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On the geology and mineralogy of the occurrence of native antimony at Seinäjoki, Finland

by Veikko Pääkkönen

Geologinen tutkimuslaitos • Otaniemi 1966

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ON THE GEOLOGY AND MINERALOGY OF THE OCCURRENCE OF NATIVE ANTIMONY AT SEINÄJOKI, FINLAND

BY

VEIKKO PÄÄKKÖNEN

WITH 53 FIGURES AND 17 TABLES IN TEXT AND ONE APPENDIX

GEOLOGINEN TUTKIMUSLAITOS
OTANIEMI 1966

ABSTRACT

The history of the discovery of the antimony mineral occurrence at Seinäjoki is presented in the introduction. The results of the lithological and geochemical investigations are represented by diagrams.

The general geological features and especially the tectonic circumstances of the antimony ore occurrences are described by maps and profiles. The native antimony and sulfide mineralization of the ore zone is elucidated and pictured by photographs.

On the basis of investigations carried out in the years 1955—1958, the ore reserves of the deposit are less than 500 000 tons and the tenor of ore, too, is so modest (Sb = 0.30 % — 2.63 %) that the deposit today (1966) has no commercial significance. Gold and tungsten have been traced.

According to comparisons with other antimony occurrences in the world the ore minerals of the deposits in question were crystallized at temperatures approaching the high-hydrothermal phase.

Helsinki 1966. Valtioneuvoston kirjapaino

ERRATA

p 55 line 25 occurs for occur

p 56 lines 1 and 2 changed

p. 59 TABLE 15 to be substituted by the following

	Weight per cent	Molecular proportion	Weight norms		or: ab: an
SiO_2	64.62	10 755	Q	23.10	
TiO_2	0.60	75	or	7.35	13.15
Al_2O_3	15.80	1 550	ab	30.94	55.36
Fe_2O_3	0.49	31	an	17.60	31.49
FeO	4.76	663	en	7.46	100.00
MnO	0.08	11	fs	7.34	
MgO	3.00	744	ms	0.15	
CaO	3.99	711	cor	1.99	
Na_2O	3.66	590	mt	0.72	
K_2O	1.24	132	il	1.14	
P_2O_5	0.12	9	ap	0.31	
CO_2	0.21	48	$CaCO_3$	0.48	
H_2O+	1.03	611	H_2O	1.09	
H_2O-	0.07				
Cu	0.02	3	Cu	0.02	
S	0.02	6	S	0.02	
	99.71			99.71	
Sb	0.00(5)				

CONTENTS

PREFACE

The field operations in the Seinäjoki area were carried out in connection with the investigation program of the Exploration Department of the Geological Survey in the years 1951—1958. I had the opportunity of taking part in this work from the very beginning and of carrying out fairly thorough laboratory investigations of the collected material. For valuable support in many ways during the course of the work, I extend my thanks to Professor Aarno Kahma, chief of the Department.

I am indebted to Professor K. J. Neuvonen of the University of Turku for valuable criticism and suggestions given me during the course of the work.

Professor Vladi Marmo, Director of the Geological Survey, showed continued interest in all phases of the study and kindly accepted my paper for publication in the series Bulletin de la Commission géologique de Finlande.

I am grateful also to all the persons who assisted me in the field and to my colleagues on the staff of the Geological Survey for lending me a hand in the work. Especial thanks go to Miss Karin Dahl for the graphical figures and maps.

It also gives me pleasure to acknowledge my appreciation to Mr. Paul Sjöblom, M. A., who translated the main part of the manuscript into English, and to Mrs. Gillian Häkli for revision of the completed manuscript.

Otaniemi, August 1966

Veikko Pääkkönen

INTRODUCTION

Location

This paper deals with an occurrence of antimony ore in the area of Seinäjoki, which is situated in the western part of central Finland (Fig. 1). More precisely stated, antimony-bearing minerals have been found chiefly at Törnävä, roughly 4 km to the south of the railroad station of Seinäjoki. The Törnävä locality, which lies on an average 60 m above sea level, is rather flat, partly inhabited and weakly forested. The urban district does not touch the zone found to contain antimony. The locality will apparently be set aside as a public park for the most part, but in the immediate vicinity are a church, cemetery, elementary school, old peoples' home and the old buildings belonging to the Törnävä estate. Across the ore prospect toward the north flows the Seinäjoki river, which gave the community its name. The motor highway running south from the town passes through Törnävä.

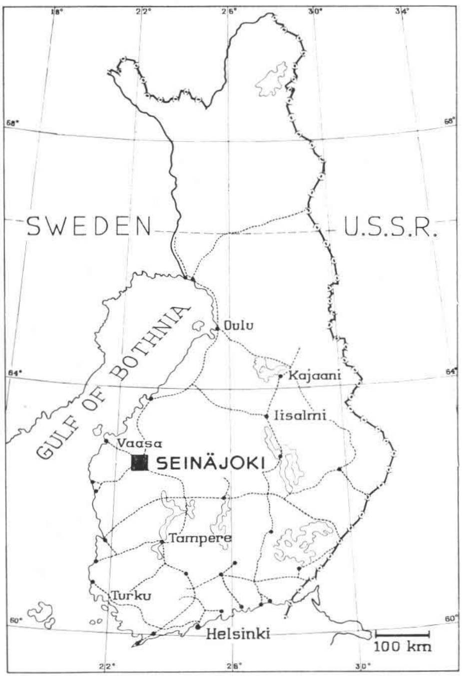

FIG. 1. Location map.

Report of the discovery

Earlier studies

The first indications that antimony minerals exist in the Törnävä locality of the Seinäjoki district came to the attention of the Geological Survey as early as 1936. In that year a pocket of quartz turned up in the macadam quarry of Satamo, south of Törnävä, which in addition to chalcopyrite and pyrrhotite contained an antimony-bearing fahlerz mineral (Saksela 1952). The occurrence was so small, however, that it was significant only as a mineralogical curiosity.

In the autumn of 1951 some sharp-edged, rusty rock fragments, found beside the Törnävä highway, proved on closer investigation to contain not only pyrrhotite and arsenopyrite but also stibnite. Analysis revealed that the specimen contained a trifle gold (0.7 g/tn) besides its very small content of antimony (0.79 %). The prospect was regarded then as unimportant and attracted no further attention.

Ore boulder find of Malinen

Interest revived, however, when in the autumn of 1953 the Geological Survey received from Törnävä a specimen of silicified rock in which native antimony was present both as an impressive pocket and as a coarse dissemination. This boulder was found on the eastern side of a new building when farmer Jopi Malinen was clearing out his yard. The metal-bearing tip of the rock rose up only about 10 cm above the surface of the ground, which consists of till, but when dug up it measured 20 × 20 × 50 cm and weighed an estimated 70 kg. According to report, approximately half the boulder was substantially metallic and the other half almost completely lacking in ore or with only a weak scattering of it. The part rich in ore mineral proved on the basis of the specimens obtained from it to contain about 50 % native antimony. Consequently, it was not difficult to obtain pure pieces of metal as samples. To demonstrate the high grade of his find, Jopi Malinen sent the Geological Survey a chunk that, on account of its extraordinary purity, was judged to be metallic antimony obtained as a factory product. Such products had previously been met with several times in different localities in Finland, but always in places where a piece of metal could have found its way as a result of industrial activity. No precise conception of the boulder could any longer be gained when geologists came to investigate it, as the rock had been completely broken up and a large proportion of the best pieces had been passed on to various people as interesting specimens. Still, what was left of the rock revealed that the native antimony occurred partly veinlike, partly as pockets varying in diameter between five and ten centimeters (Fig. 2).

Malinen's boulder is schist approximating quartzite, in which both small-grained (0.1 mm) and coarser-grained (1 mm) quartz with a prominent undulating extinction occur in zones. The diameter of the grains of the quartz veins and pockets intersecting quartzite ranges between five and ten millimeters. Likewise they have a strong undulating extinction. The most abundant content of native antimony is concentrated around these quartz bodies and weakens farther in the quartzite schist, where also stibnite and arsenopyrite appear in minor amounts, a few grains of gudmundite, and finally unaltered, bright but ragged grains of pyrrhotite.

The arsenopyrite mostly occurs, according to its fashion, as separate idiomorphic grains but often also as inclusions in native antimony. Unchanged chalcopyrite is

FIG. 2. Specimen of Malinen's boulder. Light grey is native antimony and dark grey is chiefly quartz. About half of the natural size. Photo E. Halme.

present to a slight extent in the corners of a few pyrrhotite grains which have been altered to marcasite for the most part. In the quartz vein itself there are only a few small grains of antimony at the edges of quartz grains. The quartzite, furthermore, contains a considerable amount of small-grained and partially shredded epidote, which is situated either as rows of grains parallel to the schistosity or as clusters of grains stretched in the same direction. In addition, one can observe a few small plagioclase grains and bits of muscovite.

The native antimony of Malinen's boulder contains 3.74 % arsenic, 3.0 g of gold per ton, 2.5 g of silver per ton and, according to spectrographic analysis 0.008 % bismuth as well as traces of silicon, aluminium, iron, calcium, magnesium and copper. The specific gravity of this native antimony is 6.62. Near the metallic pocket the country rock in the boulder contains 0.44 % antimony, and 0.6 g/t of silver but no gold at all.

FIG. 3. Outcropping mica gneiss with glacial striations (N 12°—37° W) and an older groove (N 82° W). 1/10 natural size. Site: Törnävä, bed of brook 30 m south of the spot where Malinen's boulder was found.

Lithologic stone counts

Since the specimens proved to come from an erratic block (Malinen's boulder), systematic ore prospecting was started in the area. It was immediately ascertained that the antimony- and gold-bearing rock fragments, met with along a stretch of about 40 meters by the roadside, had been quarried from local bedrock at Törnävä. Many rock fragments containing antimony minerals were also found in nearby stone fences, having evidently been broken off local outcrops by glacial erosion. Observations on boulder distribution indicated that the antimony mineralization extended in an east-west direction. Nearly the same trend was shown by the schistosity of the rocks in exposures.

As at first simply a boulder find was involved, the investigation started out by concentrating only on observations of boulders and glacial striae on exposures (Fig. 3). Thereby a more accurate map of the region's bedrock could be drawn, while many stone counts threw light on the transportation of material as well as enabling boulder maps (Fig. 4—8), which added to the knowledge of the bedrock, to be worked out. It was ascertained that the boulders were mostly of local origin and that only about 10 % of them had been transported some distance. It would seem evident, therefore, that the parent rock from which Malinen's boulder had been broken off could not be far away. Since, however, in spite of thorough searching, no sister fragments have been found, it must have come from some small, isolated vein or pocket without any appreciable practical significance. One such one inch native antimony vein has indeed

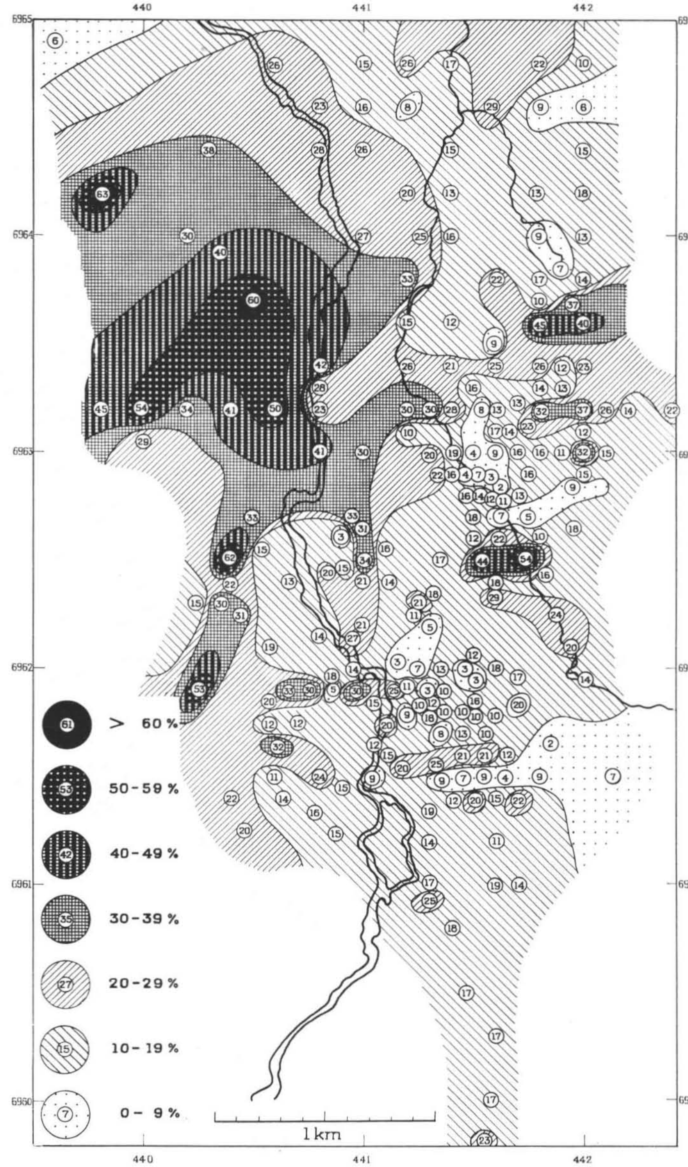

FIG. 4. Percentile content of pegmatite granite stones in till of the Kivistönmäki and Törnävä areas.

been discovered on the western side of the river, at the site of drill hole no. 22, which proves that the ore occurrence of Törnävä extends westward.

The distribution of porphyrite blocks in till (Fig. 6) shows that the moraine was transported from the north-west.

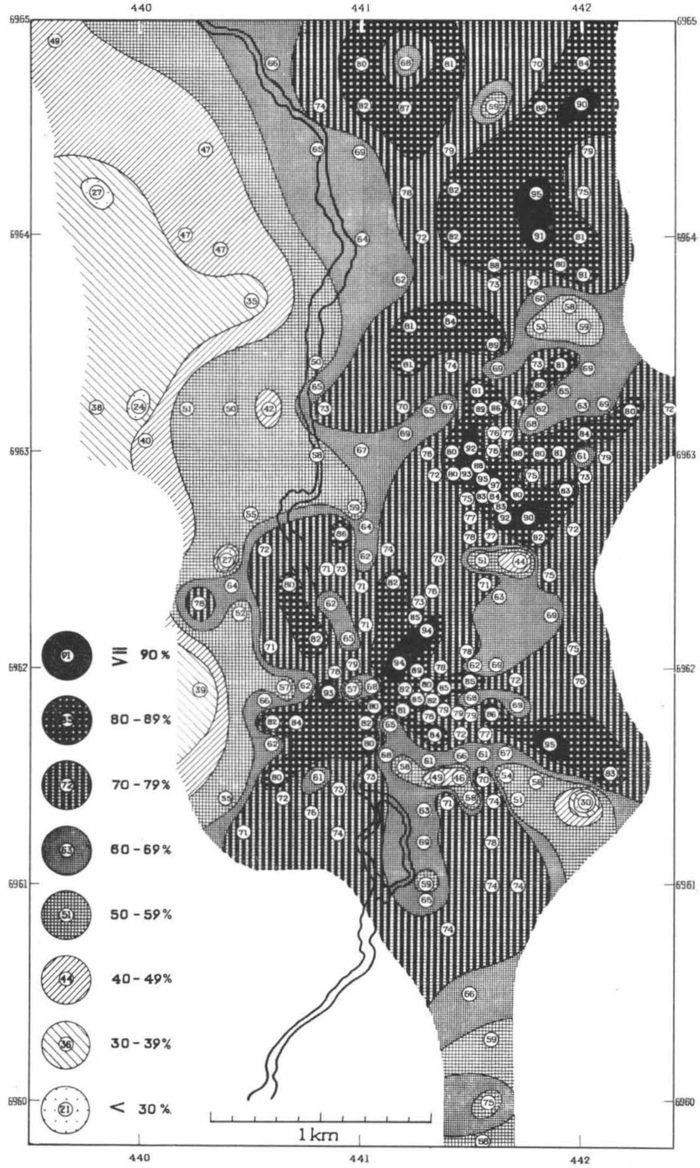

FIG. 5. Percentile content of mica gneiss and mica schist stones in till of the Kivistönmäki and Törnävä areas.

