

## VUORELAINENITE, A NEW SPINEL, AND ASSOCIATED MINERALS FROM THE SÄTRA (DOVERSTORP) PYRITE DEPOSIT, CENTRAL SWEDEN

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### ABSTRACT

Vuorelainenite, with end-member formula  $MnV_2O_4$ , is a new mineral of the spinel group from the Sättra (Doverstorp) pyrite deposit in Bergslagen, central Sweden. The name honors Yrjö Vuorelainen, who described similar material from Outokumpu, Finland. The mineral is cubic, space group  $Fd\bar{3}m$ , with  $a$  8.48(5) Å,  $Z = 8$ ; the strongest five lines in the powder diffraction pattern [ $d$  in Å (I)( $hkl$ )] are: 2.985(4)(022), 2.559(10)(113), 2.118(3)(004), 1.633(8)(115, 333), 1.502(8)(044). The mineral is opaque; in reflected light it is isotropic, brownish grey in color, and darker than sphalerite. Reflectance (nm, %): 470, 15.7; 546, 15.4; 589, 15.6; 650, 16.2. The calculated density is 4.64 g/cm<sup>3</sup>;  $VHN_{50} = 900$ . Electron-microprobe analyses show considerable substitution of chromium for vanadium; a number of spinel grains have a manganochromite composition. Vuorelainenite occurs as small, euhedral single crystals in pyrrhotite-rich ore; it seems to have formed by an interaction between the sulfide and silicate or oxide phases under highly reducing conditions in ores remobilized under amphibolite-facies metamorphism. The Sättra mine is also one of the type localities of benavidesite,  $Pb_4(Mn, Fe)Sb_6S_{14}$ , and is the second occurrence of schreyerite,  $V_2Ti_8O_9$ .

**Keywords:** vuorelainenite, new mineral, spinel group, manganochromite, benavidesite, schreyerite, Bergslagen, Sweden.

### SOMMAIRE

La vuorelainenite, de formule idéale  $MnV_2O_4$ , est un nouveau spinelle découvert dans le gisement de pyrite de Sättra (Doverstorp, Bergslagen, Suède centrale). Cubique, groupe spatial  $Fd\bar{3}m$ ,  $a$  8.48(5) Å,  $Z = 8$ . Les cinq raies les plus intenses du cliché de poudre [ $d$  en Å (I)( $hkl$ )] sont 2.985(4)(022), 2.559(10)(113), 2.118(3)(004), 1.633(8)(115, 333) et 1.502(8)(044). C'est un minéral opaque; isotrope et d'un gris brunâtre en lumière réfléchie, il est plus foncé que la sphalérite. Réflectance (nm, %): 470, 15.7; 546, 15.4; 589, 15.6; 650, 16.2. Densité (calc.) = 4.64, dureté  $VHN_{50}$

= 900. Les analyses à la microsonde électronique indiquent un remplacement notoire du vanadium par le chrome: plusieurs cristaux de spinelle ont la composition de manganochromite. La vuorelainenite, que l'on trouve dans le minerai en petits monocristaux idiomorphes avec pyrrhotine abondante, résulterait d'une interaction sulfure-silicate ou sulfure-oxyde en milieu fortement réducteur dans le minerai remobilisé par le métamorphisme (facies amphibolite). Le nom honore Yrjö Vuorelainen, qui avait trouvé un échantillon semblable à Outokumpu (Finlande). La mine Sättra est aussi l'une des localités-types de la benavidesite,  $Pb_4(Mn, Fe)Sb_6S_{14}$ , et le deuxième gîte de schreyerite,  $V_2Ti_8O_9$ .

(Traduit par la Rédaction)

**Mots-clés:** vuorelainenite, minéral nouveau, groupe du spinelle, manganochromite, benavidesite, schreyerite, Bergslagen (Suède).

### INTRODUCTION

In the course of an investigation of manganoean sphalerite and alabandite from the pyrite deposit of Sättra (Fig. 1), in the Doverstorp ore field (Zakrzewski 1980), euhedral grains of an unknown isotropic mineral were observed to have a reflectance lower than the enclosing sphalerite (Fig. 2). Electron-microprobe analyses suggested a formula  $(Mn, Fe)(V, Cr)_2O_4$ , and X-ray-diffraction data confirmed the spinel structure. Similar results had been obtained by Long *et al.* (1963) on an unnamed mineral in their study of karelianite from Outokumpu.

The mineral is named after Yrjö Vuorelainen, formerly exploration geologist with the Outokumpu Company and discoverer of the Outokumpu manganese vanadium spinel. The mineral and the name *vuorelainenite* have been approved by the IMA Commission on New Minerals and Mineral Names. Type-specimen material is preserved in the collections of the Free University in Amsterdam (No. 153A4).

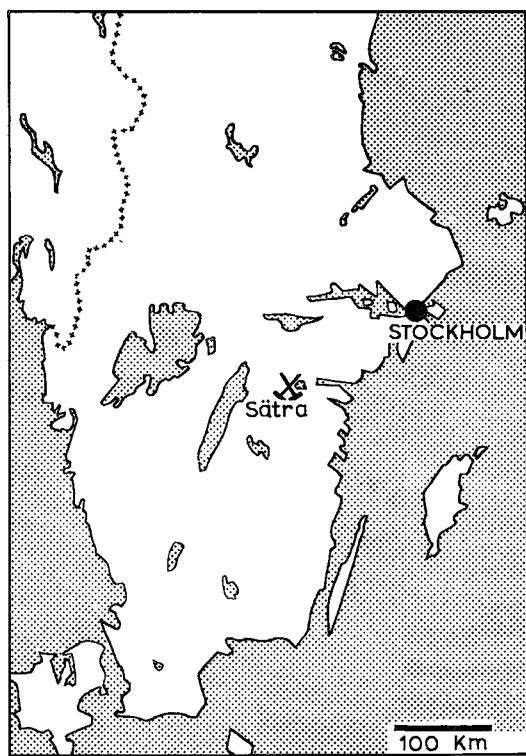


FIG. 1. Location of the Sättra mine.

