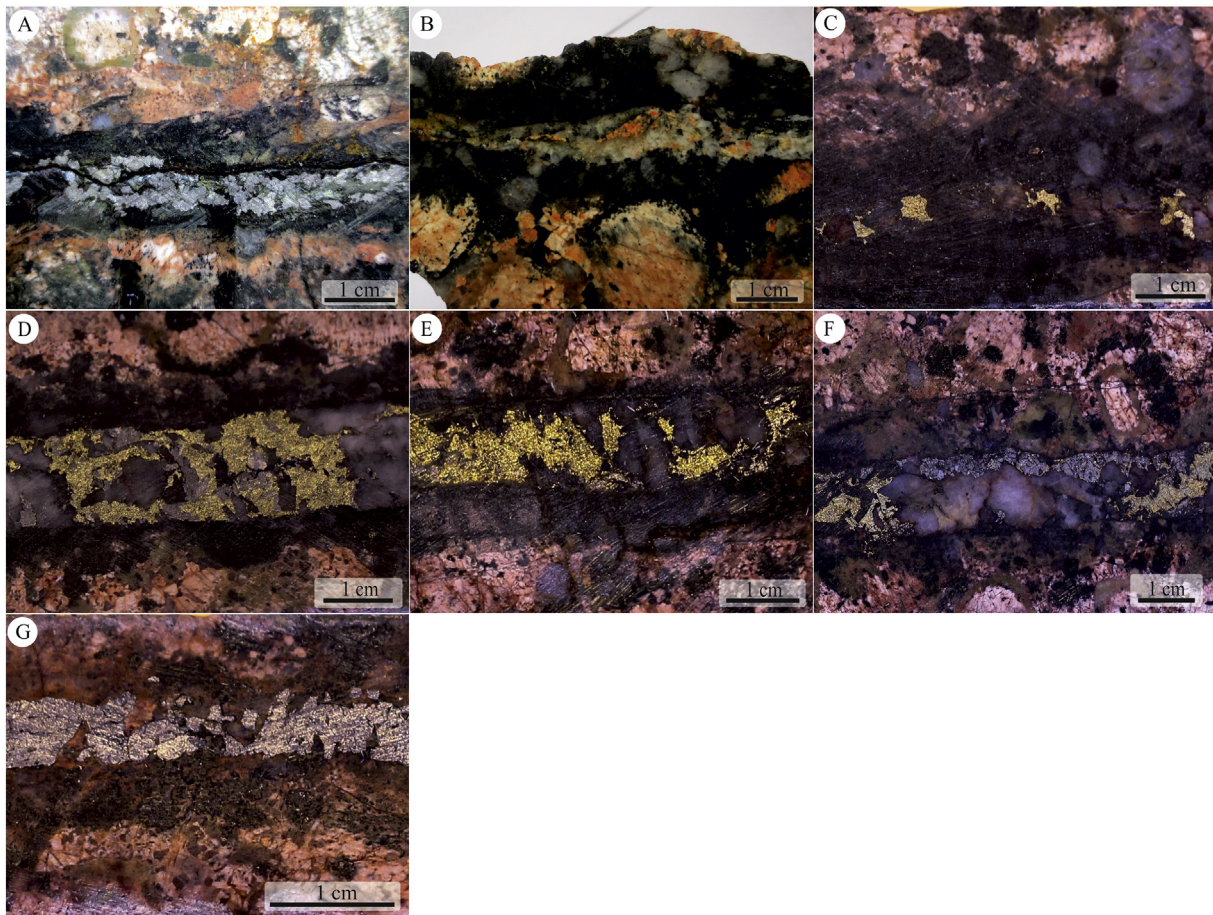
Fig. 5. Photographs of selected Wiborgite-hosted polymetallic quartz veins in hand-specimens. A The Högberget-1 vein with arsenopyrite. B The Mjölknäs vein with distinct alteration and only rare ore mineral grains. C The Virbäcken vein with scattered chalcopyrite grains. D The Korsvik-1 vein with chalcopyrite (yellow), arsenopyrite (silver) and wolframite (black). E The Korsvik-2 vein. F The Korsvik-3 vein. G The Korsvikberget vein with massive arsenopyrite grains.

similarly high Li signature as the Högberget-1 vein and shows also some enrichment of As, Bi, Sn, W, Zn and Mn when compared to the background wiborgite.

Geochemical data from a local boulder are also included in Table 1. This boulder was discovered between the Högberget-1 and Högberget-2 veins, is about one dm³ large and contains several, up to 1.5 cm-wide, parallel quartz veins in a sulphide-bearing dark alteration zone in wiborgitic rapakivi granite. High Li and As contents are characteristic also for this boulder and it is suggested that it is derived from the NNW extension of the Högberget-2 vein (applying the local ice-movement directions of Punakivi et al., 1977).

Ore minerals in the Högberget-1 vein are dominated by arsenopyrite, averaging 2–3 mm in size, and lesser amounts of sphalerite and chalcopyrite. Some of the sphalerite grains have bleb-like inclusions of bornite, and occasionally, traces of other Cu-minerals (covellite and digenite), especially when the grain is associated with chalcopyrite. The bornite also occurs as <0.01 mm-sized inclusions in arsenopyrite. Furthermore, arsenopyrite is sometimes also enveloped by chalcopyrite. The appearance of covellite and digenite suggests that they replaced chalcopyrite. Moreover, small amounts of molybdenite, cassiterite, pyrite, galena, native bismuth, matildite and wolframite (partly altered to scheelite) are present. With the exception of the wolframite, all other accessory minerals are <0.1 mm in size. Wolframite (and scheelite) occur as 0.5 mm-sized grains (Fig. 6A) in the central part of the vein, sometimes displaying twinning.

The Högberget veins (the Li–As–W–Zn–Mn association) consist of single major veinlets with thick alteration zones, and several other smaller black veinlets with different orientations. Sulphides are mainly

hosted by dark mica (e.g., siderophyllite), chamosite and fluorite, rather than quartz, which only occurs as rare small grains in the main vein. Euhedral grains of siderophyllite also display compositional zoning, possibly indicative of alteration around the grain margin or multiple stages of crystallization. More Fe–rich inner parts are surrounded by later, more Al-rich and slightly sericitized outer parts (Fig. 6B). The chemistry of the latter suggests muscovite, confirming a sericitization process. It is also worth noting that the sulphides cut the siderophyllite and thus appear to have crystallized late in the evolution of the vein. The matrix outside the alteration zone includes quartz, orthoclase, plagioclase, hornblende, chlorite and sericite with less amounts of biotite, zircon, fluorite, apatite and monazite.

The Högberget boulder consists of vein quartz with disseminated sulphides, mainly arsenopyrite (or löllingite), with a few small grains of chalcopyrite as well as monazite, ilmenite and rutile. The core of the vein consists of quartz bordered by mica and chlorite. Some of the thicker veins appear as chaotic mixture of these minerals without clear margins with the host rock.