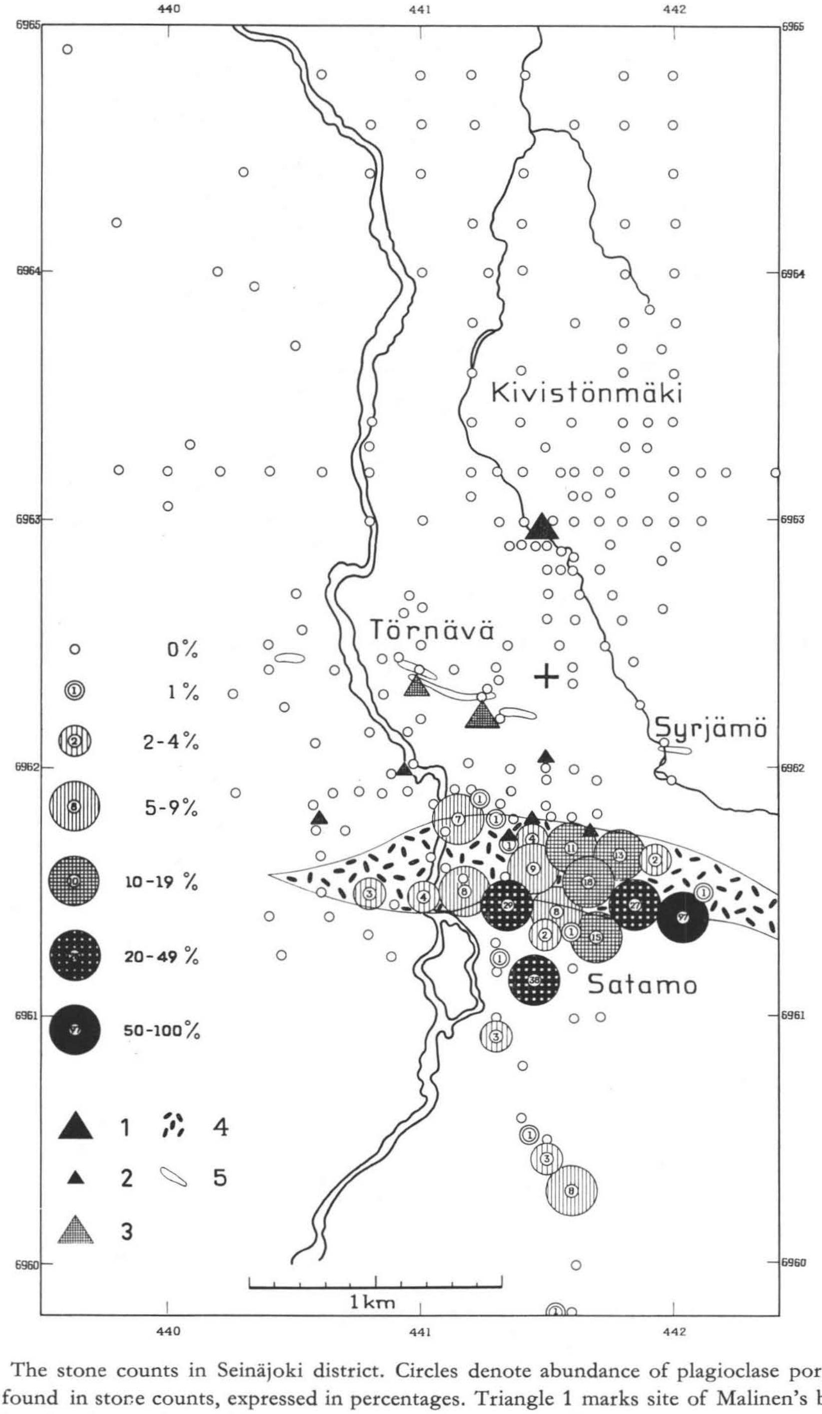

FIG. 6. The stone counts in Seinäjoki district. Circles denote abundance of plagioclase porphyrite blocks found in stone counts, expressed in percentages. Triangle 1 marks site of Malinen's boulder containing abundant native antimony. Triangle 2 marks the sites of other finds of erratic antimony-bearing blocks. Triangle 3 marks a spot where several blocks containing antimony minerals have been found. 4 stands for plagioclase porphyrite in bedrock, 5 for antimony-bearing bedrock.

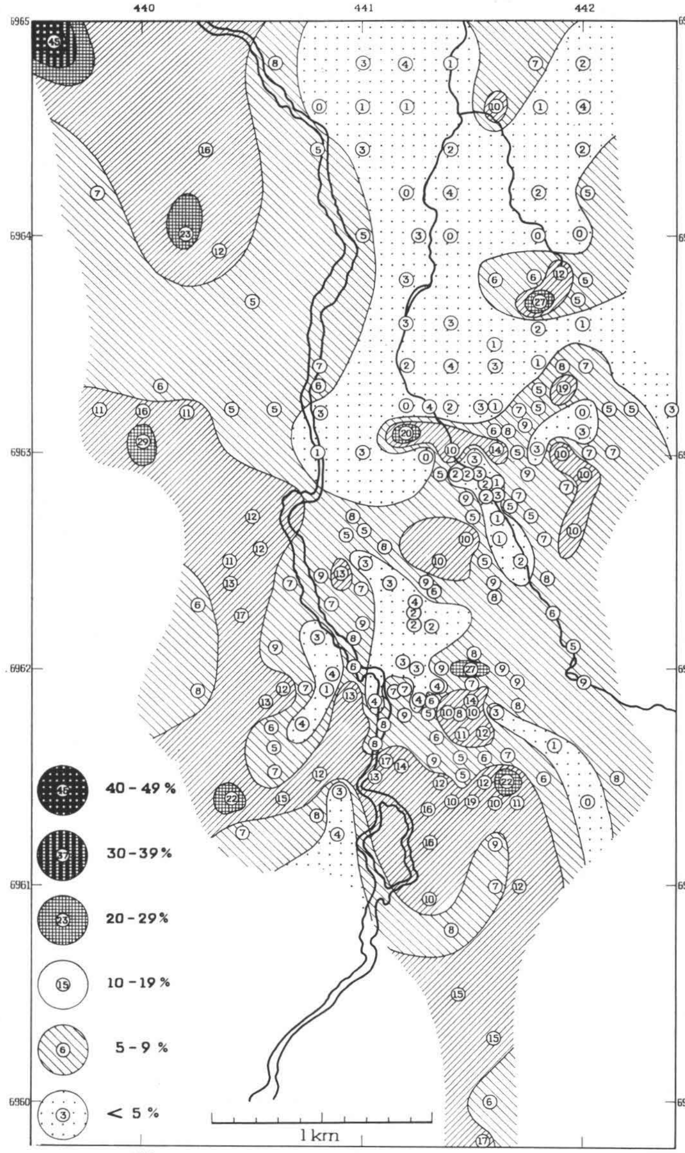

FIG. 7. Percentile content of granite and granodiorite stones in till of the Kivistönmäki and Törnävä areas.

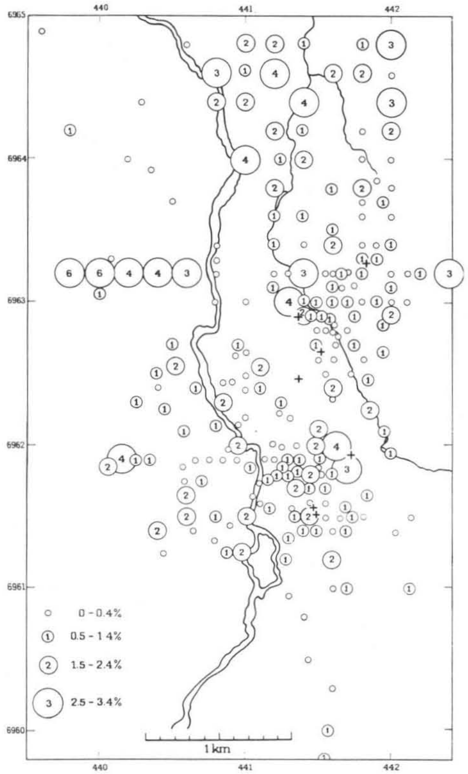

FIG. 8. Percentile content of quartzite stones in till of the Kivistönmäki and Törnävä areas. Cross (+) denotes acid volcanite.

Geophysical investigations

Since an airborne magnetic survey had traced a weak anomalous zone in the Törnävä area and the rocks found along the roadside which contained antimony minerals also had a slight content of pyrrhotite, efforts were made to determine the trend of the ore deposit by electromagnetic and magnetic measurements carried out on the ground. Weak anomalous zones were registered (Fig. 9), some of which run across the spot where antimony mineral-bearing samples had been obtained earlier. In the light of bedrock observations, the most marked electromagnetic anomalies appeared to be caused by weakly pyrite-bearing graphite phyllite. On the other hand, at the point where the weak electromagnetic and magnetic anomalies meet, there occurs in addition to a poor dissemination of pyrrhotite also a slight content of antimony mineral, as was noted in the rock exposed during excavation work in 1955. Since the diamond drillings were made at points selected with these circumstances in view, the ore occurrence could be followed for a distance of several hundred meters. The points drilled indicated a significant antimony content only in exceptional cases, and the content of precious metals likewise remained insignificant. As both farther north

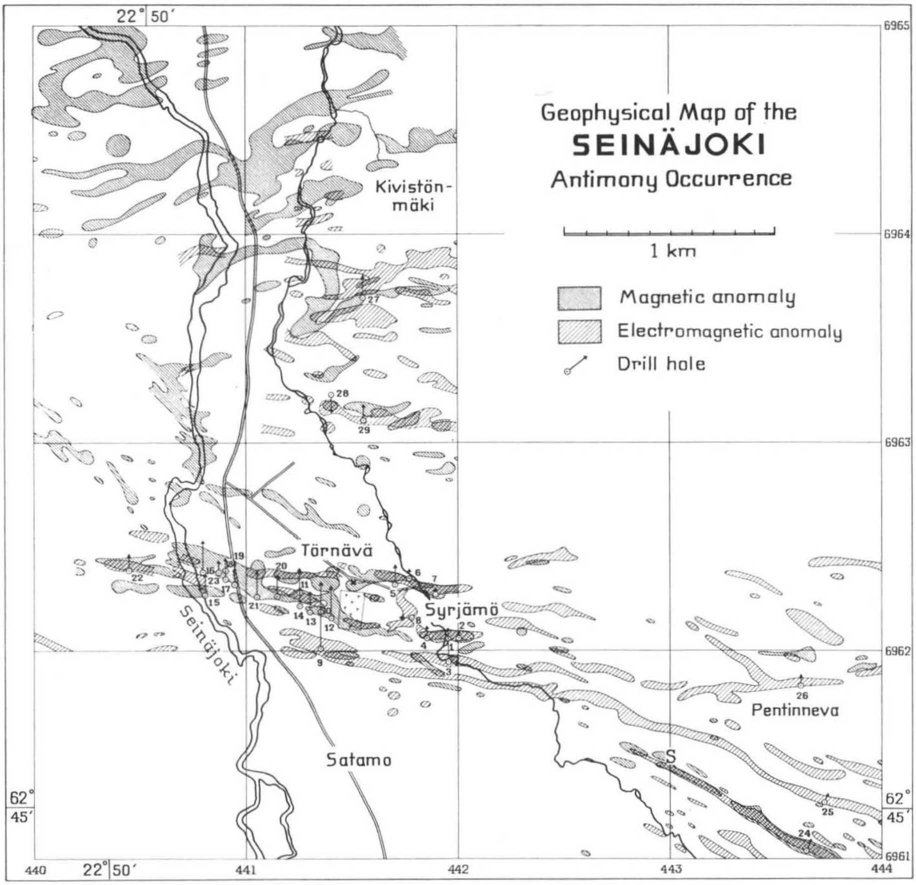

FIG. 9. Magnetically and electromagnetically investigated area with the sites of the drill holes. Magnetic anomaly 500—2000 γ. Electromagnetic anomaly 1—2 %.

and farther east there existed combined magnetic and electromagnetic anomaly zones, a few trial drillings were carried out in these areas; but only weak occurrences of pyrrhotite and graphite could be detected.

Geochemical investigations of the till

The site where Malinen's boulder was found lies some 800 m to the north of the Törnävä antimony ore prospect — that is, in the opposite direction from what one would expect in view of glacier movement during the Ice Age. Also the fragment differs somewhat from the ore types met with in the bedrock. It is not plausible that it originated in the known ore-bearing zone. It is possible that farther north there are other deposits of antimony minerals, in which the ore might be of an appreciably superior grade to that which has been unearthed in the area investigated and better correspond to the type represented by Malinen's boulder. As the geophysical anomalies at this site proved to be due only to pyrrhotite and graphite, it was necessary to resort to geochemical investigation (*cf.* Sainsbury 1957, Kauranne 1958). Preliminary analyses of the till samples collected from the areas lying both to the north and to the south of the site of Malinen's find yielded promising indications of the presence of arsenic, antimony and even tungsten in the ground. To further investigate the geochemical occurrence of antimony and tungsten, samples were taken at 70-m intervals with a ground auger from an area covering 1.5 km², largely representing the vicinity of Kivistönmäki, whence Malinen's boulder most probably originated.

The analytic results yielded by 326 samples (Figs. 10—15) show that arsenic, antimony and tungsten occur in the till in the area of the investigation in larger amounts than is general in Pohjanmaa (Tables 1 and 2). Weak concentrations are to be noted, but their sporadic occurrence sooner suggests qualitative variableness of the till samples than any enrichment of the ore content. Also the alternation of zones of schist and pegmatite seems to have a bearing on the variation in the metal content of the till. Upon comparing the metal contents obtained with the sampling depths and the nature of the sample deposits, one will notice a clear increase in the copper, zinc and arsenic contents with sampling depth (Fig. 16) and clayeyness (Fig. 17 and Table 1), whereas the antimony, lead and tungsten show this tendency only to a slight degree.

Both the electromagnetic and, especially, the magnetic anomaly zones (*cf.* Fig. 18) also appear to coincide largely with the maxima of copper, zinc, lead and arsenic. This phenomenon can be attributed to the scattered occurrences of pyrrhotite in the schist zones combined with the fairly common presence of chalcopyrite and sphalerite. Electromagnetic and magnetic anomaly zones do not coincide equally well with the maxima of tungsten and antimony. The occurrence of tungsten and antimony is highly sporadic and caused by occasional scheelite and arsenopyrite grains respectively.

In Table 2 the mean values yielded by till sampled along the highways of central and southern Pohjanmaa are presented. These values show the general tendency except for the five-fold value yielded by lead which is obviously due to the contamination of the roadsides by gasoline containing lead.