#### OCCURRENCE

The Doverstorp ore field represents a fahlband-type pyrite-pyrrhotite deposit typical of the Ämmeberg-Tunaberg metallogenic belt in the southern part of the Proterozoic Bergslagen province of central Sweden (Fig. 1). The ore deposits of this province are associated with a supracrustal complex consisting of felsic metavolcanic and metasedimentary rocks, with subordinate metamorphosed mafic rocks and marbles. In Doverstorp the metavolcanic rocks are dacites to rhyolites; the metasedimentary rocks range from sandstones to arkoses (Wikström 1976). Ores and supracrustal rocks have been affected during the Svecokarelian orogeny (about 1800 Ma) by metamorphism to the amphibolite facies (Wikström 1976).

The ores of the Doverstorp field occur in several zones in the supracrustal rocks. A zone of quartz-bearing skarn-type iron ores extends for a distance of four kilometres. Several units impregnated with iron sulfides occur parallel to this zone. Magnusson (1960) has suggested that these fahlband units had a paligenetic origin connected with late kinematic granites.

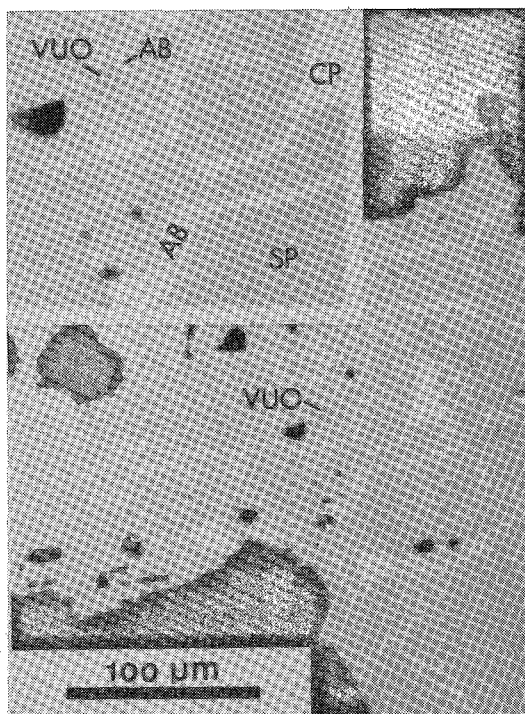


FIG. 2. Vuorelainenite (VUO) in manganoan sphalerite (SP). The granoblastic texture of sphalerite is visible through the chalcopyrite (CP) exsolutions. On the blow-up picture in upper left corner exsolutions of alabandite (AB) and two minute grains in contact with vuorelainenite are shown. Reflected light, oil immersion.

According to this theory, metals were driven out of the sediments and pre-existing sulfide ores and were concentrated outside the migmatite front. The stratiform ore deposits are localized in certain horizons, and suggest a volcanosedimentary origin as postulated by Henriques (1964) and Koark (1962) for other parts of the Bergslagen province. The sulfides appear to form a facies equivalent to oxide iron ores, both originating from essentially a single volcanic stage (Zakrzewski 1982).

The pyrite-pyrrhotite-bearing zone is traceable for a distance of about eight kilometres. Although no mine is presently in operation, the largest one in the ore field, the Sättra mine, has produced about 60,000 tonnes of ore containing 20.5 wt.% S, 21.6% Fe, 54.2% silica and silicates, 0.04% Ni and Co, 0.05% As and 0.28% Zn, in the period 1917-1919 (Tegenren 1924). On the basis of mineral composition and the Zn content, the overall Mn content is estimated to be in the range of 0.1 wt.%.

In the past the sulfide ore has been used in the production of red paint.

The Sättra orebody has a lenticular form with a thickness up to 40 m; it has been explored by means of drill holes for a length of 200 m (Tegengren 1924). Pyrite-pyrrhotite ore occurs as dense disseminations concordant with the enclosing supracrustal rocks, and as massive concentrations up to 6 m thick that are somewhat discordant to the disseminated type. In the discordant type, pyrrhotite dominates over pyrite, suggesting that it has been formed by remobilization of disseminated-type material during regional metamorphism. The presence of an andalusite-cordierite-quartz-muscovite-microcline assemblage in ores allows the conditions of remobilization to be estimated: 2-3 kbar total pressure, and temperature of about 550°C (Dietvorst 1982). The low pressure is suggested

also by the high iron content of sphalerite co-existing with pyrrhotite and pyrite; however, the exceptionally high Mn content (see below) did not permit a more accurate estimate.

MINERALOGY

Minerals thus far recorded from the Sättra mine include pyrite, pyrrhotite, chalcopyrite, sphalerite, galena (Tegengren 1924), alabandite, gudmundite, freibergite, pyrophanite, rutile, spessartite (Zakrzewski 1980) and benavidesite (Oudin *et al.* 1982). Several other mineral species were recognized during the present investigation (Table 1).

*Vuorelainenite*

Vuorelainenite is an accessory mineral in 15 of the 21 polished sections studied. It occurs in pyrrhotite-rich ore as euhedral, single grains, from 5 to 80 μm in diameter, usually at contacts between pyrrhotite and gangue, or between pyrrhotite and grains of rutile and pyrophanite (Figs. 3A, 3B, 4). The association with sphalerite (Fig. 2) is rare. The absence of Mn-bearing minerals (pyrophanite and alabandite) and the presence of titanite (?) is typical for sections devoid of vuorelainenite. There is no apparent correlation with the occurrence of graphite.

Vuorelainenite is opaque in transmitted light. In reflected light the mineral has a brownish grey color, darker than sphalerite. The mineral is isotropic; internal reflections have not been observed. The polishing hardness is higher than for pyrrhotite, pyrophanite and rutile. The microindentation hardness *VHN*<sub>50</sub> of 900 is lower than that of vanadiferous manganochromite (Graham 1978) but higher than that of the Outokumpu vuorelainenite (Long *et al.* 1963). Etch-test reactions have been given for the Outokumpu mineral by Long *et al.* (1963): negative with HCl (1:1), FeCl<sub>3</sub> (20%), HgCl<sub>2</sub> (5%), KOH (40%), KCN (20%) and HNO<sub>3</sub> (1:1) on chromian vuorelainenite; low-Cr vuorelainenite reacts positively with HNO<sub>3</sub> (1:1).