The Pb–Zn association has only been recognized in one vein, at Mjölknäs on the western side of the Sarvlaxviken bay (Fig. 5B), where a 0.5–0.8 cm-wide sulphide-bearing vein is located, with 0.5–2 cm wide alteration borders. It is exposed over a length of 5 m along strike (325°) and dips 85° to NE. Even if this vein is macroscopically very similar and fits well into the structural pattern of the veins with the Li–As–W–Zn–Mn association of the Högberget veins, it has a very different metal association; up to 1.84 wt.% Pb, up to 0.84 wt.% Zn and up to 0.45% Mn and very low contents of As, Bi, Co, Cu, Fe, In, Li and S. The opaque mineral assemblage is dominated by scattered magnetite grains
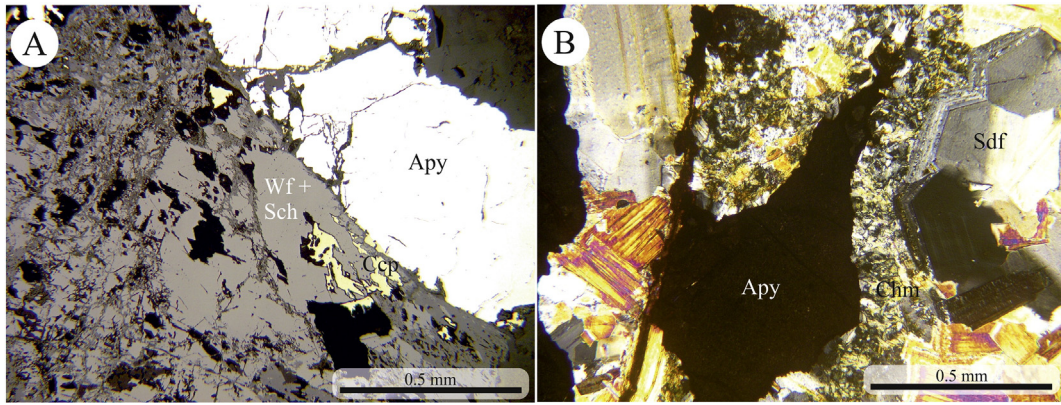
Fig. 6. Photomicrographs of the Högberget-1 vein in reflected (A) and transmitted (B) light. A Arsenopyrite (Apy), chalcopyrite (Ccp) and wolframite/scheelite (Wf/Sch). B The core of the vein including chamosite (Chm), arsenopyrite and compositionally-zoned siderophyllite (Sdf).

of less than 0.1 mm, partially replaced by gangue minerals, together with <0.01 mm-sized grains of sphalerite, galena and remnants of chalcopyrite. Magnetite is concentrated towards the centre of the vein but is also common among the gangue minerals. The inner part of the vein consists mainly of quartz and chlorite. Garnet and fluorite are common components of the granite in the immediately adjacent surroundings of the vein.

4.2.1.2. Generation 2 (the Cu–As–In association). The most common vein type in the Sarvlaxviken area belongs to generation 2, which formed under more brittle conditions and is associated with significantly less alteration compared to the Högberget and Mjölknäs veins (generation 1). The veins belonging to generation 2 contain mainly quartz, occasionally with abundant sulphide minerals, but sometimes only open fractures.

This vein generation can be structurally subdivided into generations 2a and 2b (Figs. 7 and 8). Veins of generation 2a have a general NE–NNE strike direction while the veins of generation 2b are oriented in a NW–NNW direction, cutting the veins belonging to generations 1 and 2a. The mineralized quartz vein at Virbäcken belongs to generation 2a (cut by a barren quartz vein belonging to generation 2b), while the mineralized quartz veins at Korsvik and Korsvikberget belong to generation 2b. Since these two sub-generations generally have the same metal signature, it is suggested that the time difference between the emplacement of vein generations 2a and 2b is very small, and that generation 2 represents a single vein-forming event.

The Cu–As–In association has locally very high (but variable) metal contents; up to 12.3 wt.% Cu, up to 17.3 wt.% As and up to 1490 ppm In. The Cu-As-In association includes several subgroups; Virbäcken,
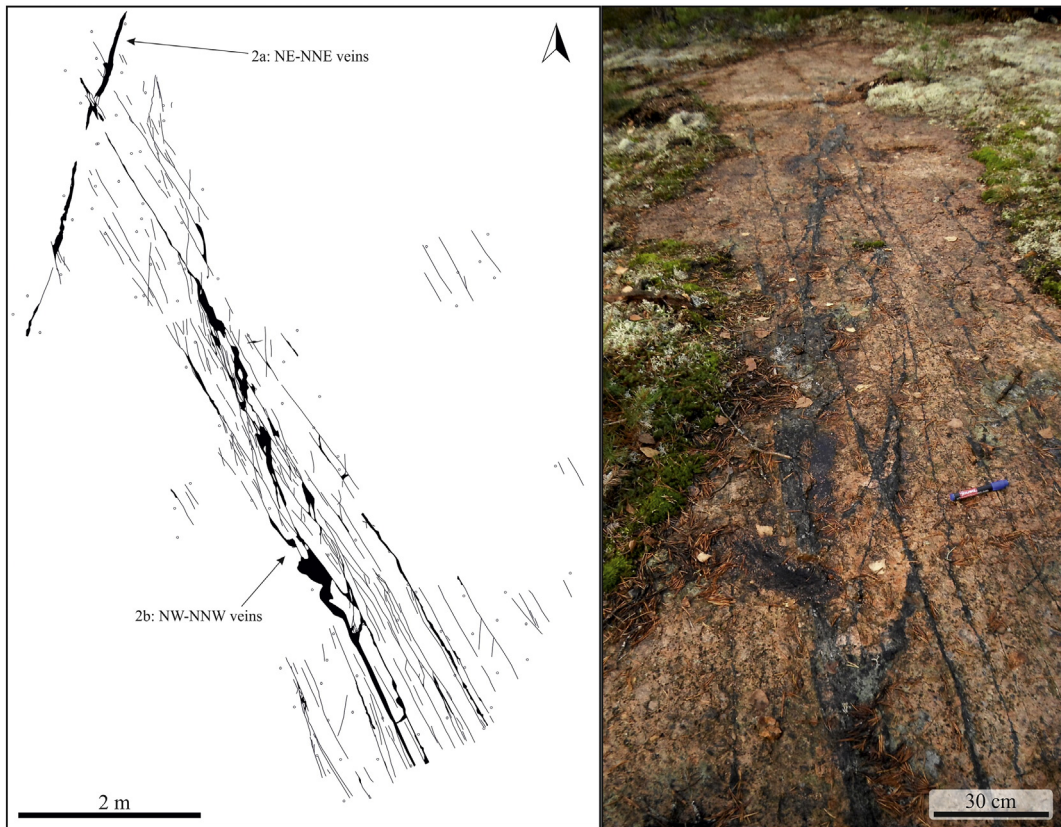

Fig. 7. Two quartz vein generations (2a and 2b) in a horizontal outcrop surface of wiborgitic granite at 3455320, 6700545, located between the Högberget −1 and −2 veins belonging to generation 1: The NE-NNE trending veins of generation 2a are consequently cut by NW-NNW-trending veins of generation 2b. The detailed sketch map on the left of the figure is drawn after a slightly larger area of the outcrop on the right.
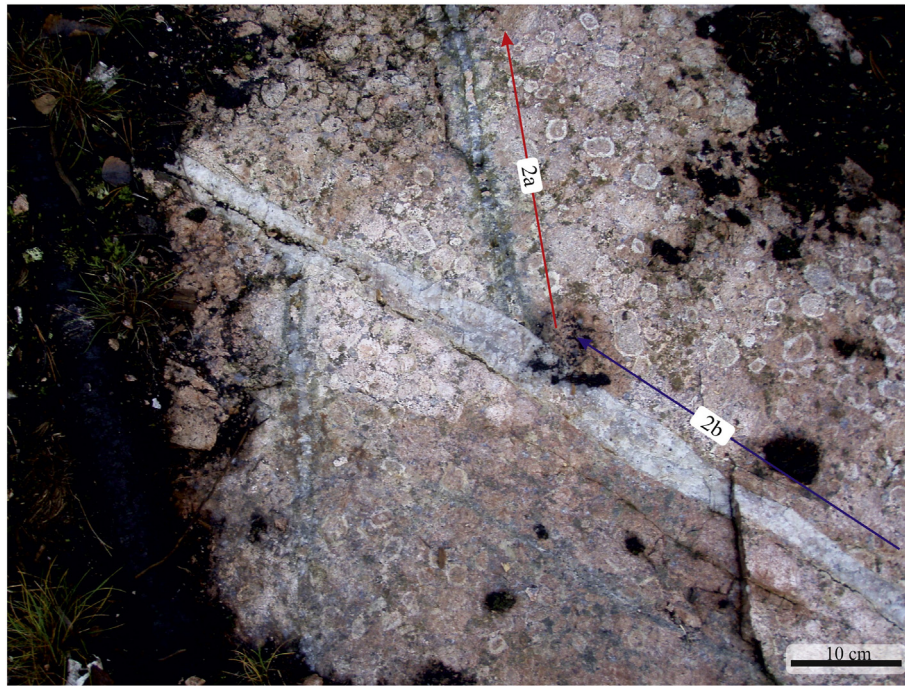
Fig. 8. Two quartz vein generations in a horizontal outcrop surface of wiborgitic granite at Virbäcken. The NNE-trending sulphide-bearing quartz vein of generation 2a is cut and dextrally faulted by the NNW-trending barren quartz vein of generation 2b.