TABLE 1

Mean values for certain metals, expressed in millionths (ppm), contained in soil deposits at Kivistönmäki, Seinäjoki

326 samples	Sb	W	As	Pb	Cu	Zn
Sand	3.4	0.7	6.5	8.6	18.8	57.0
Clay	3.5	9.1	9.5	8.8	29.0	75.2
Till	3.8	5.3	6.3	8.2	15.9	52.5
	3.6	5.0	7.4	8.5	21.2	61.6

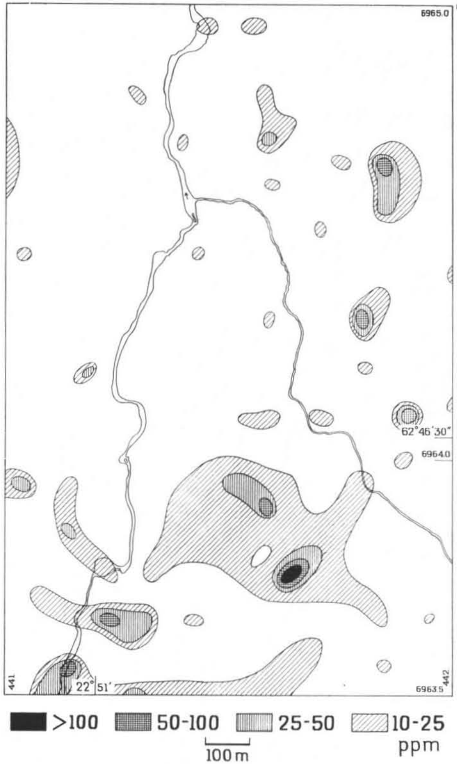

FIG. 10. Arsenic content of soil in ppm, Kivistönmäki area.

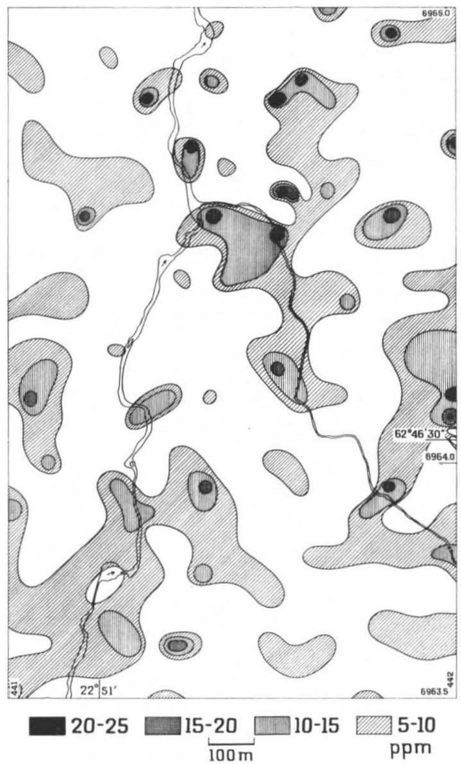

FIG. 11. Antimony content of soil in ppm, Kivistönmäki area.

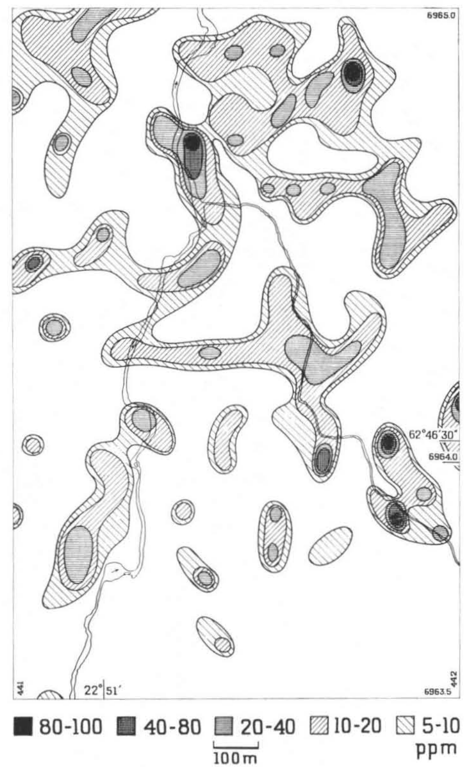

FIG. 12. Tungsten content of soil in ppm, Kivistönmäki area.

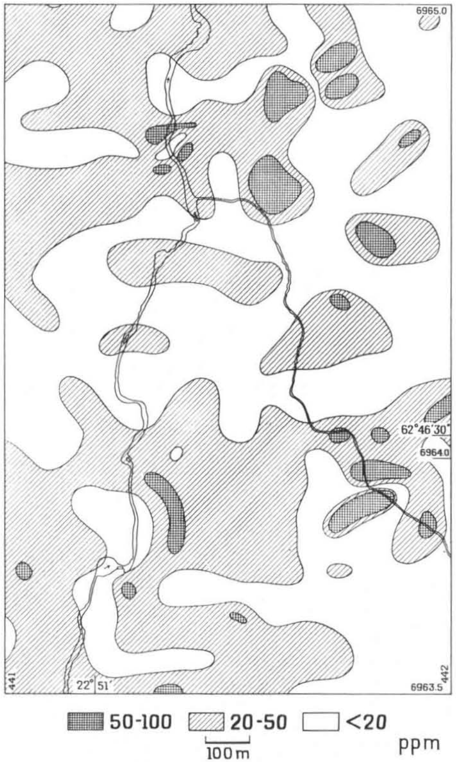

FIG. 13. Copper content of soil in ppm, Kivistönmäki area.

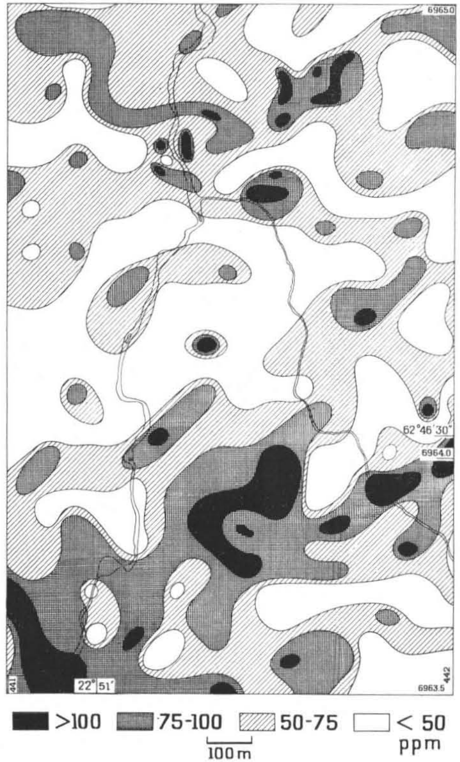

FIG. 14. Zinc content of soil in ppm, Kivistönmäki area.

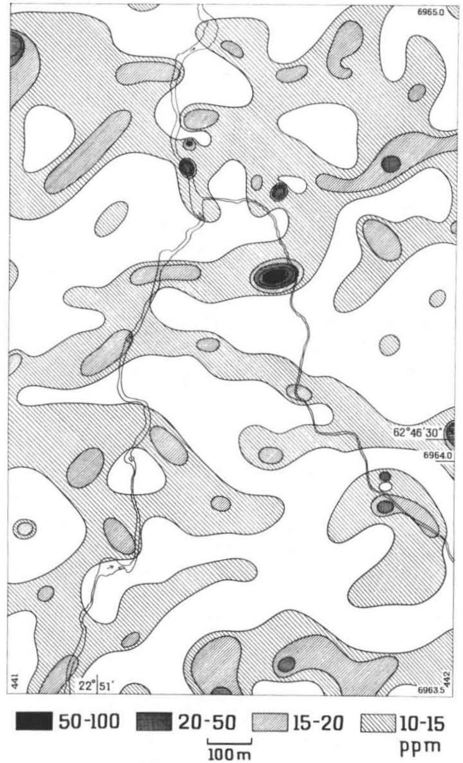

FIG. 15. Lead content of soil in ppm, Kivistönmäki area.

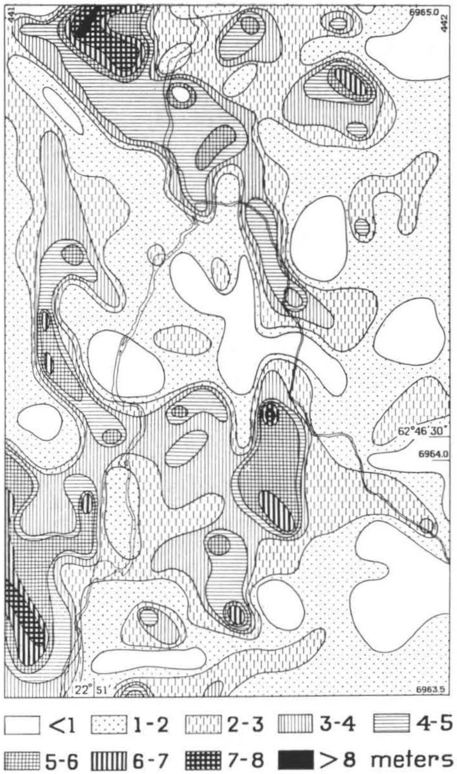

FIG. 16. Soil sampling depths in the geochemical exploration area of Kivistönmäki.

FIG. 17. Types of soil samples in the geochemical exploration area of Kivistönmäki.

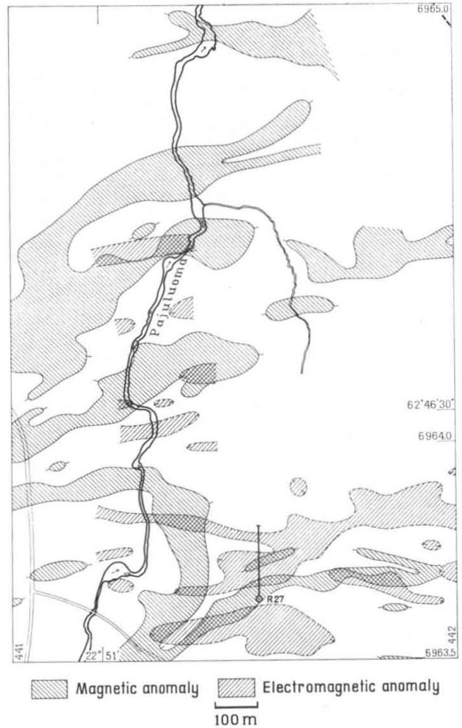

FIG. 18. The magnetic and electromagnetic anomaly zones in area of Kivistönmäki at Seinäjoki.

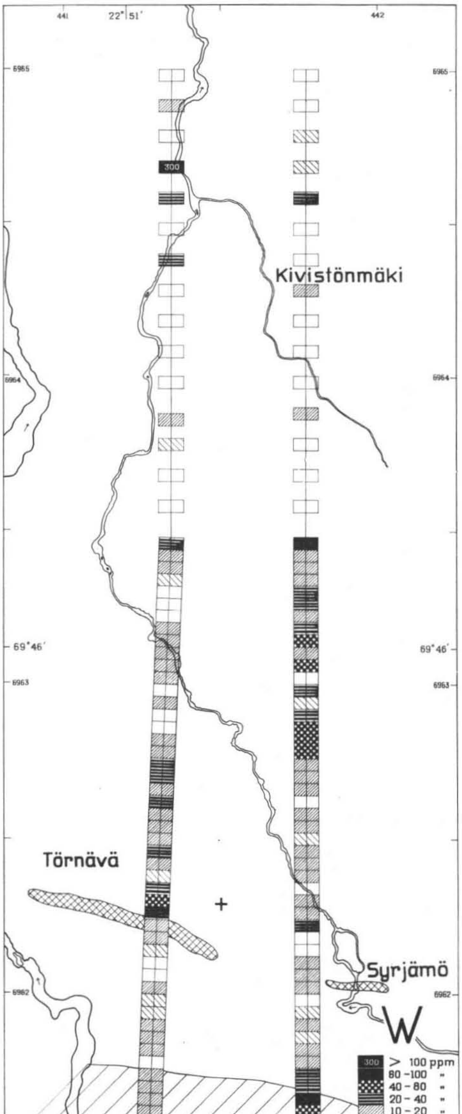

FIG. 19. Content of tungsten in soil.

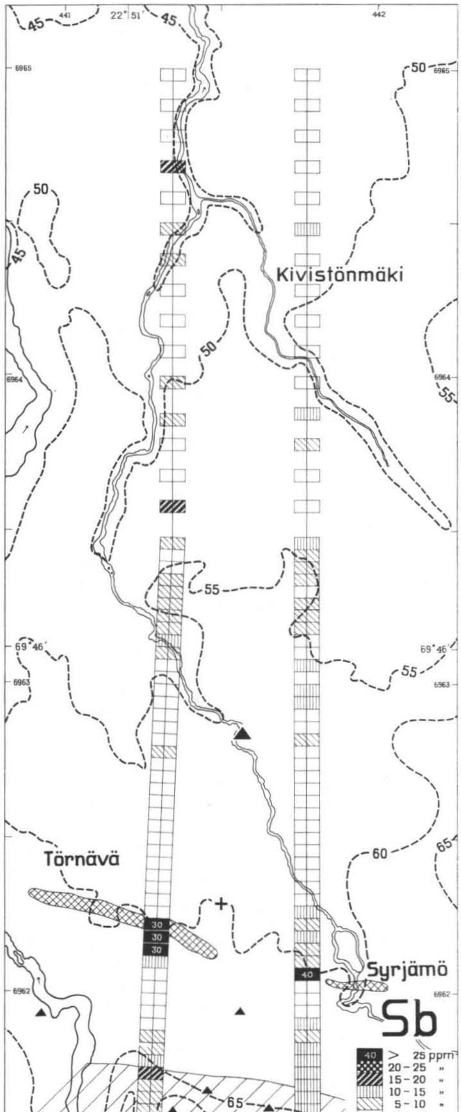

FIG. 20. Content of antimony in soil. The dashed lines are contour lines in meters above sea level, at intervals of 5 m.

TABLE 2

Mean values for certain metals, expressed in ppm, contained in soil deposits from scattered points in central and southern Pohjanmaa

52 samples	Sb	W	As	Pb	Cu	Zn
Till	2.2	5.0	0.5	37.9	17.0	64.3

Tables 1 and 2 reveal that in the Seinäjoki district antimony and arsenic are clearly ascendant, though tungsten, copper and zinc are quantitatively in the same order as in usual.

For the sake of further comparison two pedogeochemical investigation lines were continued from Kivistönmäki to the porphyrite in Satamo. The results of the analyses are seen in Figs. 19 and 20. The maxima of antimony and tungsten appear partly in separate places but also together in zones investigated by diamond drillings and excavations.

The occurrence of antimony and tungsten in the area north of the observed ore zone could be caused by slope of ground (ground water flow). The contour lines in Fig. 20 show the sloping quality of the ground.

The sites of the antimony-bearing boulders are shown also in Fig. 20.

Geochemical peat investigations

Salmi's (1959) peat investigations at Pentinneva (site S in Fig. 9) were likewise negative with respect to antimony but brought to the fore an appreciably higher lead content than had been observed to occur in the peat deposits of the Törnävä area 200 m W of the church. (Tables 3 and 4). Diamond drillings nos. 24 and 25 did not, however, yield any indications of lead minerals. The rather numerous exposure and boulder observations made here do not point to any significant ore prospects, although small amounts of pyrrhotite and pyrite do occur.