The reflectance in air has been measured with a Leitz MPV microscope photometer using carborundum as a standard (nm, %): 470, 15.7; 546, 15.4; 589, 15.6; 650, 16.2 (for the grain corresponding to analysis 153A4C A in Table 2). This is somewhat higher than for vanadiferous manganochromite (Graham 1978), but the difference is too small to be observed through the microscope even by direct comparison, as seen on grain 153A5 Q (Fig. 4, Q). It confirms the observation of Graham (1978) that, despite the large differences in composi-

TABLE 1. MINERALS OBSERVED AT THE SÄTTRA MINE

Mineral	Abundance*	Average chemical composition	
Bismuth	R	Bi	
Graphite	C	C	
Alabandite	R-C	Mn <sub>0.9</sub> Fe <sub>0.1</sub> S	
Breithauptite	R	NiSb	
Chalcopyrite	C	CuFeS <sub>2</sub>	
Galena	C	PbS	
Marcasite	C-R	FeS <sub>2</sub>	
Pb-Mo sulfide	R	Pb <sub>0.9</sub> Bi <sub>0.2</sub> Fe <sub>0.3</sub> Mo <sub>0.8</sub> W <sub>0.2</sub> V <sub>0.1</sub> S <sub>4</sub>	
Pyrite	M	FeS <sub>2</sub>	
Pyrrhotite	M	Fe <sub>0.85</sub> S	
Sphalerite	C	Zn <sub>0.75</sub> Fe <sub>0.15</sub> Mn <sub>0.1</sub> S	
Arsenopyrite	R	FeAsS	
Benavidesite	R	Pb <sub>4</sub> Mn <sub>0.65</sub> Fe <sub>0.4</sub> Sb <sub>5.6</sub> Bi <sub>0.3</sub> S <sub>14</sub>	
Boulangerite	R	Pb <sub>5</sub> Sb <sub>3.9</sub> As <sub>0.2</sub> S <sub>11</sub>	
Freibergite	R	Cu <sub>7</sub> Ag <sub>3</sub> Fe <sub>1.8</sub> Zn <sub>0.3</sub> Sb <sub>4</sub> S <sub>13</sub>	
Geocronite	R	Pb <sub>7</sub> As <sub>2</sub> Sb <sub>4</sub> S <sub>23</sub>	
Gudmundite	R	FeSbS	
Stannite	R	Cu <sub>1.9</sub> Fe <sub>0.9</sub> Zn <sub>0.1</sub> SnS <sub>4</sub>	
Ullmannite	R	NiSbS	
Ilmenite (?)	R	FeTiO <sub>3</sub>	
Magnetite (?)	R	FeFe <sub>2</sub> O <sub>4</sub>	
Manganochromite	R	Mn <sub>0.85</sub> Fe <sub>0.15</sub> Cr <sub>1.0-1.1</sub> V <sub>0.9-1.0</sub> O <sub>4</sub>	
Pyrophanite	C	Mn <sub>0.8</sub> Fe <sub>0.2</sub> Ti <sub>3</sub> O <sub>9</sub>	
Rutile	C	TiO <sub>2</sub>	
Schreyerite	R	V <sub>1.8</sub> Cr <sub>0.2</sub> Ti <sub>3</sub> O <sub>9</sub>	
Vuorelainenite	C	Mn <sub>0.85</sub> Fe <sub>0.15</sub> V <sub>1.0-1.1</sub> Cr <sub>0.2-1.0</sub> O <sub>4</sub>	
Andalusite	C	Plagioclase	C
Apatite	C	Quartz	M
Biotite	C	RE-minerals	R
Cordierite	C	Spessartite	C
Microcline	M	Titanite (?)	C
Monazite	R	Xenotime	R
Muscovite	C		

\* M - major, C - common but in small quantities, R - rare.

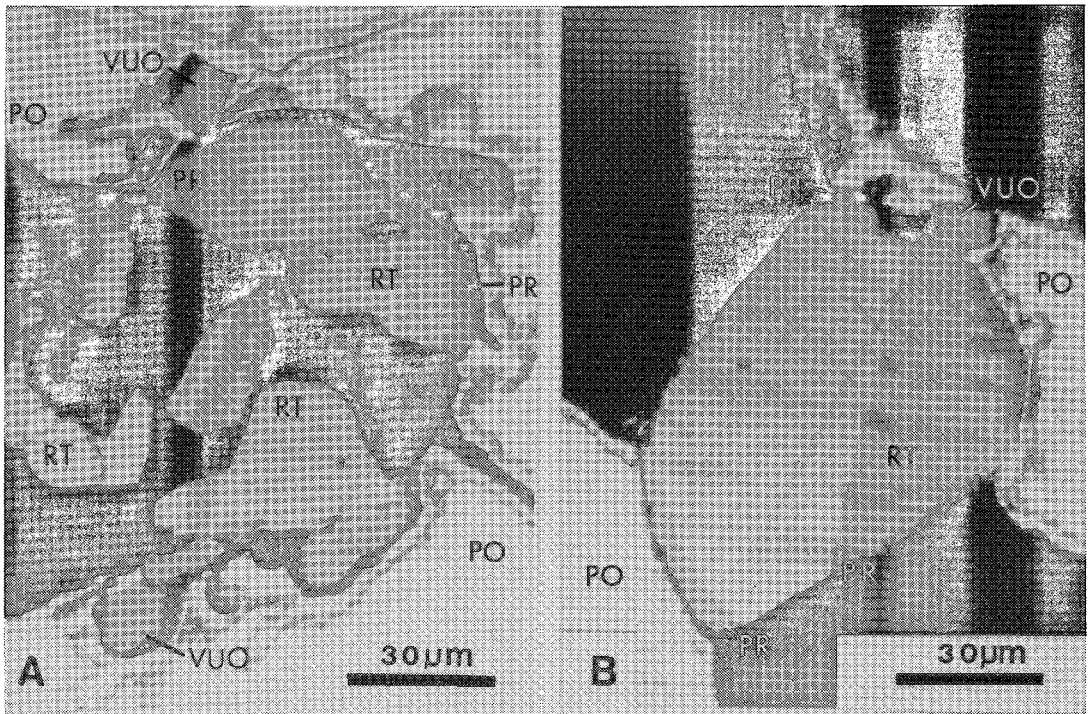


FIG. 3. A, B. Complex intergrowths of rutile (RT), pyrophanite (PR), vuorelainenite (VUO) and pyrrhotite (PO). Note the euhedral grains of vuorelainenite in pyrrhotite, and the pyrophanite rims around rutile grains on the contacts with pyrrhotite.