Korsvik and Korsvikberget, divided by characteristic geochemical compositions and mineral assemblages.

The sulphide-bearing Virbäcken quartz vein belongs to generation 2a which has a strike direction of 200° and is cut by a barren quartz vein belonging to generation 2b with a strike direction of 330° (Fig. 8). The vein belonging to generation 2a is exposed over a length of ~10 m but the sulphide-bearing part is restricted to a metre-long section of 0.3–0.6 cm width and a 0.6–1.5 cm wide alteration zone (Fig. 5C). The mineralized part is strongly enriched in Cu (up to 4.4%), Bi (up to 2100 ppm), Ag (up to 200 ppm), In (up to 150 ppm), Be (up to 2100 ppm) and Li (up to 1100 ppm). Significant enrichments are also noted for Fe, and to some extent As, Sn, W, Ga and Mn. The opaque minerals of the Virbäcken vein are dominated by chalcopyrite with smaller amounts of arsenopyrite (Fig. 9A), sphalerite, pyrite, cassiterite, bornite, galena and a group of different bismuth-bearing minerals. The chalcopyrite grains are about 2.5 mm in size and appear in the centre of the vein. Small inclusions, as well as star-shaped sphalerite exsolutions, are common in the chalcopyrite, which also is replaced by gangue minerals as well as small grains of digenite and/or covellite. The arsenopyrite grains are on average 0.5 mm large and are locally replaced by chalcopyrite but retain their primary grain morphology in the outer parts of the vein. All grains of the accessory minerals are <0.1 mm in size. A complex assemblage of Bi-minerals, including native bismuth,

emplectite, wittichenite, matildite and bismuthinite, appear together with, or occur as inclusions within, chalcopyrite as well as in the alteration zone among the gangue minerals. The borders of the Virbäcken vein are less obscure than for the Högberget veins but also less clear than in the Korsvik group. The host of the sulphides consists of quartz, dark mica (e.g., siderophyllite and ferrophengite), chlorite, beryl and fluorite (Fig. 9B–C). The immediately adjacent granite is dominated by altered mica and sericite. Quartz, orthoclase, plagioclase, hornblende, garnet, biotite, apatite, muscovite and zircons occur further away from the vein.

Three sulphide-bearing quartz veins have been recognized at Korsvik, 0–200 m from the eastern shoreline of Sarvlaxviken bay (Fig. 5D–F). All veins are 1–1.8 cm in thickness, with 0.5–1.5 cm-wide alteration borders. The Korsvik-1 vein is exposed over a length of 3 m along a strike direction of 003°, and with a dip of 80° to the E. The Korsvik-2 and 3 veins have roughly the same orientations (340–355°), and are exposed over c. 15 m along strike and with dips of 80° to the E.

The Korsvik group is geochemically characterized by high contents of Fe (up to 18.6 wt.%), Cu (up to 12.3 wt.%), In (up to 1490 ppm), As (up to 7.8 wt.%), Bi (up to 598 ppm) and locally W (up to 35,800 ppm), as well as Sn (up to 15,300 ppm). Compared to the other vein groups, the Korsvik group is conspicuously the poorest in both Ag and Au.
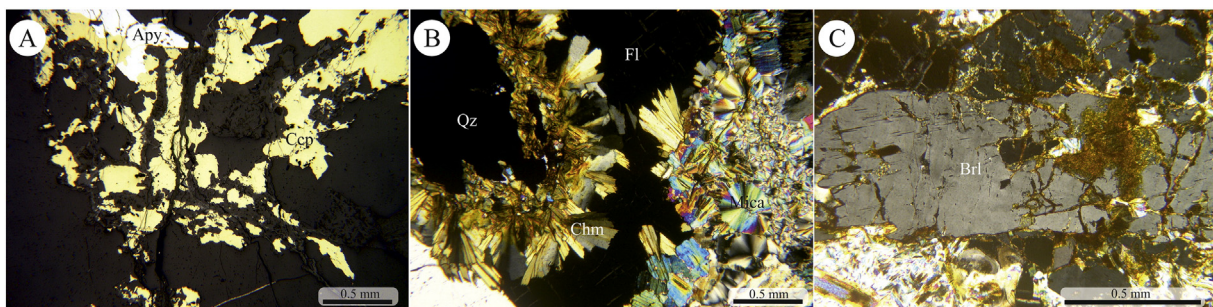

Fig. 9. Photomicrographs of the Virbäcken vein (generation 2a) in reflected (A) and transmitted (B–C) light. A Chalcopyrite with small amounts of arsenopyrite in the vein centre. B The dominating host mineral assemblage consists of quartz, fluorite (Fl), chamosite and various micas. C A distinct cm-sized grain of beryl (Brl).

The Korsvik group is dominated by anhedral chalcopyrite, subhedral arsenopyrite and accessory sphalerite, roquesite, cassiterite, pyrite, native bismuth, wittichenite and wolframite (partly altered to scheelite). Arsenopyrite and chalcopyrite form up to 4 mm sized grains and arsenopyrite is commonly replaced by chalcopyrite. Wittichenite and cassiterite occur in close contact with chalcopyrite (Fig. 10A). Pyrite, as well as the wolframite-scheelite association, occurs only in cracks.

The different textures displayed by roquesite in the Korsvik −1 and 2 veins were described by Cook et al. (2011); while the Korsvik-3 vein is described here for the first time. It is the most In-rich vein in the Sarvlaxviken area (1490 ppm) and exhibits roquesite with analogous textures as in the other Korsvik veins. Sphalerite and roquesite, sometimes associated with bornite or stannoidite, occur within chalcopyrite blebs, commonly around 0.2 mm in size (Fig. 10B). Roquesite can also coexist with sphalerite forming sub-μm-scale crystallographically-oriented lamellar exsolutions (Cook et al., 2011) (Fig. 10C). The majority of the larger sphalerite grains display typical chalcopyrite disease textures.

The Korsvik-1 and −3 veins also contain emplectite and stannoidite, which are absent in the Korsvik-2 vein. Emplectite forms up to 0.6 mm-sized anhedral grains in close contact with chalcopyrite. Native bismuth occurs often together with both emplectite and chalcopyrite, and as inclusions within arsenopyrite. Anhedral, 0.02 mm-sized grains of stannoidite occur in chalcopyrite and are associated with sphalerite and roquesite (Fig. 10D). The bornite in the Korsvik-2 vein occurs as much larger grains (0.1 mm) than the stannoidite grains in the Korsvik-1 and 2 veins. Sometimes it displays exsolutions of crystallographically-oriented chalcopyrite lamellae which are superimposed by exsolutions of wittichenite and roquesite (Cook et al., 2011). Such bornite grains are often accompanied by covellite, digenite and chalcosite.

The principal host of these sulphides is coarse-grained quartz with minor amounts of dark mica and chlorite. The border between the ore-bearing quartz vein and the surrounding alteration zone is fairly clear and sharp. The alteration zone consists of a proximal part containing altered mica (including siderophyllite, ferrophengite and annite) and chamosite (Fig. 10E–F), followed, further outwards, by heavily sericitized K-feldspar, remnants of plagioclase rims, fluorite and smaller grains of quartz. The presence of sericite and chamosite was also detected with the VNIR-SWIR spectra. Outside this alteration zone, the host rock consists of the normal mineral assemblage of the rapakivi granite; quartz, orthoclase, hornblende, chamosite and plagioclase with accessory muscovite, zircon, monazite, apatite, fluorite and sericite. Rutile, ilmenite, and sometimes magnetite, are common within the matrix.