TABLE 3

Results of analyses of peat ash from Törnävä, Seinäjoki (Salmi 1959 and 1963)

Sampling depth cm	Ash	Amount in parts per million (ppm)					
	%	Sb	Pb	Ag	Ni	Zn	Cu
0—25	61.48	600	20	170	30	1 300	—
25—50	34.55	1 500	50	40	30	—	—
50—75	76.28	300	10	5	20	—	—
0—25	27.59	2 500	60	30	100	—	—
25—50	30.78	4 000	30	30	50	—	—
50—75	35.06	4 000	50	60	100	—	—
0—25	25.03	4 000	150	250	100	600	2 000
25—50	28.28	4 500	70	60	50	—	—
50—75	38.90	1 500	10	30	100	—	—

TABLE 4
Results of analyses of peat ash from Pentinneva, site S, Seinäjoki (Salmi 1959)

Sampling depth cm	Ash %	Amount in parts per million (ppm) Sb	Pb	Ag	Ni	Zn	Cu
0—10	2.89	—	700	120	10	2 500	800
10—25	6.69	—	700	120	80	1 000	—
0—20	2.31	—	1 000	500	250	2 500	1 800
20—40	1.43	—	500	40	400	500	400
40—60	4.75	—	350	20	200	200	400
0—20	1.60	—	600	80	60	3 000	800
20—40	1.38	—	600	70	200	1 500	500

Investigation of the ground waters in the Seinäjoki district

Since the area under investigation is a densely populated locality with many wells, it might be expected that an analysis of the water in these wells could bring to light significant data (*cf.* Marmo 1958). In connection with investigations of ground waters, water samples were taken from 903 wells, the locations of which are marked in the map shown in Fig. 21. As analysed, the water in a number of wells does contain small amounts of tungsten, antimony and arsenic (Table 5), but no conclusive local maxima appear. It is noteworthy that the water samples taken from the wells near the ore zone in Törnävä did not contain antimony with the exception of the samples taken from the Syrjämö drill hole no. 3 and from the Törnävä drill hole no. 23. The highest contents were noted in the Kivistönmäki area as much as about 500 m to the north of the Törnävä ore zone. There a small amount of antimony was yielded by the water from one well out of every five. The concentration is not, however, very much greater than still farther north, where the water from one well out of every ten or twenty was found to contain a slight amount of antimony.

The slight dominance of antimony in the ground waters of the Kivistönmäki area may be attributed to the transportation of drift farther north by the littoral forces of the ancient shore as well as by the flow of ground waters in a northward direction, since material has been available in the surficial deposits of the ore zone.

Discussion of the prospective results

The question remains unanswered as to where in the Seinäjoki area Malinen's boulder originated. Slight mineralogical differences do not wholly eliminate the possibility of its being associated with already known ore occurrences. The occurrence at Syrjämö, in particular, is likely to include ore of the type represented by Malinen's boulder. The glacial transportation of drift northward seems, however, to lie outside the bounds of possibility, considering that the boulder investigations indicate the exact opposite (Fig. 6). A possibility that cannot be ruled out is, of course, transportation on ice floes. It has, at any rate, been deemed wise to prospect

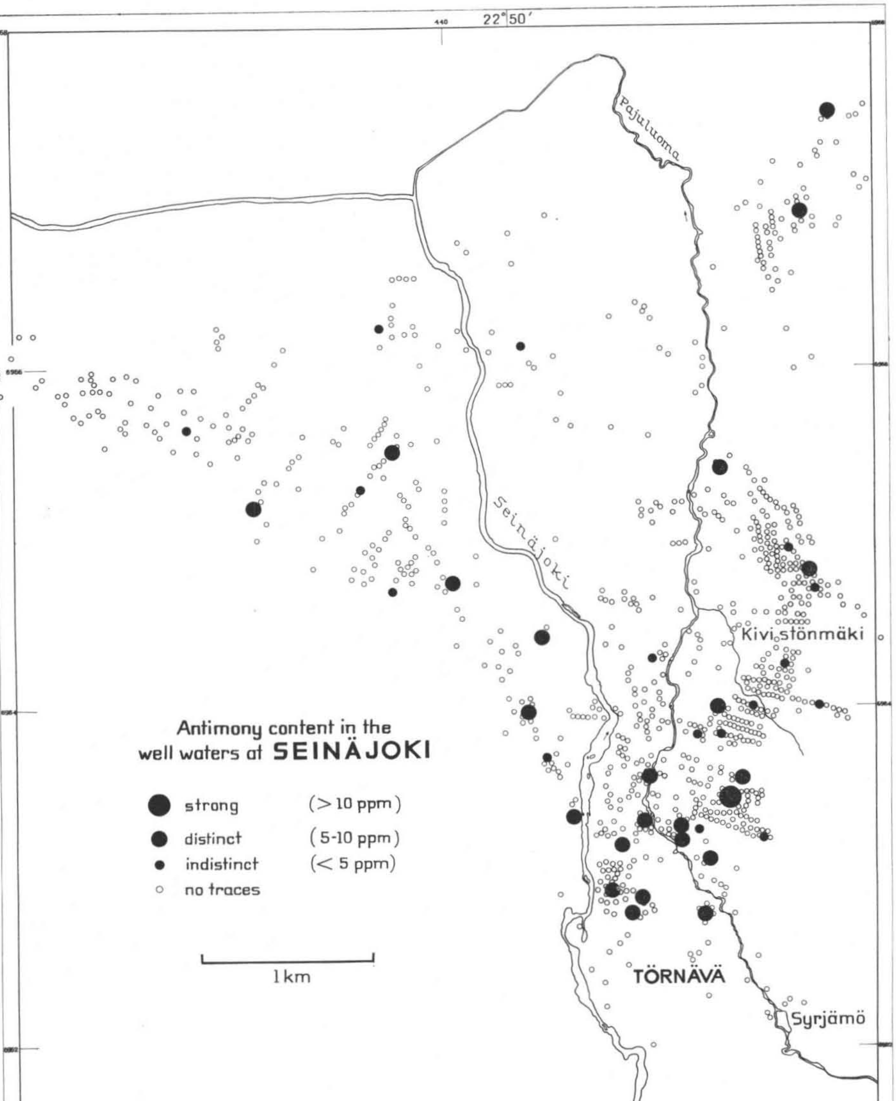

FIG. 21. Seinäjoki region.

TABLE 5
Distribution of antimony, tungsten and arsenic in the wells of Seinäjoki, determined colorimetrically from water samples concentrated in the ratio 1:25

Number of samples			Content ppm
Sb	W	As	
		1	20
4	7	1	10
	31		6
9			5
7			3
9	2	7	2
13			1
861	863	894	0
903	903	903	

the area to the north of the site of Malinen's find, since both geochemical and geophysical indications have been promising. The drillings carried out to date have shown, however, that the geophysical anomalies are due to the presence of scattered pyrrhotite and graphite phyllite.

The contour lines of the area in question show (Fig. 20) that the surface of the earth dips to the north. Evidently antimony, arsenic and tungsten migrated with the groundwater flow in the same direction and caused the anomalous concentrations found in the geochemically investigated area.

Another cause for the geochemical anomalies in the same area and a very possible cause for the anomalous site of the ore boulder named »Malinen» is due to the shore forces during the Litorina stage of the Baltic sea. The altitude of the boulder site corresponds to well-developed Litorina beaches in Hyyppä's (1963) relation diagram showing the tilted and raised beaches of the Baltic Sea.

If no new indications of significance come to light, there is no sound reason for continuing the search for antimony ores in the Seinäjoki district.

THE GENERAL GEOLOGICAL FEATURES OF THE SEINÄJOKI DISTRICT

The general geological structure of the Precambrian area in question has been previously described by four investigators (Väyrynen 1920, 1923, 1936, Saksela 1935, Laitakari 1942, Neuvonen 1961).

As the Vaasa sheet (Saksela 1934) of the General Geological Map of Finland shows, the Seinäjoki region is situated in approximately the center of the great zone of metamorphic supracrustal rocks arching across the map sheet area. This zone of schists is bordered and penetrated by granodiorites and dioritic gneisses only along the outskirts of the Seinäjoki region, otherwise pegmatite granite bodies cut the schists.

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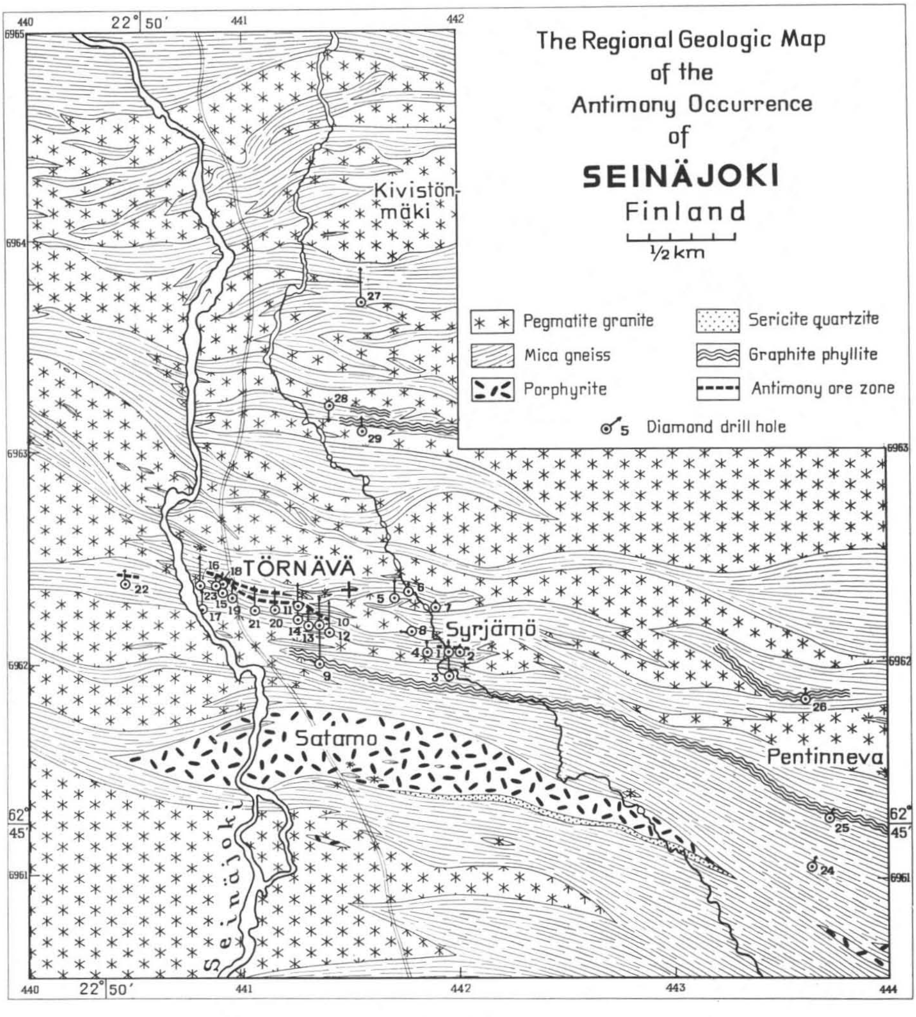


FIG. 22.

Both of the intrusive rocks form migmatites with sedimentogeneous schists or mica gneisses. Noteworthy as a special feature is a metamorphic formation — previously designated as basic leptite — which is only about half a kilometer wide and runs almost east-west at Satamo (Fig. 22), to the south of the church of Törnävä.

No appreciable changes have been brought about in these general features in connection with the ore prospecting, but many small details have come to light (Fig. 22). The aeromagnetic map (Fig. 9) enables one to follow the continuity of the pyrrhotite-bearing schist sequences in areas lacking rock exposures. New outcrop observations and, especially, profiles obtained by the investigation of diamond drill

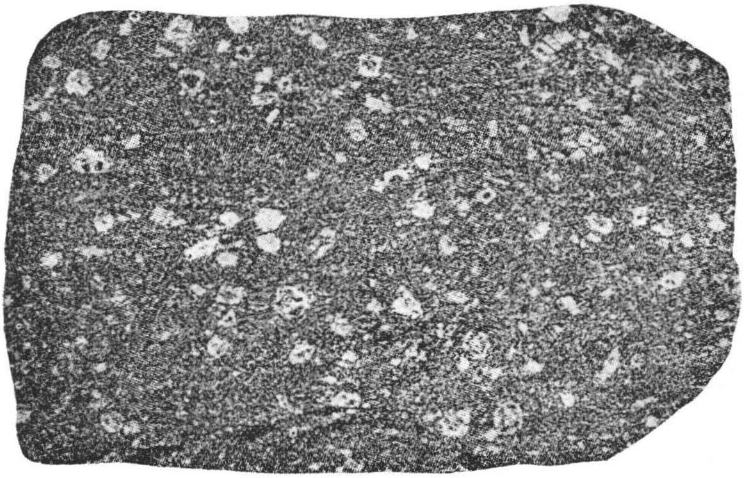


FIG. 23. Porphyrite. Satamo, Seinäjoki. Half of the natural size. Photo M. Saksela.

cores have provided evidence that the pegmatite areas are divided into small parts. Drill cores have revealed the variableness of the schist material. Although mica gneiss gives the geological map of the area its basic colour, it frequently appears in fragmentary form in the pegmatite granite bodies. In some exposures and drill cores the pegmatite penetrates the schist as narrow, densely packed veins, the rock having the appearance of veined gneiss.

Petrographic description of the principal rocks

Mica gneiss is the designation given to the markedly schistose quartz-rich, stratified sediments. These sometimes include various graywacke or biotite-plagioclase gneisses, fine-grained mica schists and highly quartz-rich schists, which closely resemble quartzite but which contain considerable amounts of mica and even some feldspar. Purer quartzites are not to be found until the Munakka-Nurmo zone farther north is reached. The mica gneisses quite commonly exhibit narrow quartzitic stripes running parallel to the schistosity.

The Satamo formation (Fig. 22), which is closely connected with the mica gneisses in age but differs from them in character, is termed in the present study as porphyrite, for both the plagioclase and hornblende grains appear as phenocrysts (Fig. 23). Although the appearance of the rock, especially in the marginal portions of the formation, is conspicuously metamorphic, it should be regarded as a hypabyssal dike formation. The porphyrite has been observed to start from the western side of the Seinäjoki river and to continue parallel to the general strike toward east-southeast, beyond the area now under study.

The pegmatite granite varies in mineral composition, being dominated either by microcline or plagioclase but also being rich in muscovite and quartz. Characteristic of this rock is its high tourmaline content. In many cases, it also contains striking amounts of greenish apatite and reddish garnet. Beryl is very seldom found. The grain size of the pegmatite varies considerably, though mostly it is of a coarse grained nature. Frequently the pegmatite may be seen to contain schist fragments or ghostly schist relicts. Commonly quartz is crushed and has an undulating extinction. Also the twins of the plagioclase (An_{10-20}) are bent and broken.

Stratigraphy and tectonics

In the Seinäjoki region the metamorphic sequence situated in the supracrustal belt area of southern Pohjanmaa, can be divided into upper sedimentary strata and an earlier volcanic group (Saksela 1935, p. 31). This division is not presented in the geological map of the Seinäjoki region compiled by Neuvonen (1961).

Because of surficial deposits and stormy tectonic phenomena the determination of the stratigraphic sequence usually involves great difficulties in South Pohjanmaa. It has not been possible either to create any sure method for identifying the same stratum series in different areas or to determine the basal rock of the sediments. In the connecting zones granodiorite and pegmatitic granite have formed migmatites with the sedimentogenous schists. Since pegmatite granite and granodiorite do not contain magnetic minerals but the schist zones frequently have strata with pyrrhotite or magnetite dissemination, airborne magnetic surveys supply valuable data in the construction of stratigraphic and tectonic features. Aeromagnetic maps reproduced on a scale of 1: 400 000 make the large-scale tectonic features fairly clear.

The magnetic anomaly sequences occurring in the Vaasa—Seinäjoki region have been marked on the map of Fig. 24 in a simplified way. This has been done assuming that magnetic anomalies are caused by one sedimentogenous stratum characterised by strong formation of pyrrhotite or magnetite. It is also possible that the primary hydrate material has changed into these minerals during the metamorphism.

In the magnetic map of the strongly folded schist area series of anomaly lines and curves picturing the horizontal section of the magnetic schist zones are to be noticed. Nevertheless, the parallel recurrence of the schist sequences is also to be observed.

Where there is only one layer causing magnetic disturbance in the original series of deposits, the number of folds can be ascertained. Examples are shown in Fig. 25.

1. Should the fold axis lie horizontally, two parallel section lines on the horizontal plane are formed by a single magnetic layer of the fold.

2. In a special case, one straight line can be seen when the fold intersects the culminating line of the magnetic stratum or when the overthrust half of the fold is cut horizontally.