TABLE 2. RESULTS OF ELECTRON-MICROPROBE ANALYSES OF OXIDES FROM THE SATRA MINE

Mineral	Grain code	Weight %										Atomic proportions								
		TiO <sub>2</sub>	V <sub>2</sub> O <sub>3</sub>	Cr <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	MnO	FeO*	ZnO	MgO	Total	Ti	V	Cr	Al	Mn	Fe	Zn	Mg	O	
Vuorelainenite	Outokumpu**	-	63.3	4.7	-	22.0	7.6	(2.4)	-	100.0										
	153A4 E2	0.6	58.3	5.8	1.4	27.1	5.8	0.5	-	99.5	0.02	1.87	0.14	0.06	0.69	0.23	(0.06)		4	
	153A5 Q3	n.d.	54.5	12.6	n.d.	26.5	5.6	0.6	n.d.	99.8		1.62	0.37		0.83	0.17	0.02		4	
	Outokumpu**	n.d.	53.0	16.1	n.d.	n.d.	n.d.	n.d.	n.d.	-		1.54	0.46						(3)	
	153A4 G	-	52.0	15.8	n.d.	26.1	6.2	0.7	-	100.8		1.53	0.46		0.81	0.19	0.02		4	
	153A4C CF	0.1	47.4	19.5	-	26.4	5.7	0.8	0.1	100.0		1.41	0.57		0.83	0.18	0.02	0.01	4	
	153A4 B	-	46.4	18.7	0.2	26.0	5.8	2.7	0.1	99.9		1.39	0.55	0.01	0.82	0.18	0.07	0.01	4	
	153A4C A	-	40.5	26.3	-	26.5	5.7	0.8	0.2	100.0		1.20	0.77		0.83	0.18	0.02	0.01	4	
	153A4C CG	0.1	36.3	30.6	-	26.5	5.6	0.8	0.2	100.1		1.08	0.90		0.83	0.17	0.02	0.01	4	
	Manganochromite	153A5 M	-	32.0	33.3	-	26.8	5.2	1.0	0.2	98.5		0.97	0.99		0.86	0.16	0.03		4
153A5 Q4		0.2	30.5	35.9	-	26.3	5.3	0.7	-	98.9	0.01	0.92	1.06		0.83	0.17	0.02		4	
Schreyerite	153A5 G	59.9	31.5	5.2	0.3	0.2	1.6	-	-	98.7	2.98	1.67	0.27	0.02	0.01	0.09			9	
	153A4 E	63.0	32.4	1.7	0.2	0.1	1.2	-	-	98.6	3.11	1.70	0.09	0.02	0.01	0.07			9	
	153A4 EA	60.7	35.1	1.9	0.3	0.2	1.5	n.d.	-	99.7	2.98	1.84	0.10	0.02	0.01	0.08			9	
	153A4 F	60.2	36.2	1.0	0.4	0.2	0.7	-	-	98.7	2.98	1.91	0.05	0.03	0.01	0.04			9	
Pyrophanite	153A5 J	52.2	0.1	0.1	-	44.8	2.3	-	-	99.5	0.99				0.96	0.05			3	
	153A4 PJ	52.5	-	-	-	41.8	3.9	-	-	98.2	1.01				0.90	0.08			3	
	153A5 E	50.9	0.6	0.3	n.d.	38.2	8.8	-	-	98.8	0.98	0.01	0.01		0.83	0.19			3	
Rutile																			Nb	
	153A4 F	98.2	0.3	0.1	0.1	0.1	0.3	-	0.5	99.6	0.99									2
	153A5 LA	97.3	1.4	0.1	n.d.	0.1	0.2	-	0.9	100.0	0.99	0.02								2
	153A5 LC	96.7	1.7	0.1	n.d.	-	0.1	-	1.5	100.1	0.98	0.02						0.01		2
	153A5 I	97.3	1.3	2.2	n.d.	0.1	0.6	n.d.	n.d.	101.5	0.97	0.01	0.02							2

\* All Fe taken as FeO \*\* Analyses from Long et al. (1963), ZnO by difference.

tion, reflectance and microhardness do not vary greatly.

Electron-microprobe analyses (Table 2) have been done on the Sättra vuorelainenite with a Cambridge Instruments Microscan 9 using corundum, hematite, rhodonite, olivine, synthetic  $V_2O_5$ ,  $Cr_2O_3$ ,  $ZnO$  and metallic Nb as standards. Apparent concentrations have been ZAF-corrected with the Microscan 9 on-line ZAF program. The atomic proportions (Table 2) have been calculated on the basis of four oxygen atoms in the spinel formula with Mn, Zn and all Fe as divalent, and trivalent V and Cr, in analogy with the data of Graham (1978) and consistent with evidence for reducing conditions. The considerable replacement of vanadium by chromium leads to a continuous series between chromian vuorelainenite and vanadiferous manganochromite, suggesting a complete solid solution between the end members (Fig. 5). Scanning profiles have been obtained on

some selected grains (Fig. 4). They show that there is a great variation in composition even in single grains. The V/Cr ratio decreases from the core towards the rims; it is also higher close to the contacts with pyrrhotite and lowest close to the contacts with silicates. The considerable variations in the trivalent cations are not related to changes in the contents of divalent cations (Mn, Fe, Zn). This contrasts with the results obtained by Graham (1978) on manganochromite from Nairne (South Australia), in which an increasing V/Cr ratio is accompanied by changes of the Mn/(Fe + Zn) ratio (Fig. 5). The analyses of vuorelainenite from Outokumpu (Table 2, Fig. 5) are from Long *et al.* (1963). The balance of these analyses has been assigned to ZnO by Graham (1978), a sound assumption in view of the results on the V/Cr spinels from Sättra and Nairne (Fig. 5). The Mn/(Fe + Zn) ratio for the two analyses from Long *et al.* (1963) is shown as identical in