A single sulphide-rich vein has been recognized at Korsvikberget, approximately 500 m E of Korsvik. The vein is 0.3–0.6 cm in width with 0.7–1 cm-wide alteration borders (Fig. 5G). It is exposed over a length of approximately 5 m along a NS-trending direction. The Korsvikberget vein is characterized by very high contents of As (up to 17.3 wt.%), Fe (up to 16 wt.%) and Sn (up to 2000 ppm). Bismuth and Ga are also above the average concentration in the host rock, while the contents of Pb, Cd, Cu, In, Mn and Li are low. The opaque mineral assemblage of the Korsvikberget vein is strongly dominated (99%) by arsenopyrite, which contains inclusions of chalcopyrite and small blebs of bornite, as well as small (<0.3 mm) grains of pyrite, sphalerite and ilmenite. An Ag-Pb-Bi-sulphosalt, possibly an Ag-bearing member of the lillianite homologous series, occurs as very thin bands between the gangue minerals, which consist of quartz, plagioclase, fluorite, chlorite and epidote.

4.2.2. Marviken granite-hosted veins (the As–Cu–Sn and Mo–Bi–Be associations)

Ore-bearing veins are also common in the Marviken granite, west of Sarvlaxviken, although the evidence for these veins so far is restricted to discoveries of a number of glacial transported boulders, distributed over a 150 m long NNW-trending line (Fig. 11). Nevertheless, a local (600–750 m) origin of these boulders from a site to the NNW of the location of the boulders has been deduced from information on the main glacial transport direction (Punakivi et al., 1977), soil geochemistry data (Valkama and Sundblad, in preparation) and the matching granitic lithology in the boulders vs. the bedrock (Fig. 3). As a consequence, even if the source of the ore boulders are safely connected to a site in the northeastern part of the Marviken granite, it is impossible to make any evaluation of the structural relations of these ore-bearing veins. The relative timing between the veins hosted by the Marviken granite vs. the wiborgite-hosted veins is also uncertain and the Marviken
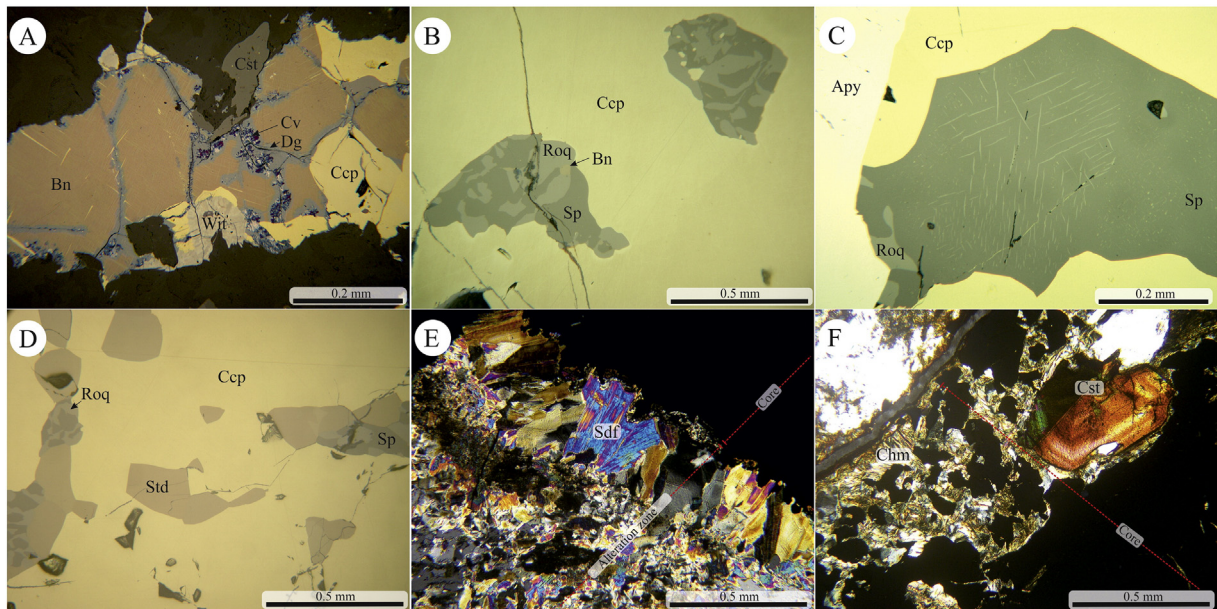

Fig. 10. Photomicrographs of typical ore mineral associations in the Korsvik group of veins; A–D reflected and E–F transmitted light. A Chalcopyrite (Ccp), bornite (Bn), wittichenite (Wit), digenite/covellite (Dg/Cv) and cassiterite (Cst) in the Korsvik- 2 vein. B Inclusions of sphalerite (Sp), roquesite (Roq) and minor bornite in chalcopyrite (Ccp) in the Korsvik-2 vein. C Crystallographically oriented lamellar exsolutions of roquesite in sphalerite within chalcopyrite, associated with arsenopyrite (Apy) in the Korsvik-2 vein. D Sphalerite, roquesite and stannoidite (Std) within coarse chalcopyrite in the Korsvik-1 vein. E Contact between sulphides and alteration minerals in the Korsvik-1 vein with the proximal alteration assemblage mainly consisting of mica (e.g., siderophyllite, Sdf). F The core of the Korsvik-2 vein with dark chamosite and coarse, zoned cassiterite (Cst).
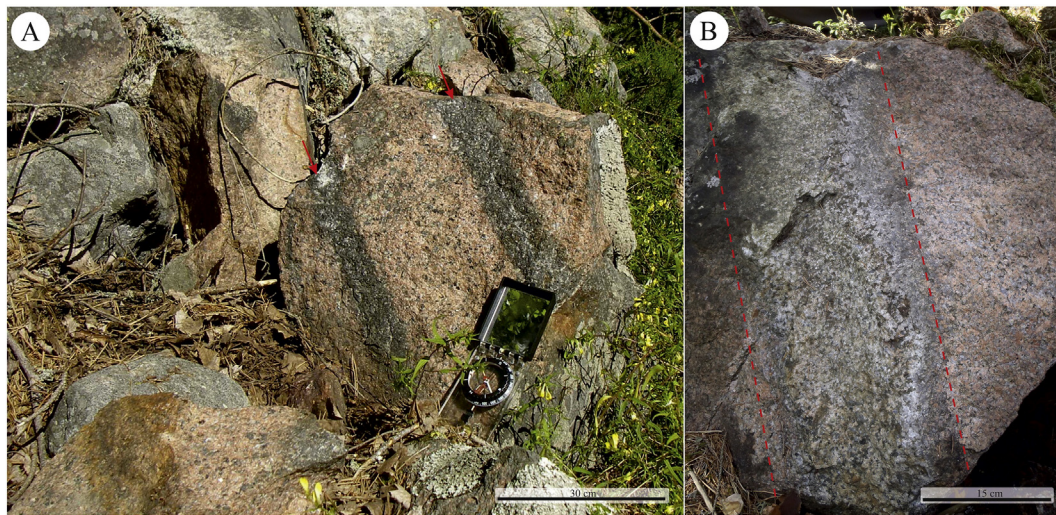
Fig. 11. The ore-bearing alteration zones in the Marviken granite seen in boulders. A The As-Sn-Cu association in dark greisen veins. B The Mo-Bi-Be association in a light-green Be-rich alteration zone.

veins are therefore referred to as "Generation x" in Table 1 (see also the last sentence in the discussion on page 13).There are two major differences between the veins hosted in the Marviken granite compared to those hosted in the wiborgites: There are no high contents of In or low-temperature metals like Pb and Ag and there is no significant input of hydrothermal quartz in the alteration assemblages. Two main groups can be distinguished based on the metal contents; As-Cu-Sn and Mo-Bi-Be. The soil geochemical data at the proposed source area (Valkama and Sundblad, in preparation), together with the fact that two ore types are found in the same boulder train, suggest that the ore types form parts of the same mineralized body.