3. A gently tilted axis causes a V-shaped section pattern of the magnetic stratum.

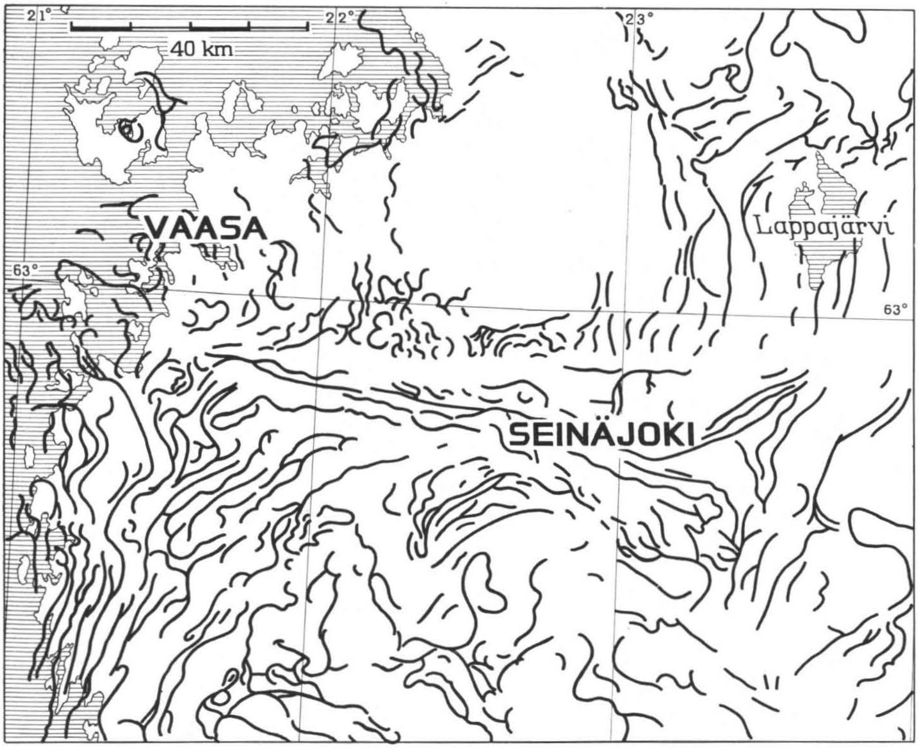


FIG. 24. Trends of magnetic anomalies in the Vaasa—Seinäjoki region.

4. Where the culmination or depression of the axis is involved (dome or basin fold), the pattern of the anomaly becomes shuttle-shaped.

5. A complex fold which is synclinal in one section and anticlinal in the cross section (Lahee 1941).

6 and 7. A perpendicular axis often produces S-shaped (Fig. 25. 6) or horseshoe formed (Fig. 25. 7) horizontal sections.

8. Axial plane folding has caused the form seen in Fig. 25. 8 (Hills 1963).

The anomaly patterns of basic intrusions can usually be distinguished by their roundish forms, but in joining the anomaly sequences of schists they often only reinforce the anomaly caused by them.

Considering the map of magnetic patterns of the Seinäjoki—Vaasa region (Fig. 24), one cannot escape the conclusion that it reveals the existence of four different tectonic features in the region:

1. Anomalies in the middle of the map form fairly straight lines directed NNW—SSE and on an average less straight lines in the direction N—S, on both sides of the map.

2. The large curves in the SW-quarter of the map.

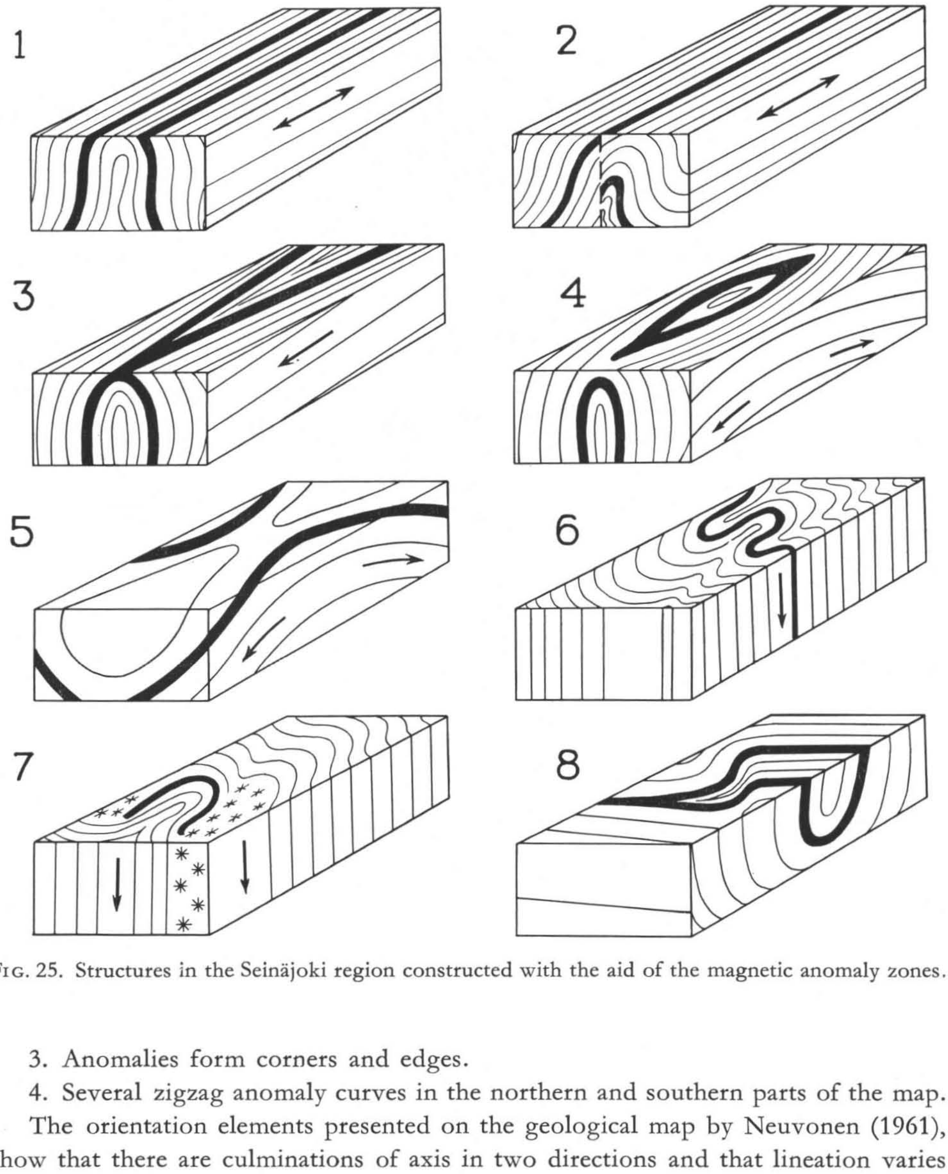


FIG. 25. Structures in the Seinäjoki region constructed with the aid of the magnetic anomaly zones.

3. Anomalies form corners and edges.
4. Several zigzag anomaly curves in the northern and southern parts of the map.

The orientation elements presented on the geological map by Neuvonen (1961), show that there are culminations of axis in two directions and that lineation varies a great deal (Figs. 26 and 27). Similarly, according to the same map, there are also considerable variations in the strike of the schistosity, though it averages E—W. The dip of the schistosity (Fig. 28) is mainly toward the north in a zone about 10 km wide on the northern side of the Seinäjoki area, whereas on its southern side it runs, likewise in a zone about 10 km wide, toward the south.

Detailed examination of both the geological and the magnetic map of the Seinäjoki region gives a rough idea of the stratigraphic system. The principal variety of

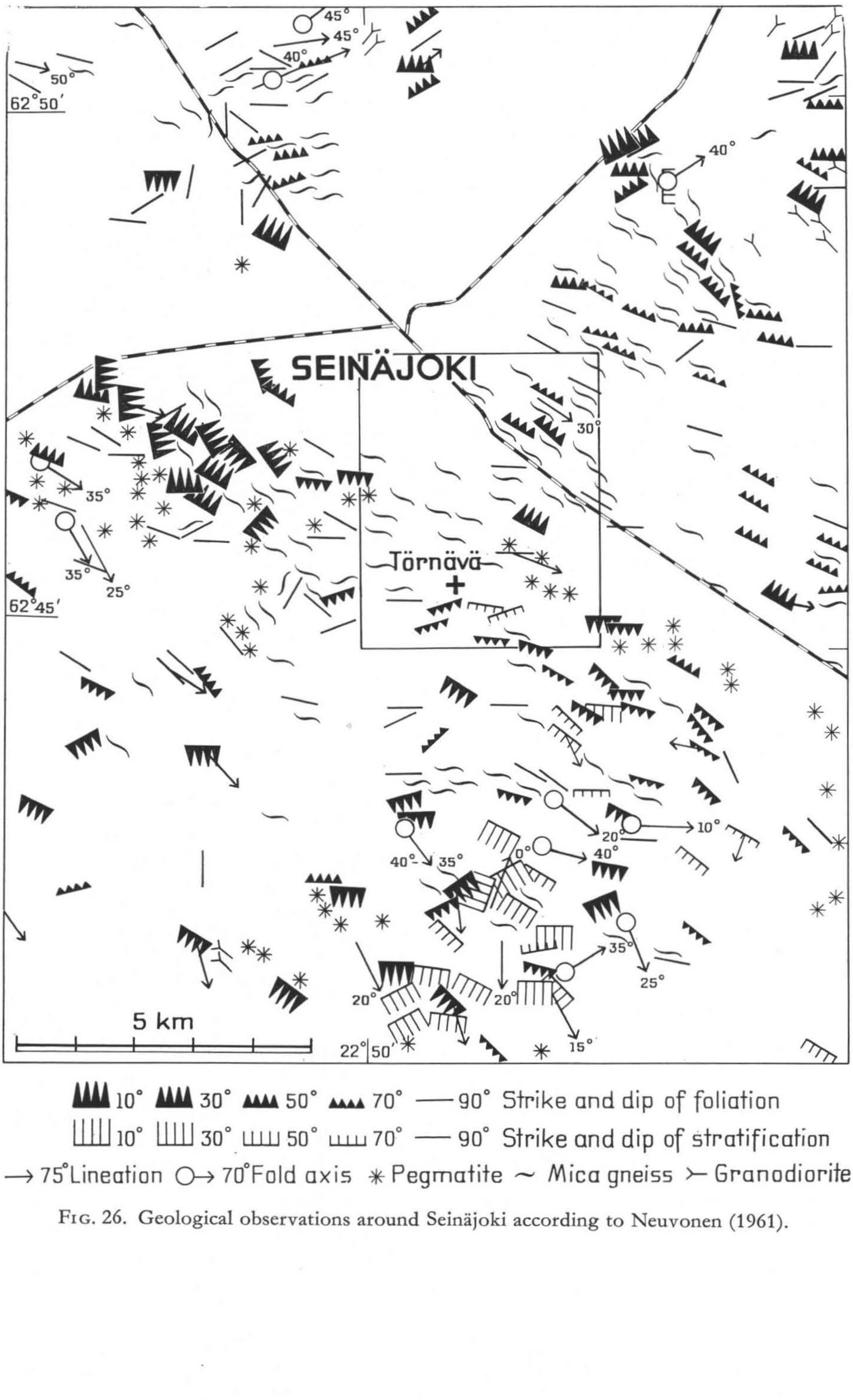


FIG. 26. Geological observations around Seinäjoki according to Neuvonen (1961).

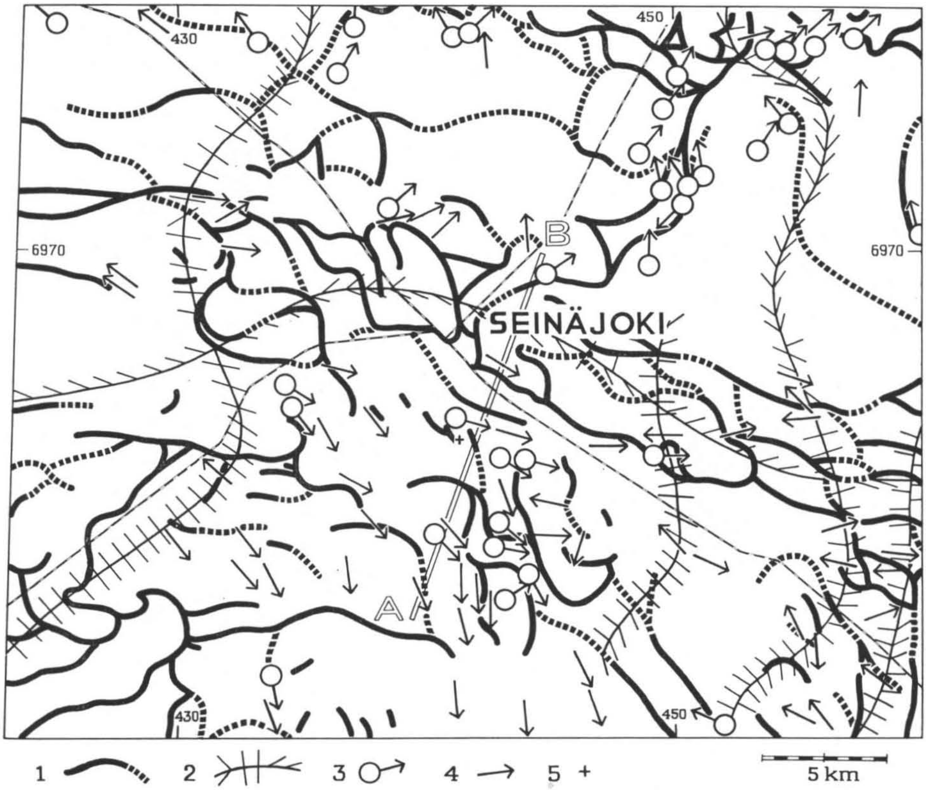


FIG. 27. Tectonic features around Seinäjoki. 1. The aeromagnetic anomaly zones. 2. Axial culmination zones. 3. Fold axis. 4. Lineation. 5. Church.

rock in the region consists mainly of a layered and partly laminated sedimentary horizon that has metamorphosed into mica schist and mica gneiss and in whose steep series of layers there occur intercalations of amphibolite and quartzite. Associated with the intercalations there are often fine-grained graphite-bearing schists or graphite phyllites.