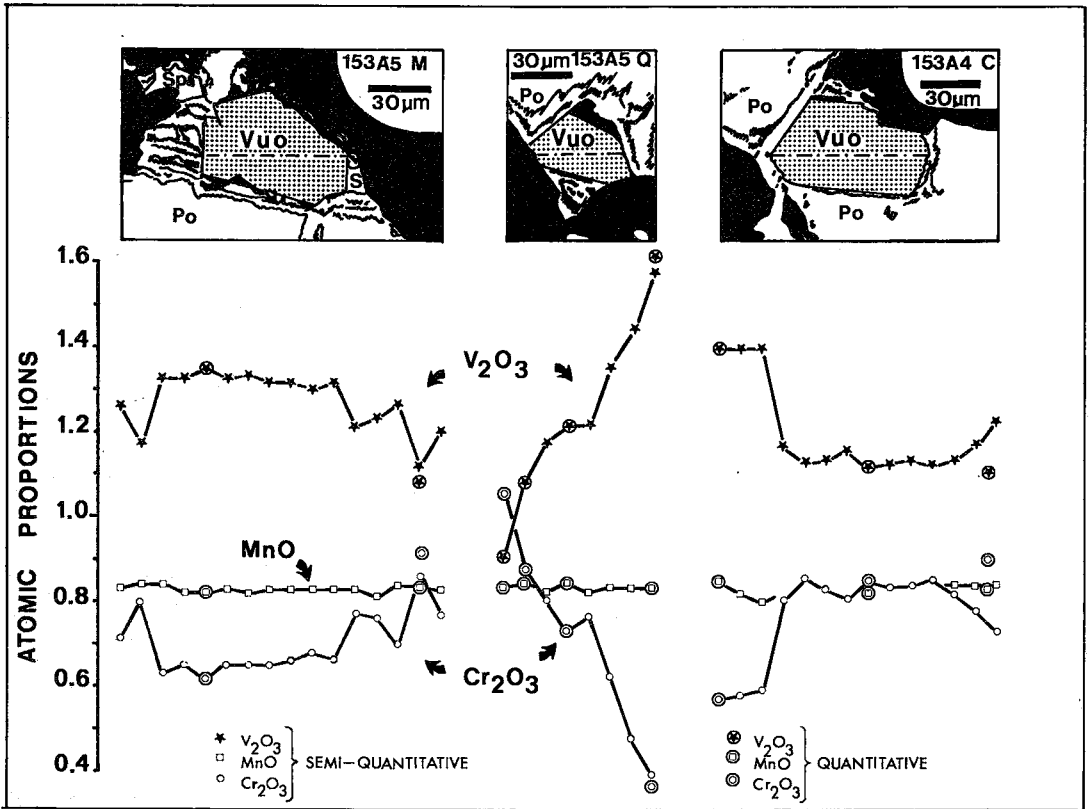


FIG. 4. Scanning profiles across 3 vuorelainenite grains. The left-hand part of grain Q has a manganochromite composition. Location of the profile lines on drawings after microphotographs. Sp is sphalerite, Po pyrrhotite and Vuo vuorelainenite. Quantitative analyses in Table 2 are not always on the profile lines.

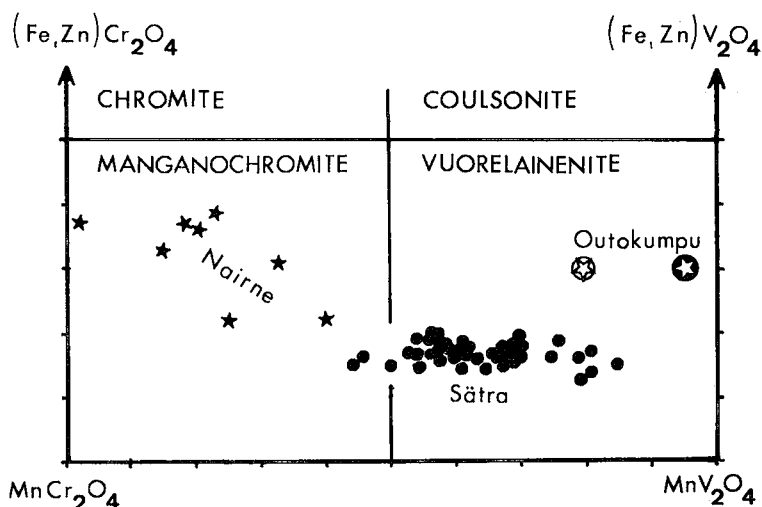


FIG. 5. Chemical composition of spinels in the vuorelainenite-manganochromite series.

Figure 5 because Fe and Mn were reported for only one analysis.

X-ray-diffraction data for the Sätra vuorelainenite have been obtained on fragments removed from polished section 153C4 with a microscope-mounted drill (Verschure 1978). A 57.54-mm-diameter Gandolfi camera has been used with Fe-filtered  $\text{CoK}\alpha$  radiation. The X-ray powder-diffraction pattern of vuorelainenite is presented in Table 3 and compared with those of coulsonite (Radtko 1962), Mn-V spinel (Long *et al.* 1963) and manganochromite (Graham 1978). The pattern is indexed on a cubic cell,  $a$  8.48(5) Å,  $Z = 8$ , by analogy with other spinels. The  $hkl$  indices obtained do not violate the extinction rule for space group  $Fd\bar{3}m$  assigned to minerals of the spinel series. The density, calculated using a composition of  $(\text{Mn}_{0.8}\text{Fe}_{0.2})(\text{V}_{1.5}\text{Cr}_{0.5})\text{O}_4$  and the unit-cell dimension, is 4.64 g/cm<sup>3</sup>.