The As-Cu-Sn association is represented by several tens of boulders. The sulphide-bearing alteration zones are up to 6 cm wide, surrounded by slightly potassium-enriched varieties of the Marviken granite with well-defined borders between the granite and the sulphide-bearing alteration zone (Fig. 11A). In contrast to the wiborgite-hosted quartz veins on the eastern side of the Sarvlaxviken bay, there is no hydrothermal quartz in the alteration zones and no quartz veinlets or open fracture fillings are seen.

Three of the samples (SWAS 258, SWAS 259A-C and SWAS 250) were collected from boulders located within 20 m from each other with similarly high metal contents in the sulphide-bearing alteration zones: As (up to 10,200 ppm), Cu (up to 3010 ppm), Zn (up to 1650 ppm), Li (up to 298 ppm), Pb (up to 318 ppm), Ag (up to 24 ppm), In (up to 15 ppm) and U (up to 60 ppm). The veins consist of quartz, plagioclase, orthoclase and accessory amphiboles, fluorite, beryl, zircons and apatite (all representing the original igneous mineral assemblage) as well as chlorite and mica as alteration products. Scattered sulphides (<5% of the whole vein) are the main hydrothermal products constituting subhedral arsenopyrite and anhedral chalcopyrite with grain sizes up to 2 mm and small amounts of sphalerite.

A slightly different metal association has been distinguished in the sulphide-bearing alteration zone in sample SWAS 247, collected from a m³-sized boulder located 100 m closer to the assumed bedrock source. This alteration zone has slightly higher contents of Be and Mo, as well as lower contents of Zn (220 ppm) and Ag (0.6 ppm) than the three As–Cu-dominated samples. In this way, this sample is geochemically a link between the As-Cu-dominated vein type and the Mo-Bi-Be-dominated vein type (see below). Sulphides are scattered in the entire alteration zone with arsenopyrite as the main opaque phase but with significant amounts of cassiterite and minor amounts of chalcopyrite. The border between the alteration zone and the surrounding granite (Marviken type) is not sharp, the alteration zone includes a significant amount of garnet, which has not been noticed in any other ore boulder.

The Mo–Bi–Be association is only represented by one (but important) ore boulder, located in the southeastern end of the ore boulder train. This boulder is c. one m³ big, partly rounded and partly edgy indicating a moderate transport distance from the NNW. It consists of a 2 dm-wide hydrothermal alteration zone (Fig. 11B). All parts of the alteration zone exhibit a relatively well-preserved granitic texture, reminding of the texture in the surrounding Marviken granite, but the colour is light green, which together with the frequent occurrence of 5 mm large molybdenite stars makes this ore type very distinct. Two subtypes can be identified: a 3–4 cm wide quartz-rich marginal zone (sample SWAS 248 A) along each side of the 15 cm wide central alteration zone (sample SWAS 248 B). The alteration zone is characterized by an increasing breakdown of feldspars from the margins towards the centre, accompanied with a decrease in the K and Na contents. The decreasing K and Na contents, combined with increasing contents of Mo (3510 ppm), Bi (848 ppm), F (0.78%), and Be (3.07%) is reflected in a gradual break-down of the igneous phases orthoclase, plagioclase and biotite (to muscovite and chlorite), retained igneous quartz as well as hydrothermal production of beryl, fluorite, epidote, molybdenite, chalcopyrite and unidentified Bi-bearing minerals.

5. Discussion

5.1. Presence of indium in granites and veins

Very little is known in detail about the crustal distribution of indium. Nevertheless, the average In content in the continental crust has been estimated to 0.05 ppm by Taylor and McLennan (1985) and the average In content in the topaz-bearing granites of SW England was reported by Simons et al. (2013) to be 0.11 ppm. Of the granites in the Sarvlaxviken area, elevated indium concentrations are observed in a few wiborgite samples (up to 0.4 ppm), but the average content of thirteen wiborgite samples (Table 1) still results in <0.2 ppm In. The In concentration of the Marviken granite are under the analytical detection limit (0.2 ppm) in all analysed samples (Lammi, 2008; Nygård, in preparation; Penttinen, in preparation).

The highest indium concentrations in the Sarvlaxviken veins are recorded in the three Korsvik veins (1000–1500 ppm), where also the ratios of ppm In/wt.% Zn are extremely high (up to 8,400) compared to any other vein in the area. The In/Zn ratio in the ore can be assumed to correspond to the In/Zn ratio in the ore-forming fluid and can thus be used as an estimate of the ability to form proper In minerals (like roquesite or other In-rich mineral phases). When Zn is abundant in an ore-forming system, the In/Zn ratios are likely low and all In will

precipitate together with base metals in the sphalerite or chalcopyrite lattices. With less Zn in the system, the In/Zn ratios will become higher, leading to oversaturation of indium in the sphalerite grains and providing a high potential for roquesite to be formed (Cook et al., 2011). With indium grades in the per mil magnitude, and In/Zn ratios of several thousands, it is logical that the roquesite will become abundant, as is the case in the Korsvik veins. The polymetallic Pitkäranta skarn ores in the Ladoga region is a good example on what happens with more modest In/Zn ratios (and still high In contents). With the highest In/Zn ratio recorded in the Pitkäranta ores (51), and with an In grade of 291 ppm, only minute roquesite grains were formed while the bulk of the indium in that sample crystallized in sphalerite and chalcopyrite (Valkama et al., in press). With even lower In/Zn ratios, all available indium was incorporated into the sphalerite and chalcopyrite lattices and an In/Zn ratio of 50 appears to be close to the minimum for creating In minerals. Another important factor for creating macroscopically or microscopically visible roquesite is the indium grade. If the In/Zn ratios are high, but the In grades not high enough, roquesite may still form, but in that case only in sub-microscopic amounts, which may explain why no roquesite was observed in the veins at Korsvikberget (up to 29 ppm In) and Virbäcken (up to 146 ppm In) in spite of high In/Zn ratios (c. 2000). The veins in the Marviken granite have even lower In/Zn ratios (at maximum 338) as well as very low In grades (<20 ppm), which implies that it was only possible to create very small amounts of roquesite, if any at all, in the Marviken veins.

In the Sarvlaxviken area, the roquesite occurs always in the Cu-As-In association, together with sphalerite and chalcopyrite and sometimes with bornite or stannoidite. Cook et al. (2011) took the observed paragenesis of sphalerite, chalcopyrite, stannoidite/bornite and roquesite, as well as the characteristic textures, to imply "formation via cooling and sequential exsolution of a high-temperature Cu–Zn–(Fe)–In-sulphide".

5.2. Further mineralogical aspects

The abundant lithium in the Li–As–W–Zn–Mn association (the Högberget veins) is most probably hosted by mica (e.g., siderophyllite), while most of the manganese probably is hosted by sphalerite, which can incorporate wt.% levels of Mn in the lattice (e.g., Graeser, 1969; Cook et al., 2009). The presence of Cd was also suggested (Bernardini et al., 2004) to affect the distribution of Mn and Fe in the sphalerite. The strong correlation between Fe and Mn, as well as between Zn and Cd, in the Högberget veins would thus indicate that most (or all) of the Mn and Cd are present within sphalerite.

The Pb-Zn dominated metal signature in the Mjölknäs vein, and the absence of Li in the associated alteration zone, may suggest that this vein formed at a higher crustal level than the Li–As–W–Zn–Mn dominated veins at Högberget.

Even if the three Korsvik veins (the Cu-As-In association) display large similarities with respect to the geochemical compositions and mineral assemblages, stannoidite is common in the Korsvik-1 and Korsvik-3 veins, but absent in the Korsvik-2 vein. In contrast, the Korsvik-2 vein is the only vein with abundant bornite. This difference can be explained by the significantly higher Sn contents in the Korsvik-1 and Korsvik-3 veins compared with the Korsvik-2 vein, which favoured crystallization of stannoidite instead of bornite in the Korsvik-1 and Korsvik-3 veins.