The exposures on the northern and southern sides of the area of the anticlinorium contain granodiorite including many schist fragments with a conformable trend. Evidently the granodioritic bodies have penetrated between layers of sedimentogeneous schist in the direction of the fold axis. Similarly, the pegmatitic granite forms conformable lenses between layers and folds of the schist. The Seinäjoki junction primarily consists of one large horizontal section of an anticlinorium averaging 20 km in width. In the crest and, to some extent, in the sides the mica schist also occurs as vertical zones. It is apparent that both sides of the large anticlinorium are divided into numerous small isoclinal folds (Fig. 29). Sure observations are availa-

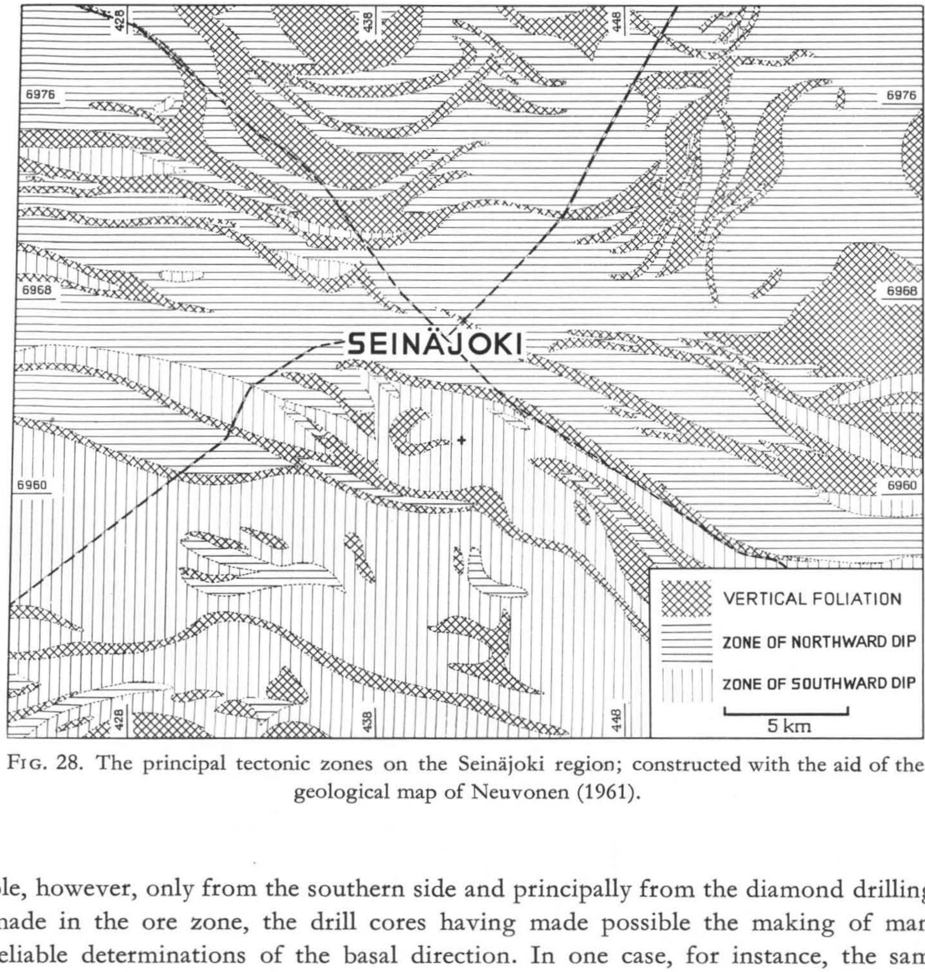


FIG. 28. The principal tectonic zones on the Seinäjoki region; constructed with the aid of the geological map of Neuvonen (1961).

ble, however, only from the southern side and principally from the diamond drillings made in the ore zone, the drill cores having made possible the making of many reliable determinations of the basal direction. In one case, for instance, the same drill hole penetrates a pyrrhotite-bearing layer several times over a distance of two hundred meters without any change in the dip (Appendix). Considering the variations of the basal directions, several isoclinal folds are in question. The drill cores have also revealed much miniature folding, and at a number of places a gradual contrarywise change in the deposition direction could be detected. Such miniature folds also are clearly to be seen in a vertical section at Alakylä (Fig. 30) situated in the same schist zone as the Törnävä formation but 5 km to the west of it.

Taking into consideration the bending axial planes (bending magnetic anomaly trends in Fig. 27) and the geotectonic observations in the vicinity of Seinäjoki (Fig. 26) the conclusion can be drawn that there are two folding directions. Evidence of the same phenomenon is pointed out by Anna Hietanen (1938) in her quartzite investigations in the vicinity of Seinäjoki: »The traces from two folding series are visible in the petrofabrics of several quartzite areas».

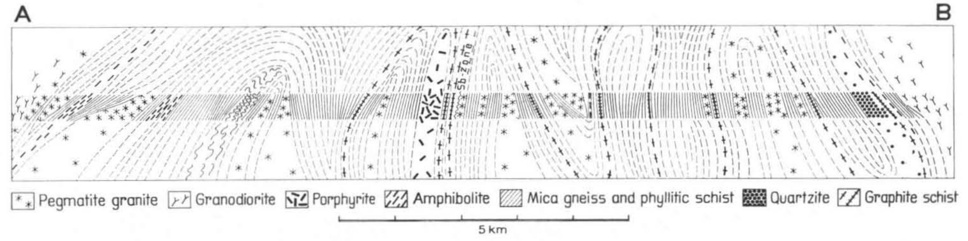


FIG. 29. A vertical cross-section of the schist zone at Seinäjoki. The profile is drawn according to the geological map of Seinäjoki (Neuvonen 1961), completed by the results of magnetic and electromagnetic measurements. Location of the profile line A—B is seen in Fig. 27.

FIG. 30. A vertical section of a fold at Alakylä, 5 km W of Seinäjoki. Mica schist, grey; pegmatite, white. Half of the natural size.

FIG. 31. Exposure of ore at site of drill hole no. 11, Törnävä.

THE REGIONAL OCCURRENCE OF ANTIMONY MINERALS

Although the site of the mineralization has been designated as the Törnävä antimony occurrence of Seinäjoki, it is possible also to speak of the ore prospects of Satamo and Syrjämö in addition to the Törnävä region. Syrjämö might, it is true, also be regarded as an eastern extension of the Törnävä sequence, for it is very similar in character, although much smaller and weaker. Satamo, on the other hand, is quite different in character in addition to its isolated position. The Törnävä occurrence extends on both sides of the highway running south and has been penetrated by 15 drill holes nos. 9—23, whereas 4 holes nos. 1—4 were drilled to investigate the Syrjämö ore. The slight mineralizations of Satamo have come to light in quarries producing macadam, situated about $\frac{1}{2}$ km to the south of the Törnävä zone.

The ore prospect of Törnävä

Petrographic description

Under the Quaternary cover, on the average one meter thick (Fig. 31), the country rock consists principally of a mica gneiss and schist (Fig. 32), the chief minerals of which are biotite, quartz and muscovite. Microcline (Fig. 33), plagioclase (Fig. 34), apatite, epidote and zircon are present in small amounts. Small tourmaline grains occur in a few zones, and here and there also garnets. As the grain size diminishes, the rock takes on a phyllitic appearance, but as the biotite content increases, it clearly changes to mica schist. Although the most common mineral

FIG. 32. The different schist types in the Törnävä ore field. Half of the natural size. Photo E. Halme. 1. Graphite phyllite with white calcite as fissure veins. 2. Phyllitic mica schist. 3. Phyllitic schist with varying lamination. 4. Laminated mica schist. 5. and 6. Mica schist and gneiss alternate. 7. Laminated and folded mica schist. 8. Phyllite, rich in quartz. 9. Folded phyllite, rich in quartz. 10. White pegmatite veins in mica gneiss.

contained in the schist is biotite, the frequent abundance of quartz suggests the appropriateness of calling the rock quartzitic. The quartz generally has a marked undulating extinction and the biotite is quite distinctly oriented. The clear lamination of layers (Fig. 32) and the orientation exhibited by the micas derive mainly from the sedimentation stage, but regional metamorphism also appears to have influenced the result. Especially silicifications occuring as veins and small lumps, and conforming to the stratification, have evolved in connection with the formation of the schists, for their appearance suggests later origin than the deposition of the sediments. Nevertheless, their quartz shows an undulating extinction. The thickness of the silicifications varies from a millimeter to several centimeters. Smoky quartz, which occurs as veins and lumps, is appreciably larger in grain size but shows less undulating extinction than the schist layer quartz. In association with the silicifications the schist is in many instances strongly sericitized. In most cases the rock should be designated as sericite quartzite at the sites of ore occurrences. Some small ore mineral grains have been

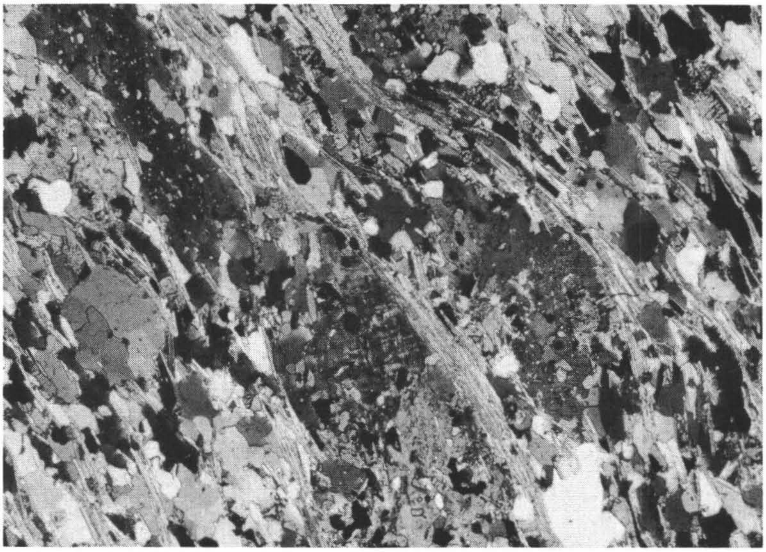


FIG. 33. Texture of mica gneiss layer containing some larger microcline grains. Nicols +. Magn. 35 x. Photo E. Halme.

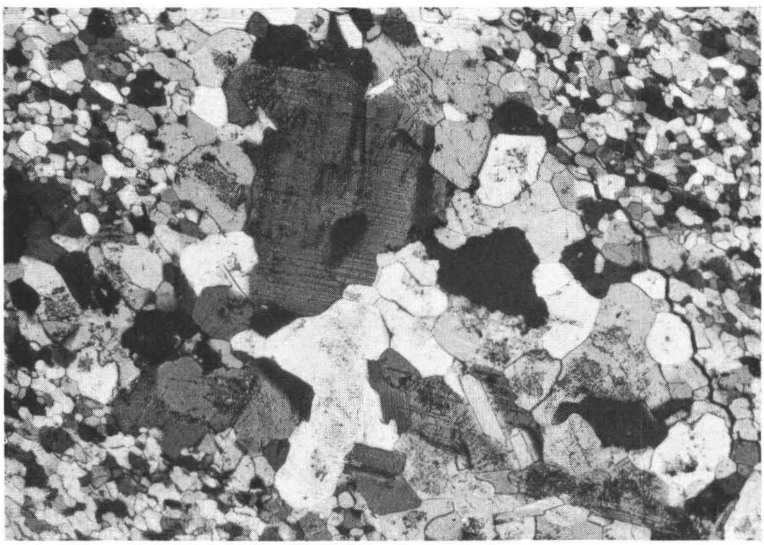


FIG. 34. Small grained gneiss layer containing groups of larger quartz and plagioclase grains. Nicols +. Magn. 35 x. Photo E. Halme.

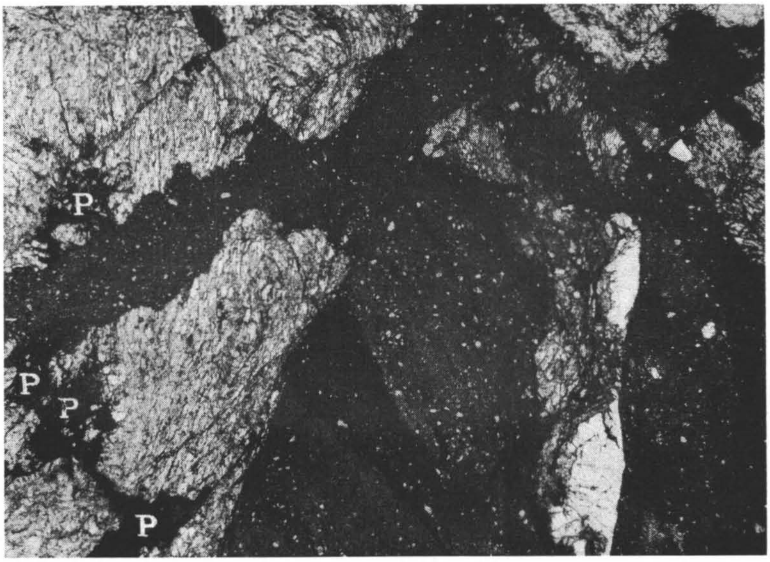


FIG. 35. The mica gneiss (grey) is strongly sheared. The pyrrhotite vein (P) brecciates the gneiss. Both are brecciated by mobilized mylonite (the dark striped rock with white quartz grains). Drill hole no. 21 (25.6 m). Thin section. One nicol. Magn. 10 x. Photo E. Halme.

observed to occur in the mica schist outside the mineralized zone and even in the mica gneiss.

The width of the schist zone at the site of the Törnävä ore deposit averages 150 meters. It is not, however, wholly uniform, for at both ends it is cut by pegmatite granite, which occurs as narrow veins also in the middle portion. The pegmatite has been formed mainly out of light gray potash feldspar containing inclusions of coarse quartz (graphic feldspar). A further characteristic is its abundant content of muscovite and tourmaline. Considerable amounts of garnet and of apatite grains of an unusually large size are met with sporadically.

Occasionally, kaolin occurs as fissure fillings in both mica gneiss and pegmatite. In drill hole no. 12 a small fissure filling was found at a depth of 27.7 m that contained a radioactive mineral, which proved under X-ray investigation to be uraninite in a state of disintegration.

The strongly metamorphic schist rock in the ore zone is generally sheared, and occasionally even brecciated thus indicating ultramylonitic texture (Fig. 35). In many places partially mended fractures occur which deviate from the trend of the schistosity and which occasionally also continue into the pegmatite. Considerable changes have frequently been observed in the general trend of the schistosity, although the plane of the schistosity is usually almost at right angles to the drilling direction, which dips on an average 45° N. In most cases the schistosity and the bedding run parallel, but not infrequently transverse schistosity occurs.

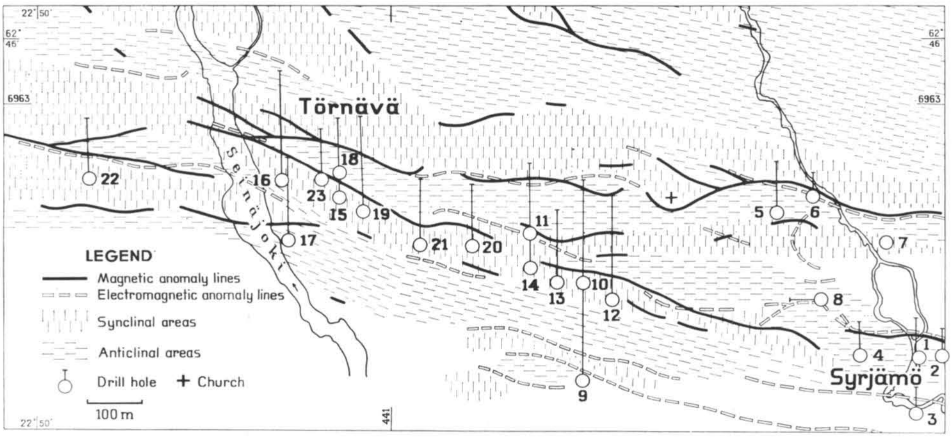


FIG. 36. The tectonic features of the Törnävä—Syrjämö zone on the horizontal plane section according to geophysical map and the observations of the basal direction of stratification from the drill cores.

Structure of the ore occurrence

In its central part, as represented by drill holes nos. 22 and 23, the ore occurrence runs in two zones (Fig. 22 and Appendix), on an average 50 m apart. The bipartite character of the formation is also noticeable at its western end, although the zones lie close together. At the eastern end only one ore zone can be clearly observed. At its western end the zone makes an abrupt turn or rises up, for drill holes nos. 16 and 17 no longer properly reach it. Both faults and intensive folding are also possible. The abundance of pegmatite dikes has naturally caused disturbances in the trend of the ore zone.