#### Schreyerite

The Sätra mine is the second occurrence of schreyerite ( $\text{V}_2\text{Ti}_3\text{O}_9$ ). The mineral forms oriented intergrowths with rutile similar to those described by Medenbach & Schmetzer (1978). The polishing hardness of schreyerite is slightly lower than that of rutile. Twinning has been observed. The results of electron-microprobe analyses are in good agreement with those obtained on schreyerite from Kwale (Kenya) by Medenbach & Schmetzer (1978). In grain 153A5 G (Table 2), a considerable degree of

replacement of V by Cr has been detected; this extends the composition of schreyerite in the direction of  $(\text{Cr,Fe})_2\text{Ti}_3\text{O}_9$ . Niobium has not been detected in the Sätra schreyerite.

#### Pyrophanite

Pyrophanite  $\text{MnTiO}_3$  forms oriented intergrowths with rutile along its pressure twins, and also occurs on the contacts between rutile and pyrrhotite (Fig. 3). The mineral contains up to 0.6 wt.%  $\text{V}_2\text{O}_5$  and up to 0.7 wt.%  $\text{Nb}_2\text{O}_5$ . Analytical results are given in Table 2. The compositional range between 5 and 20 mole %  $\text{FeTiO}_3$  may be found even within single grains. In the complex rutile-pyrophanite intergrowths an enrichment in Fe has been observed towards the contacts with rutile. These variations in iron content have no effect on the intensity or color of the internal reflections.

#### Rutile

Rutile occurs as disseminated grains enclosed in silicates and in pyrrhotite (Fig. 3). Electron-microprobe analyses (Table 2) indicate that it contains between 1.0 and 1.7 wt.%  $\text{V}_2\text{O}_5$ ; grain 153A4 F is an exception with only 0.3 wt.%. The high vanadium content is accompanied by a high niobium content. Five measured points give a  $\text{V}_2\text{O}_5/\text{Nb}_2\text{O}_5$  ratio of about 1:1. The Mn content in rutile is consistently low; and Cr is variable, in most cases 0.1 wt.%  $\text{Cr}_2\text{O}_3$ , but also as high as 2.2 wt.%. In a number of

TABLE 3. X-RAY POWDER-DIFFRACTION DATA FOR Fe/Mn-V/Cr SPINELS

hkl	1. FeV <sub>2</sub> O <sub>4</sub>		2. (Mn,Fe)(V,Cr) <sub>2</sub> O <sub>4</sub>		3. (Mn,Fe)(Cr,V) <sub>2</sub> O <sub>4</sub>		4. (Mn,Fe)(V,Cr) <sub>2</sub> O <sub>4</sub>		
	d <sub>obs.</sub>	I/I <sub>100</sub>	d <sub>obs.</sub>	I/I <sub>100</sub>	d <sub>obs.</sub>	I	d <sub>obs.</sub>	d <sub>calc.</sub>	I/I <sub>10</sub>
111	4.79	35	4.88	15	4.89	w	4.90	4.90	2
022	2.93	60	4.14	2	2.99	w	2.985	2.998	4
			2.99	40					
			2.84	1					
113	2.50	100	2.55	100	2.55	s	2.559	2.557	10
222	2.39	4	2.44	2	2.44	w	2.442	2.448	2
004	2.07	80	2.12	25	2.12	vw	2.118	2.120	3
331	1.903	4							
224	1.693	30	1.72	1	1.73	w	1.729	1.731	2
115,333	1.597	90	1.63	40	1.63	s	1.633	1.632	8
044	1.466	95	1.50	60	1.50	s	1.502	1.499	8
135	1.404	6							
026	1.312	10	1.35	1					
335	1.266	25	1.29	2			1.290	1.293	1
226	1.249	18	1.28	1					
444	1.198	8							
117,155	1.162	4							
246			1.13	1					
137,355			1.10	15			1.105	1.104	2
008			1.06	1					
157,555			0.982	8			0.978	0.979	1
a <sub>0</sub> = 8.297 Å		a <sub>0</sub> = 8.47 Å		a <sub>0</sub> = 8.47 Å		a <sub>0</sub> = 8.48 Å			

1. Coulsonite, Lovelock, Nevada, USA (Radtke 1962)
2. Mn-V spinel, now vuorelainenite, Outokumpu, Finland (Long et al. 1963)
3. Manganochromite, Nairne, South Australia (Graham 1978)
4. Vuorelainenite, Sätra mine, Doverstorp, Sweden (this study)

polished sections rutile is rimmed by an alteration product tentatively determined as titanite (?). In this type of ore no pyrophanite or other Mn-bearing mineral is present.

#### Graphite

Graphite has been found in half of the polished sections from Sätra. Usually it occurs as disseminated grains up to 0.5 mm in diameter, but also in larger essentially massive concentrations with minor amounts of sulfides. This type of ore occurs on the mine dumps in blocks averaging 20–30 cm in size.

#### Iron sulfides

Pyrite is the main ore mineral in the Sätra mine, followed by pyrrhotite. Marcasite only occurs as an alteration product of pyrrhotite. Pyrite occurs as large (up to several mm), euhedral and subhedral grains, often anomalous-

ly anisotropic, surrounded by anhedral masses of pyrrhotite. Pyrrhotite is intergrown with chalcopyrite, sphalerite and other sulfides and sulfosalts. There is a clear spatial relationship between pyrrhotite and vuorelainenite-manganochromite (Figs. 3, 4) and schreyerite.

#### Chalcopyrite, sphalerite, alabandite

Chalcopyrite and sphalerite are genetically connected with pyrrhotite and have been found as accessory minerals in almost every polished section. Sphalerite is extremely rich in manganese (Table 4), and contains exsolutions of alabandite (Fig. 2, Table 4) that have been described by Zakrzewski (1980). Sphalerite probably is the most important manganese carrier in the Sätra deposit.