5.3. Source of metals and fluids

The polymetallic veins of the Sarvlaxviken area are clearly the products of hydrothermal activity, but the source of the metal-rich fluids is poorly constrained. Based on field observations, it is evident that the wiborgite-hosted veins relate to a regional-scale NNW–trending structure with multiple vein generations. The strong tectonic control of the veins through time indicates that they were formed from a combination of magmatic-hydrothermal and structurally controlled processes. The relatively high indium contents in the wiborgites indicate that this abundant lithology is one potential metal source. The presence of a porphyritic granitic dyke with evolved geochemistry, subparallel with the quartz veins on the eastern side of the Sarvlaxviken bay, may also indicate a deeper source for both heat and metals for the wiborgite-hosted veins. The polymetallic veins in the Marviken granite represent a different mineralization style (and/or generation) compared to the wiborgite-hosted veins by the distinctly different host rock, vein types and geochemical signatures. The veins hosted by the Marviken granite are not observed in outcrop and are therefore impossible to relate to any structural framework. Nevertheless, it is evident that these veins were formed as an immediate expression of the magmatic-hydrothermal activity related to the Marviken granite emplacement, most probably involving metal derivation from the Marviken granite itself.

It is already known from elsewhere in the Wiborg Batholith that peraluminous granites, with high contents of F, Li, Ga, Rb, Sn, Nb, and low contents of Ti, Mg, Fe, Ba, Sr and Zr, are the most metal productive (Haapala, 1977b, 1995). A good example is the topaz-bearing granite in the late-stage Kymi intrusion, 40 km ENE of the Sarvlaxviken area (Haapala, 1977a; Rämö and Haapala, 1995; Haapala and Lukkari, 2005; Lukkari, 2007). The Marviken granite and the porphyritic granitic dyke east of the Sarvlaxviken bay display similar geochemical patterns with pronounced negative Eu anomalies, high contents of F, Ga, Rb, Sn and Nb (occasionally also HREEs), as well as low contents of Mg, Fe, Ba, Sr and Zr (Nygård, in preparation), and are thus comparable to ore fertile granites.

Chondrite-normalized REE fractionation patterns for the Marviken granite show a pronounced negative Eu-anomaly, as well as occasional enrichments of HREEs. In addition, high contents of F, Ga, Rb, Sn, Nb, and low contents of Mg, Fe, Ba, Sr, Zr are noted (Nygård, in preparation).

5.4. Evidence for greisenization in the wiborgite-hosted veins

Mineralization related to granites commonly feature different types of alteration processes. Greisenization is a granite-related, post-magmatic hydrothermal process, in which acidic, high-silica-, fluorine-, chlorine- and volatile-bearing solutions react with and alter the host rocks (Shcherba, 1970a, 1970b; Štemprok, 1987). During this process, biotite and feldspars become unstable and are replaced by aggregates of mica, quartz, topaz, fluorite, tourmaline and minerals containing elements such as Sn, W, Mo, Be, Li, As, Bi, REE etc. Greisenization is recognized as a multi-stage process and is often accompanied by silicification and followed by sericitic and argillic alteration (Pirajno, 1992). The initial stages of the process include acid leaching, which results in the formation of monomineralic metasomatites and subsequent increasing alkalinity. Inflow of the ore-forming fluids is weak at the early stages of greisenization. Metal accumulations (leading to the formation of cassiterite, molybdenite, wolframite etc.) will take place at the end of the acid phase and continue during the formation of quartz and quartz-feldspar veins. Finally, close to the end of the whole process, quartz-sulphide veins will form, followed by metal-free quartz veins (Shcherba, 1970a, 1970b).

The metal associations and ore minerals documented in the Sarvlaxviken area are all firm evidence for hydrothermal activity and the various vein types probably represent different stages of greisenization. The common key elements of greisenization, such as Be, F, Sn, W, Mo, Li and Bi, are all present in the various generations of the wiborgite-hosted veins. The dark coloured mica-quartz veins represent the earliest phase and are followed by the sulphide-bearing quartz veins and barren quartz veins, which probably represent the final stage of hydrothermal activity. More precise constraints on the age relationships between veins, and an assessment of fluid composition, e.g., by analysis of fluid inclusions, are clearly required but are beyond the scope of the present work.

There are also differences between the quartz-bearing sulphide veins, indicating different formation conditions, possibly different stages of the greisenization process. The Korsvik veins are rather similar with respect to geochemistry and mineralogy, and thus likely represent the more evolved stage of the alteration-mineralization process. These veins have undergone silicification with so-called quartz flooding (Pirajno, 1992) whereas the evidence for silicification in the other vein groups is less distinct. Particularly in the Högberget group, the fluid pathways and alteration are locally disordered, and quartz is less abundant. Introduction of B, F and Li create more geochemically complex systems where e.g., topaz can crystallize (Pirajno, 1992). This can be observed in the Högberget and Virbäcken veins, where fluorite is more abundant and addition of Al has led to crystallization of mica and topaz. Moreover, the Li concentrations are very high (up to 2400 ppm at Högberget and up to 1,090 ppm at Virbäcken) when compared with the other groups.

Weak to moderately intense, selective sericitization and chloritization can be observed in all vein groups. Sericitic alteration is a result of the destabilization of feldspars in acidic, K-bearing, and often S-rich fluid systems and produces quartz, white mica (e.g., muscovite and phengite) and occasional sulphides e.g., pyrite, chalcopyrite and molybdenite. During this process, Na, Mg, Ti, Fe and K are leached out (Pirajno, 1992). The majority of the mica observed around the Sarvlaxviken veins correspond to the biotite group, in most cases siderophyllite. Haapala (1977b) presented analytical data for dark mica and chlorite in the Väkkärä granite (SW Finland) and identified both Li-rich siderophyllite and Fe-rich chlorite. The Sarvlaxviken phyllosilicates are thus almost identical with the phyllosilicates reported by Haapala (1977b). The high Li contents in the Högberget and Virbäcken veins can most probably be explained by the presence of broad solid solution in the dark micas: lithian siderophyllites (Rieder, 1970), sometimes also called protolihtionites (Foster, 1960). Protolithionites are also reported from the greisen systems in Western Krušné Hory, Czech Republic (Štemprok et al., 2005). Muscovite data from the generation 2 veins in the Sarvlaxviken area display slightly higher contents of Fe and SiO_2, and a lower content of K_2O, which are consistent with the description of sericitized micas (Deer et al., 1962) containing higher amounts of SiO_2, MgO and H_2O and lower K_2O. In addition, some of the Sarvlaxviken muscovites contain more SiO_2 and FeO, and less Al_2O_3, thus representing a composition in the muscovite–aluminoceladonite-celadonite solid solution series (Rieder et al., 1998), called ferrophengites (Deer et al., 1962). The magnesium discharged during sericitization also formed chlorite, which is abundant in the vein groups. Chlorite is commonly observed within and/or close to the contact of the core of the vein but also partly replaces the plagioclase rims of the feldspar ovoids in distal alteration areas. These are all evidence for a greisenization process that was accompanied by silicification (albeit at varying intensity), and followed by sericitization and chloritization by high-fluorine, −silica and -chlorine fluids.

5.5. Metal distribution

In spite of a number of veins, each with distinct metal signatures, there is no clear spatial zonation pattern in the Sarvlaxviken area and relatively simple geochemical vectors and/or cooling gradients, as e.g., reported from the In-bearing polymetallic greisen systems of Cornwall (Guilbert and Park, 1986; Andersen, 2008; Andersen et al., 2013; Dendle et al., 2009), cannot be easily established for the Sarvlaxviken system, thus making a direct analogy with Cornwall problematic. The diversity in metal signatures may, however, imply some other spatial zoning with distance from the fluid source or changes in the composition of the vein-forming fluids with time. In many ways, the wiborgite-hosted veins in Sarvlaxviken can be conceptually considered within such a scenario.