The investigation of the structure and continuity of the ore occurrence has been performed by making more than 300 determinations for the basal direction of stratification from drill cores. Consequently, the tectonic structure of the area cannot be reproduced on the basis of these observations alone, but geophysical measurements and the petrographic analysis of drill cores must also be employed. Geophysical anomaly sequences (Fig. 36) show the trend of the folding and by and large its character as well, but observations of the basal direction often reveal, in addition to the large folds (100—400 m in diameter), also smaller folding (diameter 5—100 m) or quite miniature folding (Fig. 37). The folding is marked in the actual ore zone, where the diameter of the isoclinal folds averages 50 m and the thickness of the folded bedding is therefore only about 25 m, whereas outside the Törnävä zone a drill hole has penetrated a schist deposit over 100 m thick without any change in the basal direction. In the case of the majority of the Törnävä drillings, the basal direction changes two or three times over an average distance of 100 m; but in drill hole no. 12 the basal

FIG. 37. Folded graphite schist from Törnävä, Seinäjoki. Bright white stripes represent pyrite, light gray quartz and mica, dark shade graphite. Polished section. Magn. 4 x. Photo E. Halme.

trend was seen to change eight times over a distance of 140 m, in drill hole no. 20 thirteen times and in hole no. 14 eleven times. Most of these changes are due, however, to miniature folding, for the most distinct graphite horizon is generally encountered only once in a drilling, except in drill hole no. 9 (Fig. 38), where graphite occurs in several zones. The graphite belt at the terminal end extends to the opposite end of drill hole no. 10. Judging by this, a single large syncline lies at the site of drill hole no. 9, but the frequent variation in the basal direction occurring across the same distance nevertheless indicates dense miniature folding. Noteworthy too is the close association of a zone rich in antimony minerals with the graphite deposit just at the terminal end of drill hole no. 9 as well as in holes nos. 10 and 13, whereas the upper part of hole no. 9 penetrates a graphite zone containing pyrite and a slight amount of chalcopyrite, which is bound up with a layer containing only 0.05 % antimony. The antimony- and gold-bearing zones met with in drillings nos. 9—15 and nos. 18—21 appear to follow both northern and southern flanks of the same fold, though they are slightly disturbed by faults and bending of the fold axis.

The ore zones coincide in most cases markedly with silicified and sericitized belts in the schist. The majority of the drill holes in the region investigated penetrate the same sort of fine-grained, stratified phyllite deposit at both ends, which supports the

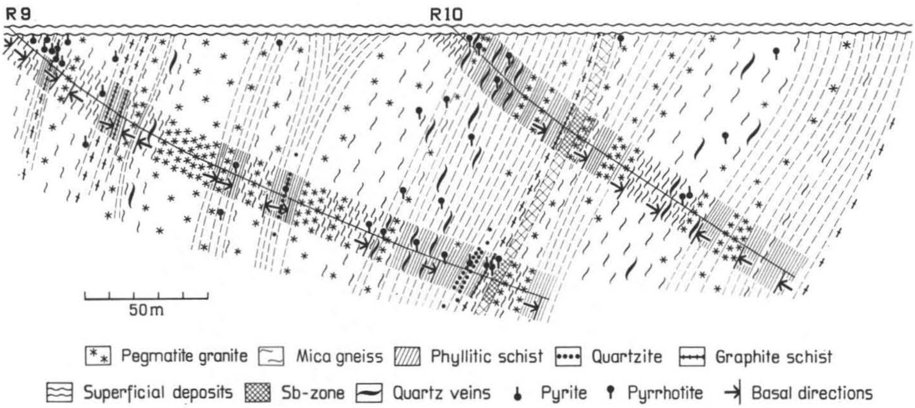


FIG. 38. A vertical cross section on the plane of drill holes nos. 9 and 10. Törnävä field.

view of a single large syncline. These sections of the phyllite deposit approach each other in the drill holes closer to the western end of the region. Similarly, there is a convergence of silicifications containing ore, the final result being the production of a single but considerably reinforced quartz-rich zone. This phenomenon indicates that the synclinal axis approaches the earth's surface at the western end of the region and conforms to the general trend of the fold axis dipping 25° E. The strengthening of the ore zone is apparent in the profile section at the sites of drill holes nos. 15 and 18 (Appendix), but it changes character at approximately drill hole no. 23, evidently on account of a pegmatite intrusion. Farther to the west, part of the ore occurrence rises above the ground, for drill hole no. 16 no longer makes contact with it (Fig. 36). Owing to the axis culmination, however, part of the ore-bearing fold presses down below the pegmatite zone. The ore horizon partly returns once more to the surface farther to the south, and gives a slight indication of containing antimony in drill hole no. 17 (Fig. 36) (between 19.43 m — 21.80 m = 0.11 % Sb). Farther westward, in hole no. 22 (Fig. 36), one native antimony vein, approx. 1 cm thick was observed in the drill core at a depth of 40 m.

The disturbance exhibited by the ore zone is seen in the pattern of the geophysical isoanomalic curves between drill holes nos. 11 and 20 (Fig. 36). This phenomenon is due apparently to a fault along the line NW—SE and a slight change in the dip of the axis. In the same place (Appendix) the character of the ore changes so that westward the amount of antimony decreases but that of gold increases.

Although the continuity of the ore body is clearly evident between nos. 10—14, the complicated tectonic structure and the disturbances caused by pegmatite dikes produce breaches and dislocations, with the result that the following of the ore-bearing zone is uncertain, at least longitudinally. During the investigations it has been possible to make out the turning points of a few of the small folds in the drill cores.

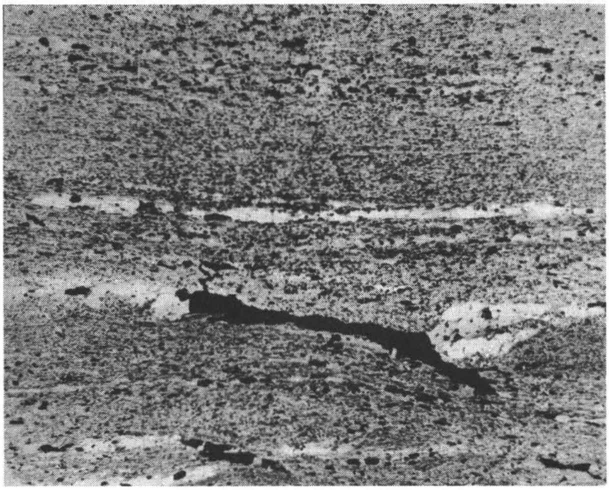


Fig. 39. Micaceous gneiss at Törnävä. Black dots are pyrrhotite, mica is grey and white is quartz. Magn. 6 x. Photo E. Halme.

Ore mineralization

In the magnetic and electromagnetic anomaly zone of Törnävä the phyllitic schist contains minor amounts of pyrite, pyrrhotite and graphite. Primarily the origin of these minerals is without doubt sedimentary. Very small mineral particles have been transported to the sea floor together with detritus or the sulfides of iron have been precipitated during the cementation process.

Melnikovite and other black unstable sulfides are known to form to a greater or lesser degree in ocean, lagoon or lake bottoms. These iron sulfides are associated with black shales high in carbonaceous material (Lepp 1957). The same phenomenon has been observed in Törnävä and in other shale formations of Finland.

The present mineralogy and texture of the rocks, however, were developed by metamorphism. The sulfides of iron are recrystallized. At the same time the carbonaceous material is crystallized into graphite. Also minor amounts of chalcopyrite, sphalerite and hematite have been formed from sedimentary matter. The amounts of graphite and sulfide minerals are variable but proportional to each other.

The actual antimony mineralization is situated in the hydrothermally silicified and sericitized zones evidently formed during the second metamorphic phase of the orogenic process. Since arsenopyrite also occurs only in the same hydrothermally metamorphozed zone, it is evident that native antimony and arsenic formed with the aid of the circulating solutions.

Pyrrhotite is a mineral that occurs generally, though in slight amounts, in the mica gneiss of the Seinäjoki region. In a few zones it occurs in such abundance as to cause considerable magnetic anomalies. In the Törnävä zone it is likewise the most common ore mineral, although it occurs only as a weak scattering of small

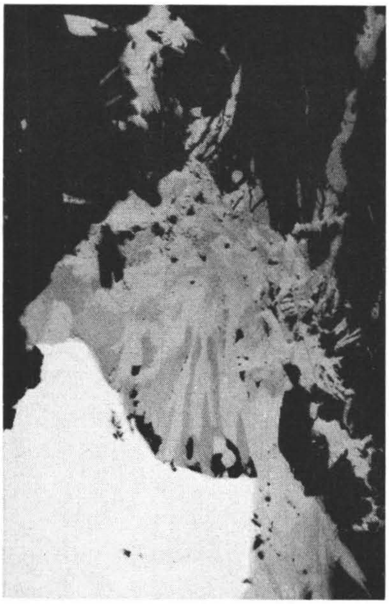


FIG. 40. Bright native antimony is bordered by pleochroic (dark and light grey) stibnite. Black is quartz. Polished section. One nicol. Magn. 100 x. Photo E. Halme.

FIG. 41. The same polished section as Fig. 40 but nicols crossed. The grain of striped native antimony is bordered by strongly anisotropic stibnite grains and quartz. Photo E. Halme.

grains (Fig. 39) — or is totally absent. Most commonly the appearance of the grains is ragged and marked by elongation in the direction of the schistosity. A few of the pyrrhotite grains exhibit marcasitization or other secondary alterations. Occasionally there occur in the ore-bearing zone pyrrhotite accumulations, at the most one cubic centimeter in size, which have formed in connection with silicification.

When X-rayed, a specimen of pyrrhotite examined by the mineralogical laboratory of the Geological Survey showed two equal peaks with FeKα radiation:

d 2.0606; d 2.0517

The appearance of two peaks is not a common feature of pyrrhotites in general.

According to Arnold and Reichen (1962) there exist two hexagonal pyrrhotites containing 46.85 and 46.14 atomic per cent metals. Groves and Ford (1963) concluded that the hexagonal pyrrhotite had been mixed with the monoclinic pyrrhotite. According to Buseck (1964) such peaks are reflections of the monoclinic pyrrhotite. If a monoclinic superstructure forms with a multiple pseudohexagonal unit cell, then the d (102) -line is divided into two: 2.05 Å and 2.06 Å (Kouvo and Vuorelainen 1962).

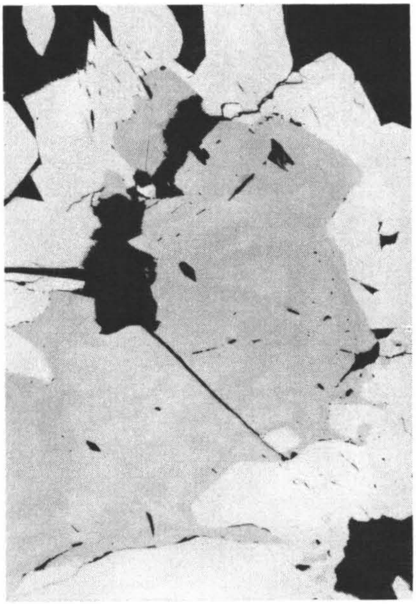


FIG. 42. Grey pyrrhotite is surrounded by light gudmundite. Dark shade is quartz. Drill hole no. 9. Polished section. One nicol. Magn. 100 x. Photo E. Halme.

FIG. 43. The same polished section as Fig. 42 but nicols crossed. Dark pyrrhotite is surrounded by anisotropic gudmundite. Photo E. Halme.

N a t i v e a n t i m o n y is the most characteristic mineral in the ore-bearing area of Törnävä. It is easy to recognize under the microscope because of its high reflectivity (Fig. 40) and its weakly anisotropic grains (Fig. 41). It is met with in almost all the drill holes and in the majority of the samples taken from ore exposures. Frequently, it is also the chief ore mineral and in various places is almost the sole antimony mineral, in which cases the diameter of the grains usually varies between 2 and 3 mm. In most instances, however, it occurs as smaller disseminated grains. Exceptionally it forms larger grain clusters or accumulations in association with quartz, occurring in mica schist as fissure veins or lumps. Frequently, the antimony grains or grain clusters are stretched in a direction parallel to the schistosity. Similarly, when disseminated in schist, the antimony grains are elongated in line on the plane of the schistosity.

The hardness of native antimony has generally been reported as being 3—3.5 (Mohs), but calcite scratches the antimony of Seinäjoki rather well. Bohemian stibnite scratches it very weakly, but it is also capable of faintly scratching Bohemian stibnite (Table 10, p. 52).

G u d m u n d i t e is also quite common in the Törnävä ore zone and it appreciably affects the antimony content of the ore. Grains measuring between 0.5 and

TABLE 6
Gudmundite

Seinäjoki		ASTM [1])			B & T [2])		
d(Å)	I	d(Å)	I	hkl	d(Å)	I	hkl
5.55	vw	5.62	10	101	5.63	1	110
4.07	mw	4.10	50	111	4.09	5	111
3.83	vw	3.84	10	210	3.87	$^1/_2$	021
2.99	m	3.00	40	301	3.00	2	130
2.97	m	2.93	40	012	2.93	2	201
2.81	mw	2.80	40	202	2.81	4	220
2.69	w	2.68	20	311	2.68	3	131
2.64	vw	2.63	20	121	2.63	1	112
2.55	vs	2.56	100	220	2.55	10	022
2.32	vw	2.33	10	410	2.32	$^1/_2$	041
2.20	w	2.20	20	103	2.21	1	310
2.06	w	2.06	10	113	2.07	$^1/_2$	311
1.91	s	1.912	80	412	1.917	7	150: 042
		1.868	10	131	1.875	$^1/_2$	113
1.84	w	1.840	20	230	1.841	1	023
1.769	vw	1.770	10		1.779	1	331
1.71	m	1.710	40		1.715	3	203
1.704	m	1.689	10		1.691	1	400
1.665	vw	1.670	10				
1.612	m	1.617	60		1.623	3	401
1.58	vw	1.587	10		1.589	$^1/_2$	
1.457	w	1.458	60		1.463	2	
1.407	m				1.416	5	
1.41	ms	1.410	70		1.406	$^1/_2$	
		1.365	10		1.367	$^1/_2$	
		1.338	10		1.342	$^1/_2$	
					1.284	3	
1.28	w	1.279	40		1.259	$^1/_2$	
1.23	vw	1.228	20		1.233	1	
1.20	vw	1.197	10				
		1.188	10				
1.17	vw	1.165	20		1.169	1	
		1.145	10				
		1.121	10 B				
		1.105	10 B		1.109	1	
1.10	vw	1.095	40		1.098	4	
					1.084	2	
1.057	vw				1.060	3	
					1.035	$^1/_2$	
1.023	vw				1.024	4	
					1.015	1	

I: vs > s > ms > m > mw > w > vw
[1]) American Society for Testing Materials Philadelphia, X-ray Powder Data File
[2]) C. G. Berry and R. M. Thompson (1962)

1.0 mm in size form clusters, which in many instances are associated with other groups of antimony mineral grains. Frequently, the mineral borders pyrrhotite, as is seen in Figs. 42—45. Sometimes pyrrhotite grains occur as residual inclusions in gudmundite [1]) (Figs. 44, 45 and 47). These inclusions, which often have a myrmekitic

[1]) Myrmekitic inclusions of the same kind have been reported by Gavelin (1936) from the Skellefte region, and his explanation is that they are disintegration products of fahlerz. Gavelin (1939, p. 144) says: »In many cases, however, pyrrhotite seems to be the mineral that has been replaced, the remainders being partly converted into gudmundite through the addition of antimony from the attacking solution».