The occurrence of galena in the Sätra mine has been noted by Tegengren (1924). Galena occurs as an accessory mineral in single grains and in aggregates that sometimes reach a size

TABLE 4. RESULTS OF ELECTRON-MICROPROBE ANALYSES OF SULFIDES AND SULFOSALTS FROM THE SÄTRA MINE

Mineral	Grain code	Weight %											Atomic proportions								
		S	Mn	Fe	Cu	Pb	Zn	Ag	Bi	Sb	Others	Total	S	Mn	Fe	Cu	Pb	Zn	Bi	Sb	Others
Pyrrhotite	153A4 MP	39.6	0.1	60.1			0.4			-	Co 0.1, Ni, Sn -	100.3	1	0.87							
	153A4 NP	40.4	-	60.2	0.1		0.2		-	-	Co 0.1, Ni 0.1, Cd 0.4, Cd 0.2, Sn -, Cd, Sn, -	100.1	1	0.86							
Sphalerite	153A4 SD	33.5	7.0	10.4	0.2		47.9					99.4	1	0.12	0.18		0.70				
	153A4 N	33.4	4.1	7.4	0.1		54.7					99.9	1	0.07	0.13		0.80				
Alabandite	153A4 A	36.4	57.6	5.0	0.3		1.3		-			100.6	1	0.92	0.08		0.02				
Galena Pb-Mo sulfide	153A4 PP	13.6	0.1	-	-	83.3		0.2	0.5	-	Cd, Sn -	97.7	1		0.95		0.01				
	153A4 H	25.3	0.1	3.7		37.1		-	6.3		W 6.2, Mo 14.9, V 0.9, Cd -, Hg -, Ni 27.1, As 0.5, Sn 27.8, In -	*94.5	4	0.3	0.9	0.2			Mo 0.8, W 0.2, V 0.1		
Gudmundite	153A4 R	15.8	0.1	26.1			0.1	-	0.5	57.4	Cd -	100.0	1	0.95					0.96		
	153A4 AB	15.3		26.3	0.1		0.3		-	57.8	Hg -	99.8	1	0.99		0.01			1.00		
Ullmannite	153A4 J	15.0		0.2						57.1	Ni 27.1, As 0.5, Sn 27.8, In -	99.9	1	0.01					1.00	Ni 0.99, As 0.01	
	153A8 S	29.9		12.0	27.9		1.4					99.0	4	0.92	1.88		0.09			Sn 1.00	
Benavidesite	153A4 SS	21.8	1.8	1.1	0.2	39.7	0.2	0.1	2.4	33.5	Hg, Sn, Te -	100.8	14	0.67	0.41	0.06	3.95	0.06	0.24	5.67	Ag 0.02
	153A4 SZ	21.5	1.8	1.0	0.2	40.2	0.1	-	3.6	32.3	Hg -	100.7	14	0.68	0.37	0.07	4.05	0.03	0.36	5.54	
Freibergite	153A4 WA	23.0	0.2	5.5	25.0		1.3	18.3	0.3	26.8	Cd, Hg, Sn -	100.4	13	0.07	1.79	7.13		0.36	0.03	3.99	Ag 3.07
	153S2 BC	18.6		0.1		54.8		0.1		25.1	As 0.7, In -	99.4	11	0.03		5.02				3.91	As 0.18, Ag 0.02
Geocronite**	153S2 DE	17.4		0.1		68.0		0.1		9.1	As 4.5	99.2	23	0.08		13.91				3.17	As 2.55, Ag 0.04
	153S2 F	16.8		0.1		67.0		0.1		12.9	As 2.4	99.3	23	0.08		14.20				4.65	As 1.41, Ag 0.04

open space means not determined; - not detected; \* semiquantitative analysis; \*\* analyst C. Kieft

of several millimetres. Chemically it is characterized by the presence of Ag and Bi (Table 4). In a few cases galena is accompanied by a number of rare minerals: benavidesite, freibergite, ullmannite, gudmundite, stannite, breithauptite, arsenopyrite, native bismuth and an unknown Pb-Mo sulfide.

All the rare minerals associated with galena occur as grains averaging 10–30  $\mu\text{m}$  in size, only in a few cases reaching 100  $\mu\text{m}$ . Their determination has been confirmed by electron-microprobe analyses (Table 4). "Geocronite" grain F (Table 4) has an As/(As + Sb) ratio of 0.23, which is lower than the limiting value of 0.33 suggested for the extent of Sb substitution for As in geocronite (Birnie & Burnham 1976). A similar low As/(As + Sb) ratio has been obtained on geocronite from Jiulong, China (Anonymous 1978).

#### Benavidesite

The Sätra mine is one of the type localities (with Uchucchacua, Peru) of benavidesite Pb<sub>2</sub>(Mn,Fe)Sb<sub>6</sub>S<sub>14</sub>, the Mn analogue of jamesonite (Oudin *et al.* 1982). The mineral occurs as rounded grains up to 50  $\mu\text{m}$  in diameter associated with freibergite, galena, gudmundite, sphalerite, native bismuth and spessartite (Fig. 6).

#### Unnamed Pb-Mo sulfide

A small inclusion with a diameter of 3  $\mu\text{m}$  in ullmannite has an unusual composition (Table 4). The optical properties of the mineral (color, reflectance, anisotropy) are very similar to those of molybdenite. The grain shows a spherulitic structure. The optical properties and the necessarily semiquantitative analytical results point to a mineral having a molybdenite-derivative structure analogous to those of castaingite CuS $\cdot$ 2MoS<sub>2</sub> (Schüller & Ottemann 1963), femolite FeS $\cdot$ 5MoS<sub>2</sub> (Skvortsova *et al.* 1964) and several Mo-Cu-S phases (CuS $\cdot$ MoS<sub>2</sub>, 2CuS $\cdot$ MoS<sub>2</sub>, and CuS $\cdot$ MoS<sub>2</sub>) described by Salamon (1976) from the Kupferschiefer-type Cu deposits of southwest Poland.