Clear spatial zonation patterns are particularly difficult to construct for elements like Sn, W, Fe and Zn. All these elements are accompanied by other main elements or are abundant in several different locations. For example, the Sn contents are highly variable in the veins with the highest contents Sn often accompanied with the highest contents of Cu or As.

In contrast to the lack of spatial zonation patterns, there are some pieces of evidence for temporal zonation patterns. One of them is the consequent increase in the In contents as well as the decrease in the Ba and Be contents when looking at the element distribution in the veins belonging to generations 1, 2a and 2b respectively, which clearly indicates that the major indium forming event was related to the very latest phase of the hydrothermal activity. Another one is that the veins hosted by the Marviken granite, as well as the veins belonging to generations 1 and 2a, have relatively low contents of In, but relatively high contents of Ba, Be and Li, which may indicate that a genetic and temporal link exist between all veins belonging to generations x, 1 and 2a in Table 1.

6. Conclusions

A number of polymetallic vein mineralizations of different styles and metal associations, including base, alloy, noble and critical metals, have been discovered around the Sarvlaxviken bay in the westernmost parts of the Mesoproterozoic Wiborg Batholith, south-eastern Finland. The veins occur in two rapakivi granite varieties, the coarse-grained wiborgite and the medium-grained Marviken granite. The veins are divided into five groups based on the dominant metal associations:

The Li–As–W–Zn–Mn, Pb–Zn and Cu–As–In associations are hosted by wiborgite and strongly controlled by a NNW-trending tectonic pattern that evolved in two main stages. The Li–As–W–Zn–Mn association (generation 1) formed in a typical greisen environment with Li-bearing mica in significant alteration halos around a narrow quartz vein. The greisenization was accompanied by silicification, followed by sericitization and chloritization. The Pb-Zn association occurs in a similar vein type but without typical high-temperature minerals and is considered to have formed at a higher crustal level. Generations 2a and 2b formed under more brittle conditions leading to fracturing, quartz veining and metal precipitation of ore minerals. This metal association is characterized by very high contents of Cu, As and up to 1490 ppm In but with ≤0.4% Zn, which leads to very high In/Zn ratios (up to 8,400) enabling formation of abundant roquesite.

The As–Sn–Cu and Mo–Bi–Be associations are hosted by alteration zones without hydrothermal quartz in the Marviken granite. Mineralization with moderately high contents of As, Sn and Cu is associated with greisenization while mineralization with spectacular contents of Be, as well as high contents of Mo and Bi, is associated with sericitization, chloritization and berylification.

The internal age relations between the wiborgite-hosted, NNW-trending veins show a clear evolution from a typical greisen type environment (the Li–As–W–Zn–Mn and Pb–Zn associations of generation 1) to cooler and more brittle conditions governing quartz veining and precipitation of ore minerals belonging to the Cu–As–In association (generations 2a and 2b). The age relations between these wiborgite-hosted veins and the veins in the Marviken granite are more uncertain but the presence of a NS-trending granitic dyke on the eastern side of the Sarvlaxviken bay, with similar ore-fertile geochemical composition as the Marviken granite, indicates that the tectonically controlled veins formed simultaneously with the emplacement of the Marviken granite and associated hydrothermal activity.

The polymetallic veins in the Sarvlaxviken bay are unique for the Fennoscandian Shield, not the least for the locally high indium grades and spectacular roquesite grains. There is an obvious exploration potential for similar veins (and hence a number of base, alloy, noble and critical metals) also elsewhere in the entire Wiborg Batholith.

References

ActLab Ltd., 2015. Ultratrace 3 — total digestion — ICP and ICP/MS, INAA (online) Available: http://www.actlabs.com/page.aspx?page=508&app=226&cat1=549&tp=12&lk=no&menu=64.

Andersen, J.C.Ø., 2008. Indium in Cornwall. Annual Mineral Deposits Studies Group Meeting. British Geological Survey, Keyworth, U.K. 2nd-4th January 2008 (Abstract).

Andersen, J.C.Ø., Stickland, R.J., Rollison, G.K., Shail, R.K., 2013. Granite-Related Indium Mineralisation in SW England. In: Jonsson, E., et al. (Eds.), Mineral Depostits for a High-Tech World: Proceedings of the 12th SGA Biennial Meeting 2013, Mineral Deposit Research for a High-Tech World, 12–15 August 2013, Uppsala, Sweden, pp. 1687–1690.

Anderson, C.A., Scholz, J.D., Strobell Jr., J.D., 1955. Geology and ore deposits of the Bagdad Area, Yavapai County, Arizona. U.S. Geological Survey Professional Paper 278.

Bernardini, G.P., Borgheresi, M., Cipriani, C., Di Benedetto, F., Romanelli, M., 2004. Mn distribution in sphalerite: an EPR study. Phys. Chem. Miner. 31, 80–84.

Bettencourt, J.S., Dall'Agnol, R., 1987. The Rondonian tin-bearing anorogenic granites and associated mineralizations. International Symposium on Granites and Associated Mineralizations (ISGAM), Salvador, Balia, Brazil, January 21–31 1987. Excursion Guide, pp. 49–86.

British Geological Survey, 2012. Risk list 2012 (online) Available: http://www.bgs.ac.uk/mineralsuk/statistics/risklist.html.

Cook, N.J., Ciobanu, C.L., Pring, A., Skinner, W., Danyushevsky, L., Shimizu, M., Saini-Eidukat, B., Melcher, F., 2009. Trace and minor elements in sphalerite: a LA-ICP-MS study. Geochim. Cosmochim. Acta 73, 4761–4791.

Cook, N.J., Ciobanu, C., Shimizu, M., Danyushevsky, L., Valkama, M., Sundblad, K., 2008. Trace element geochemistry of sphalerite: insights from LA-ICS-MS analysis. Geologi Lehti 136–137.

Cook, N.J., Sundblad, K., Valkama, M., Nygård, R., Ciobanu, C., Danyushevsky, L., 2011. Indium mineralisation in A-type granites in southeastern Finland: insights into mineralogy and partitioning between coexisting minerals. Chem. Geol. 284, 62–73.

Dagelaysky, V.B., 1997. Ukrainian Shield. In: Rundqvist, D.V., Gillen, C (Eds.), Developments in Economic Geology 30, Precambrian ore Deposits of the East European and Siberian Cratons. Elsevier Science B.V., New York, pp. 107–153.

Deer, W.A., Howie, R.A., Zussman, J., 1962. Rock forming minerals. Sheet Silicates vol. 3. Longmans, London (270 pp.).

Dendle, J.E., Stickland, R.J., Andersen, J.C.Ø., 2009. Indium in main stage polymetallic mineralisation in West Cornwall. Appl. Earth Sci. 118, 24–25.

Foster, M.D., 1960. Interpretation of the lithium micas. U.S. Geological Survey Professional Paper 354-E.

Goodman, K.S., 1986. Petrology and mineral chemical studies of the Lawier Peak Granite and associated tungsten mineralization, Yavapai County, Arizona. Unpublished MS thesis. University of Oklahoma. 101 p.

Graeser, S., 1969. Minor elements in sphalerite and galena from binnatal. Contrib. Mineral. Petrol. 24, 156–163.

Guilbert, J.M., Park, C.F., 1986. The Geology of Ore Deposits. Waveland Press; Long Grove (985pp.).

Haapala, I., 1973. Havaintoja Rapakivigraniittien Tina- ja Berylliumpitoisuuksista. Geologi 25 (6), 61–67 (and (7), 75. Helsinki).

Haapala, I., 1974. Some petrological and geochemical characteristics of Rapakivi granite varieties associated with greisen-type Sn, Be, and W mineralization in the Eurajoki and Kymi areas, Southern Finland. In: Stemprok, M. (Ed.), Metallization Associated with Acid Magmatism I. Ustrední ústav geolgický, Prague, pp. 159–169.

Haapala, I., 1977a. The controls of tin and related mineralizations in the Rapakivi-granite areas of south-eastern Fennoscandia. Geol. Fören. Stockh. Förh. 99, 130–142.