#### Other minerals

A number of phosphates have been found, including apatite, monazite and xenotime, along with unidentified rare-earth-element minerals. Graham (1978) found similar minerals associated with manganochromite in the Nairne deposit.

#### DISCUSSION

Manganese-(vanadium, chromium) spinels



also occur in the Outokumpu (Finland) and Nairne deposit (South Australia). At Outokumpu (Long *et al.* 1963) vuorelainenite and chromian vuorelainenite occur as grains up to 100  $\mu\text{m}$  in size closely associated with pyrrhotite and graphite. Vuorelainenite coexists with karelianite ( $\text{V}_2\text{O}_5$ ), which contains up to 1.1 wt.% Mn. The overall content of Mn in the Outokumpu deposit is 0.05 wt.% (Mikkola & Varsänen 1972) and that of vanadium 0.02 wt.% (Long *et al.* 1963). The Outokumpu exhalative-sedimentary ore deposit has been metamorphosed under amphibolite-facies conditions (Gaal *et al.* 1975) and has undergone considerable remobilization (Mikkola & Varsänen 1972).

The manganochromite occurrence in tension-gash veins at Nairne (Graham 1978) is very similar to the Sätra mine because of the presence of spinel on the contacts between pyrrhotite and gangue, the association with alabandite and graphite, and the minor elements in rutile (0.7 wt.% Cr, 0.25% V and 0.2% Mn). The overall content of manganese in the Nairne deposit is 0.1 wt.% and that of vanadium about 0.02 wt.% (Nenke 1972 in Graham 1978). The sedimentary Nairne deposit has been metamorphosed and remobilized under amphibolite-facies conditions (Graham 1978).

Schreyerite at Kwale (Kenya) also occurs in highly metamorphosed gneisses in association with minerals enriched in vanadium (rutile, kornerupine, kyanite, sillimanite, tourmaline) along with graphite, pyrrhotite, chalcopyrite and pentlandite (Medenbach & Schmetzer 1978).

An unnamed Ti-V-Cr oxide has been described from Bidjovagge (Norway) in an albite-rich rock with pyritic Cu ore containing REE minerals, vanadiferous rutile and V-Cr-bearing magnetite (Mathiesen 1970).

A comparison of the Sätra, Outokumpu and Nairne deposits suggests that the minerals of the vuorelainenite-manganochromite series have been formed in a sulfide-rich environment [an extremely high  $P(\text{S}_2)$  is indicated by the presence of alabandite] under highly reducing conditions (indicated by the presence of graphite) in ores that have been remobilized under amphibolite-facies conditions. Similar conditions are probably also valid for the occurrence of V-Ti-Cr oxides at Kwale and Bidjovagge. Another conspicuous characteristic of all occurrences is the great number of elements present, a feature reminiscent of Kupferschiefer-type deposits.

The Mn-(V, Cr) spinels are associated with V and Ti oxides (rutile, pyrophanite, karelianite, schreyerite) whose minor element contents point to a close genetic relationship with the

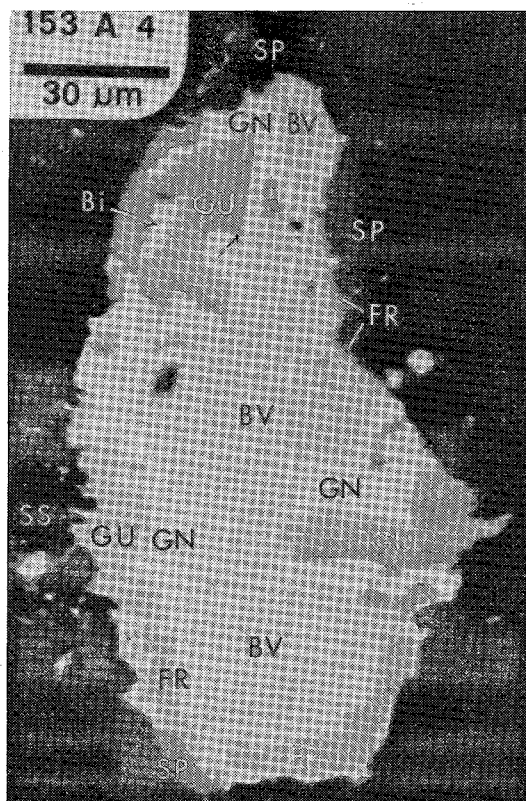
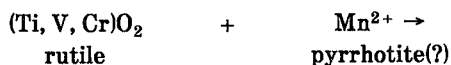


FIG. 6. Benavidesite (BV) grains rimmed by galena (GN) and freibergite (FR). Gudmundite (GU) is always separated from benavidesite by galena. SP is sphalerite, Bi native bismuth and SS spessartite.

spinel. The interpretation of this relationship, however, is equivocal. Graham (1978) has proposed that the Cr-V-Mn-bearing rutile is formed from spinel, but the textural relations of the Sätra material allow for an opposite interpretation. The restriction, in all occurrences, of the vuorelainenite-manganochromite minerals to the contacts between pyrrhotite and gangue strongly suggests formation of the spinels by an interaction between the sulfide and silicate or oxide phases.

The Sätra vuorelainenite possibly was formed during retrograde metamorphism. The drop of temperature caused a release of Mn from the sulfides, as indicated by the exsolution of alabandite from sphalerite. By analogy, vanadium and chromium were released from relatively oversaturated rutile in the form of  $\text{V}^{4+}$  and  $\text{Cr}^{4+}$ , reduced to trivalent ions that reacted with  $\text{Mn}^{2+}$  according to a possible reaction (unbalanced):



$\text{TiO}_2 + \text{MnTiO}_3 + \text{Mn(V,Cr)}_2\text{O}_4 + \text{V}_2\text{Ti}_3\text{O}_9$   
rutile pyrophanite vuorelainenite schreyerite

The fact that pyrophanite is associated with rutile in contact with pyrrhotite (Fig. 3) and not with rutile enclosed by silicates further suggests that pyrrhotite was the primary host of manganese prior to the formation of vuorelainenite.

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