Haapala, I., 1977b. Petrography and geochemistry of the eurajoki stock, a rapakivi-granite complex with greisen-type mineralization in southwestern Finland. Geol. Surv. Finland Bull. 286 (128 pp.).

Haapala, I., 1988. Metallogeny of the Proterozoic Rapakivi Granites of Finland. In: Taylor, R.P., Strong, D.F. (Eds.), Recent advances in the geology of granite-related mineral deposits. Canadian Institute of Mining and Metallurgy Special vol. 39, pp. 124–132.

Haapala, I., 1995. Metallogeny of Rapakivi granites. Mineral. Petrol. 54, 149–160.

Haapala, I., 1997. Magmatic and postmagmatic processes in tin-mineralized granites: topaz-bearing leucogranite in the Eurajoki rapakivi granite stock, Finland. J. Petrol. 38 (12), 1645–1659.

Haapala, I., Ojanperä, P., 1969. Triplite and wolframite from a greisen-bordered veinlet in Eurajoki, SW Finland. Bull. Geol. Soc. Finl. 41, 99–105.

Haapala, I., Ojanperä, P., 1972. Genthelvite-bearing greisens in southern Finland. Geol. Surv. Finland Bull. 259 (22 pp.).

Haapala, I., Lukkari, S., 2005. Petrological and geochemical evolution of the Kymi stock, a topaz granite cupola within the Wiborg rapakivi batholith. Finland, Lithos 80, 347–362.

Kisvarsanyi, E.B., Kisvarsanyi, G., 1991. Alkaline granite ring complexes and metallogeny in the Middle Proterozoic St. Francois Terrane, Southeastern Missouri, U.S.A. In: Grower, C.F., Rivers, T., Ryan, A.B. (Eds.), Mid-Proterozoic Laurentia-Baltica. Geological Association of Canada Special Paper 38, pp. 433–446.

Korsman, K., Koistinen, T., Kohonen, J., Wennerström, M., Ekdahl, E., Honkamo, M., Idaman, H., Pekkala, Y. (Eds.). 1997. Suomen kallioperäkartta – Berggrundskarta över Finland — Bedrock map of Finland 1:1 000 000. Geological Survey of Finland, Espoo.

Kurhila, M., Mänttäri, I., Vaasjoki, M., Rämö, O.T., Nironen, M., 2011. U–Pb geochronological constraints of the late Svecofennian leucogranites of southern Finland. Precambrian Res. 190, 1–24.

Laitala, M., 1964. Geological map of Finland in scale 1: 100 000, Pre-Quaternary rocks, sheets 3021 Porvoo. Geological Survey of Finland.

Lammi, M., 2008. Petrografinen Kuvailu Vulkaanisista Irtolohkareista Viipurin Batholiitista (LuK thesis) University of Turku, Finland (30 pp.).

Lukkari, S., 2007. Magmatic Evolution of Topaz-Bearing Granite Stock Within the Wiborg Rapakivi Granite Batholith (PhD thesis) University of Helsinki, Finland (19 pp.).

Nygård, E., 2016. Geokemiska och Petrologiska Undersökningar av Rapakivigranitintrusioner och Associerade Greisen-Mineraliseringar i Sydvästra Delen av Viborgs Rapakivibatolit (MS thesis) University of Turku, Finland (in preparation).

Öhlander, B., Billström, K., Hålenius, E., 1989. Geochemistry of the Proterozoic wolframite-bearing greisen veins and the associated granite at Rostberget, northern Sweden. Chem. Geol. 78, 135–150.

Penttinen, K., 2016. Geological and Geomagnetic Structures in Wiborg Rapakivi Batholith in the Lovisa Region (MS thesis) University of Turku, Finland (in preparation).

Pirajno, F., 1992. Hydrothermal Mineral Deposits Principal and Fundamental Concepts for the Exploration Geologist. Springer-Verlag, Berlin (709 pp.).

Punakivi, K., Lahermo, P., Rainio, H., Valovirta, V., 1977. Description of the Quaternary Deposits in the Porvoo map-Sheet Area (3021 and 3012). Geological Survey of Finland (40 pp.).

Rämö, T., Haapala, I., 1995. One hundred years of rapakivi granite. Mineral. Petrol. 52, 129–185.

Rämö, T., Haapala, I., 2005. Developments in Precambrian Geology. Precambrian Geology of Finland — key to the Evolution of the Fennoscandian Shield vol. 14. Elsevier, pp. 533–562.

Räsänen, M.E., Huitti, J.V., Bhattarai, S., Harvey, J., 2015. The SE sector of the middle Weichselian Eurasian ice sheet was much smaller than assumed. Quat. Sci. Rev. 122, 131–141.

Rieder, M., 1970. Chemical composition and physical properties of lithium-iron micas from the Krusné hory mts. (Erzgebirge) part A; chemical composition. Contrib. Mineral. Petrol. 27, 131–158.

Rieder, M., Cavazzini, G., D'Yakonov, Y.S., D'Yakonov, Y.S., Frank-kamenetskii, V.A., Gottardi, G., Guggenheim, S., Koval, P.V., Müller, G., Neiva, A.M.R., Radoslovich, E.W., Robert, J.-L., Sassi, F.P., Takeda, H., Weiss, Z., Wones, D.R., 1998. Nomenclature of the micas. Can. Mineral. 36.

Roberts, D.E., Hudson, G.R.T., 1983. The Olympic dam copper-uranium-gold deposit, Roxby downs, South Australia. Econ. Geol. 78, 799–822.

Shcherba, G.N., 1970a. Greisens. Int. Geol. Rev. 12, 114–150.

Shcherba, G.N., 1970b. Greisens (part 2). Int. Geol. Rev. 12, 239–255.

Simonen, A., Vorma, A., 1969. Amphibole and biotite from rapakivi. Bull. Comm. Géol. Fin. 83, 1–105.

Simons, B., Andersen, J.C.Ø., Shail, R.K., 2013. Indium Fractionation in the Granites of SW England. Mineral Deposit Research for a High-Tech World. 12th SGA Biennial Meeting 2013. Proceedings. 4, pp. 1738–1741.

Štemprok, M., 1987. Greisenization (a review). Geol. Rundsch. 76, 169–175.

Štemprok, M., Pivec, E., Langrová, A., 2005. The petrogenesis of a wolframite-bearing greisen in the vykmanov granite stock, western krušné hory pluton (Czech Republic). Bull. Geosci. 80 (3), 163–184.

Sundblad, K., Cook, N.J., Nygård, R., Eklund, O., Valkama, M., Penttinen, K., Nygård, N., Rimaila, R., Paadar, J., Lammi, M., Seifert, T., Karell, F., Huhma, H., Aino, M.-L., 2008. Polymetallic Metallogeny in the Wiborg Batholith, Fennoscandia Shield. 33rd International Geological Congress, Oslo, August 6th-14th 2008, Abstract CD-ROM.

Taylor, S.R., McLennan, S.M., 1985. The Continental Crust: Its Composition and Evolution. Blackwell scientific publication, London (312 pp.).

Törnebohm, A.E., 1891. Om pitkäranta malmfält och dess omgifningar. Geol. Fören. Stockh. Förh. 13, 313–334.

Trüstedt, O., 1907. Die Erzlagerstätten von Pitkäranta am Ladoga-See. Bulletin de la Commission Geologique de Finlande no 19. Frenckellska Tryckeri-Aktiebolaget, Helsingfors.

Vaasjoki, M., Rämö, O.T., Sakko, M., 1991. New U-Pb ages from the Wiborg rapakivi area: constraints on the temporal evolution of the rapakivi granite-anorthosite-diabase dyke association of southeastern Finland. Precambrian Res. 51, 227–243.

Valkama, M., Sundblad, K., Cook, N.J., 2016. Geochemistry and petrology of the indium — bearing polymetallic skarn ores at Pitkäranta, Ladoga, Karelia, Russia. Mineral. Deposita (in press).

Valkama, M., Sundblad, K., 2017. Metal Anomalies in Soil around Polymetallic veins in the Sarvlaxviken Area, Southeast Finland (in preparation).