TABLE 7
Stibnite

Seinäjoki		B & T [1])		
d(Å)	I	d(Å)	I	hkl
5.60		5.64	3	020; 200
5.10		5.07	4	120; 210
4.00		4.00	2	220
3.60	I	3.58	10	130; 310
3.10	III	3.14	2	230; 320
		3.06	2	121; 211
2.80	IV	2.76	3	400; 221; 140
2.70		2.67	1	301; 330
2.62		2.61	1/2	131; 311
2.53		2.52	4	240; 420
2.45		2.43	1	231; 321
2.25		2.26	1	041; 340; 430
		2.22	2	141; 411
2.10		2.10	3	241; 421; 250; 520
		1.994	1/2	440
1.95	II	1.933	5	501; 350; 530
		1.881	1/2	060; 600
		1.852	1/2	160; 610
		1.781	1/2	260; 620
1.74		1.728	3	222; 351; 531
1.70	V	1.692	4	132; 312
1.64		1.639	1/2	
		1.605	1/2	
		1.549	1	
1.53		1.528	1	
		1.484	2	
		1.445	2	
		1.415	1/2	
		1.402	1/2	
		1.361	1/2	
		1.351	1/2	
		1.312	3	
		1.293	1	

[1]) C. G. Berry and R. M. Thompson (1962) I > II > III > IV > V

appearance, give the impression that the gudmundite originated through the reaction of wandering native antimony and the pyrrhotite previously contained in the rock: $FeS + Sb \rightarrow FeSbS$ [1]). In association with pyrrhotite, gudmundite is also easy to recognize by virtue of its almost equally great polishing hardness (Sampson 1941). Characteristic of gudmundite is also a strong, in some instances lamellar anisotropy, in which the colors vary as follows: dull bluish green, orange yellow, deep bluish red. The mineral in question has also been confirmed by means of X-ray diffraction (Table 6).

Stibnite occurs rather commonly, but nowhere has it been met with in abundance; rather, it is usually found in small amounts, either as isolated shreds or as aggregates of irregular laminae associated with other antimony minerals (Figs. 40

[1]) A similar phenomenon is believed by Maucher (1937) to have occurred through the reaction of pyrite and antimony in the Turhal deposit and by Ramdohr (1938) in the formation of the antimony-rich paragenesis of Jakobsbakken, Sulitelma.

FIG. 44. Typical mode of occurrence of white berthierite together with dark grey quartz and lighter grey garnet. Syrjämö. Polished section. One nicol. Magn. 3 x. Photo E. Halme.

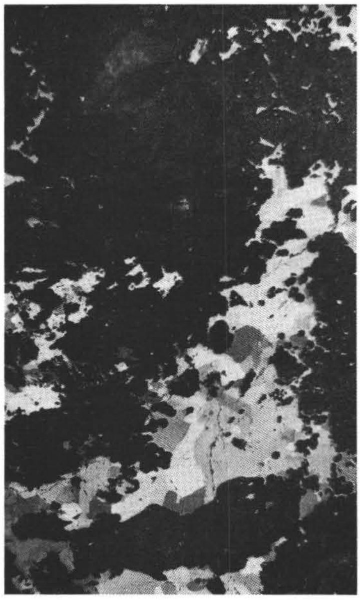


FIG. 45. The same polished section as Fig. 44 but nicols crossed. Photo E. Halme.

and 41). Stibnite also occurs frequently in narrow fracture fissures as knots of laminae running parallel to the fissure surface. This phenomenon suggests a late mobile state at a relatively low temperature (distills at 546° C). The pressure hardness (Vickers) of the stibnite and the native antimony of Seinäjoki is the same (Table 10). With respect to polishing hardness, native antimony has a slight edge over stibnite. Confirmation by X-ray diffraction has also been carried out on the stibnite of Törnävä (Table 7).

The fourth antimony mineral occurring in the Törnävä area is b e r t h i e r i t e, which is a rare mineral, however. It occurs in appreciable amounts only in drill hole no. 18 and there, too, only in spots, principally as separate grain clusters. Berthierite and stibnite have nearly the same pleochroism (Fig. 44) and anisotropy (Fig. 45), but berthierite is harder. The figure obtained for its pressure hardness was 200 (Table 10). The presence of berthierite has also been detected by means of X-ray diffraction (Table 8). It appears to have been produced easily through the reaction between migrating antimony sulphide and the pyrrhotite abundantly present in the rock in accordance with the formula $FeS + Sb_2S_3 \rightarrow FeSb_2S_4$ (Fig. 46). Berthierite precipitates artifically if a mixture of FeS and Sb_2S_3 is heated to 565° C (Grafenauer 1964).

TABLE 8

Berthierite

Seinäjoki		B & T [1]			Chyzné [2]	
d (Å)	I	d(meas)	I	hkl	d (Å)	I
4.40	vw	4.37	6	130	4.32	vw
4.26						
3.70	ms	3.68	10	310	3.64	ms
3.61		3.52	1/2	040		
3.32						
3.40		3.39	3	140	3.38	vw
3.20	ms	3.20	3	121	3.21	ms
3.05		3.02	4	240	3.02	mw
2.88	ms	2.88	3	221; 400	2.874	ms
2.63	vs	2.63	8	311: 231	2.637	vs
2.53		2.54	3	250	2.530	vvw
2.28		2.28	1	401; 350; 051	2.254	vvw
		2.23	1	510; 440		
2.18		2.18	4	260	2.178	vvw
2.06		2.05	3	431	2.054	vw
2.01		2.02	3	450	2.013	mw
		1.918	3	441; 606	1.906	vvw
1.887	m	1.888	3	610; 261; 521; 002	1.881	m
1.81	m	1.804	1	531	1.805	m
1.779	m	1.771	4	212; 451; 361; 630; 080	1.769	m
1.693		1.701	1	601; 611; 280	1.706	vvw dif.
		1.675	1	312; 232	1.672	vvw
					1.640	vvw
1.596		1.593	2	242; 720; 332; 181; 650	1.590	ms
		1.561	1	412		
		1.542	1/2	281; 422; 671		
1.497		1.512	2	471; 252	1.503	vvw
1.46		1.457	1			
1.427		1.427	1		1.433	vw
		1.406	1			
1.377		1.377	2		1.372	vvw
1.344		1.347	1		1.342	vvw
		1.313	1		1.325	vvw
		1.298	1/2			
		1.272	1/2			
		1.256	1/2		1.253	vvw
1.222		1.226	2			
		1.226	2			
		1.202	1			
		1.189	1/2			
		1.177	1			
1.115		1.114	1		1.111	vw
1.083		1.089	2		1.083	vw
1.065		1.069	3		1.065	mw
		1.051	1/2		1.048	vw

I: vs > s > ms > m > mw > w > vw > vvw

[1]) C. G. Berry and R. M. Thompson (1962) [2]) F. Novák, F. Čech and F. Kupka (1956)

FIG. 46. Dark grey pyrrhotite is partly replaced by medium grey berthierite. White is gudmundite. Polished section. Syrjämö. Drill hole no. 3 (150.35 m). One nicol. Magn. 150 x. Photo E. Halme.

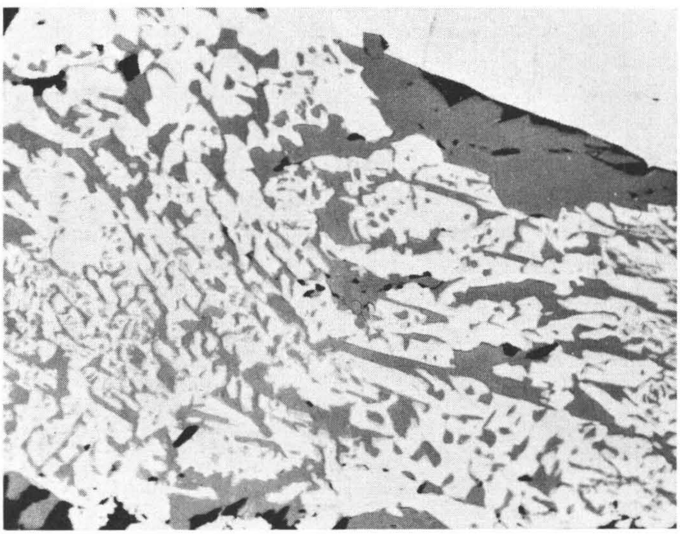


FIG. 47. The intergrowth of light gudmundite and grey pyrrhotite. Black is quartz. The same polished section as Fig. 46 but other site. One nicol. Magn. 150 x. Photo E. Halme.

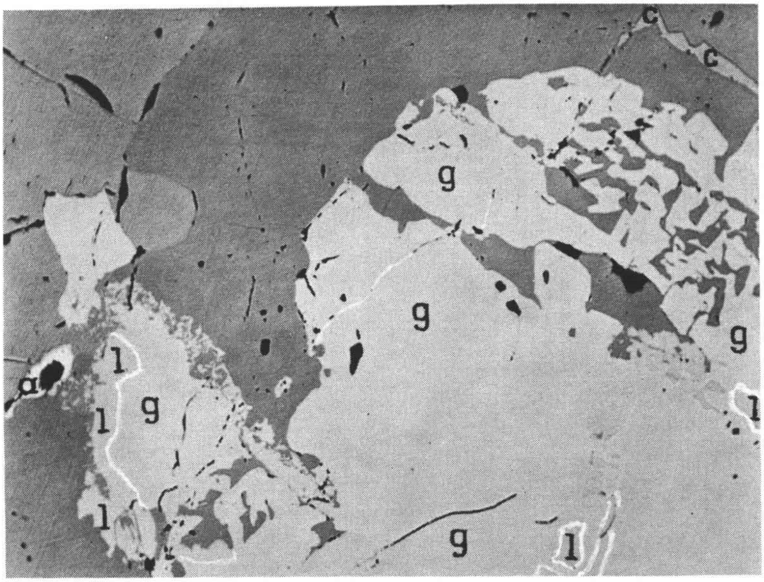


FIG. 48. Light grey gudmundite (g) replaces the dark grey pyrrhotite but not the medium grey chalcopyrite (c). Along the left border of the light area there is slightly darker löllingite (l) between pyrrhotite and gudmundite. Whitest (a) is breithauptite bordered by gudmundite and clearly seen in Fig. 50 Drill hole no. 9. Polished section. One nicol. Magn. 180 x. Photo E. Halme.

Arsenopyrite occurs rather commonly in small amounts throughout the ore zone, and even in somewhat greater abundance in its western part; but it does not form accumulations, its character remaining disseminated. It must, however, be noted that the portion of the ore-bearing rock which contains most native antimony seems to lack arsenopyrite. At least, it has not been detected in the polished sections made from ore specimens taken from drill holes nos. 9, 11, 13 and 14. Logically, arsenopyrite may be considered to have evolved from arsenic and pyrrhotite according to formula FeS + As → FeAsS (Clark 1960), although the evidence is not as clear as in the case of the formation of gudmundite.

TABLE 9

Content of antimony, arsenic, gold and silver in four drilled ore-bearing samples Törnävä, Seinäjoki.

Drill hole no.	m	Sb %	As %	Au ppm	Ag ppm
10	63.40—64.64	3.25	0.53	trace	2.0
10	64.64—66.00	3.70	0.83	0.2	0.8
15	74.20—74.72	0.0	1.68	28.0	0.6
15	79.70—80.20	1.20	0.79	0.2	0.4

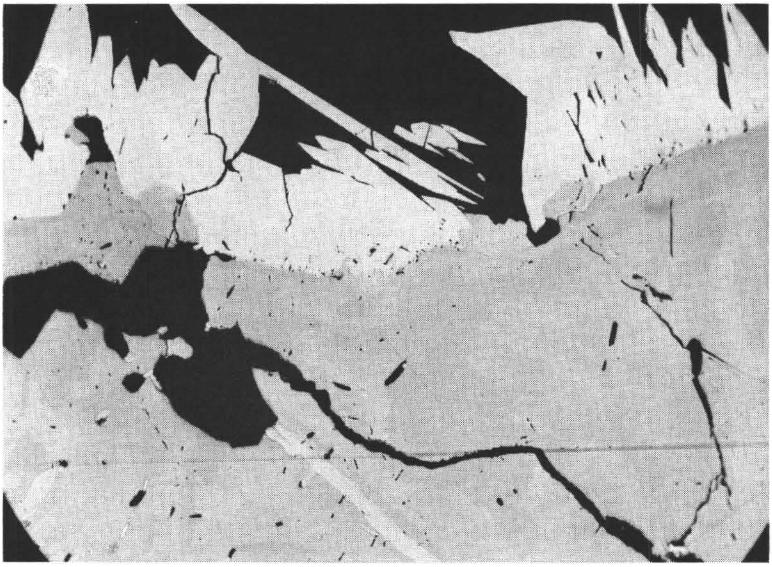


FIG. 49. Dark grey pyrrhotite is bordered by light gudmundite; the medium grey chalcopyrite occurs within both and at their contact. Black is quartz. Drill hole no. 9. Polished section. One nicol. Magn. 180 x. Photo E. Halme.

In Table 9 it is seen that the content of arsenic is lower than the content of antimony but arsenic and gold follow each other more than antimony and gold.

P y r i t e occurs very seldom in conjunction with antimony minerals and very scantily also in nearby country rocks, but nevertheless to an appreciable extent in graphite phyllite and occasionally in sericite quartzite zones. In these zones, however, the occurrence consists of small isolated grains, whereas in graphite phyllites the mineral is to be observed as grain clusters elongated in conformity with the schistosity. Pyrite is occasionally found also as filling in fracture fissures in nearly all the types of rocks occuring in the region.

C h a l c o p y r i t e occurs only in minimal amounts, usually as small, isolated grains. In general, the chalcopyrite content is quite insignificant. In Figs. 48 and 49 chalcopyrite is present both as inclusions in pyrrhotite and as grains situated between the pyrrhotite and gudmundite that often borders on it.

S p h a l e r i t e is often present but always in insignificant amounts.

H e m a t i t e has been met with in a few samples in very small amounts.

S c h e e l i t e appears in a few rock fragments in the antimony ore zone. It is present, disseminated in small amounts, in drill hole no. 18 between 34.08 and 34.48 m (W = 0.04 %) and between 35.10 and 35.32 m (W = 0.14 %).

L ö l l i n g i t e occurs sometimes as pockets in pegmatite dikes penetrated by drill as well as occasionally in the middle of clusters of arsenopyrite and silicified schist rocks.

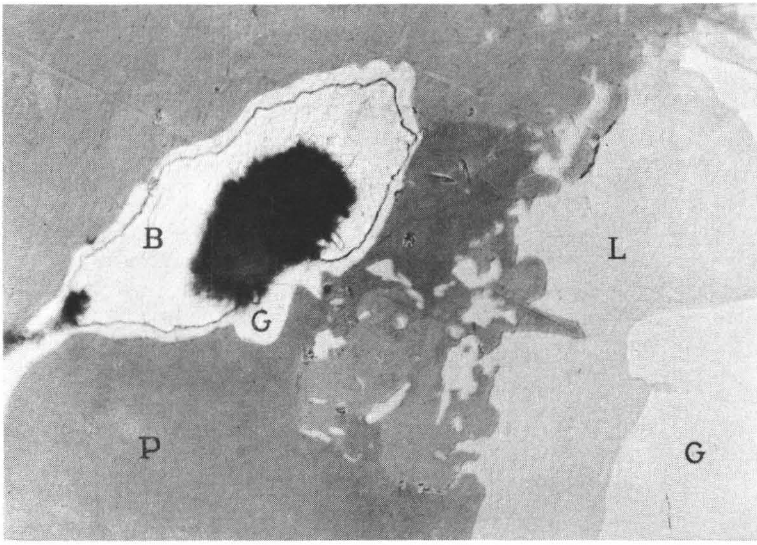


FIG. 50. Breithauptite grain (B) is bordered by gudmundite (G) and forms an inclusion in pyrrhotite (P). L = löllingite. Drill hole no. 9. Polished section. One nicol. Magn. 1125 x. Photo E. Halme.

The gold content varies considerably but generally remains low, being present appreciably only in the portions of the ore-bearing rock with the highest arsenic content. In a small space (74.20—74.52 m) in drill hole no. 15 a content as high as 28 g/ton was noted, and there it was possible microscopically to detect a few grains of native gold.

Breithauptite is encountered only in the core specimen of drill hole no. 9 (225.35 m). As seen in Fig. 50 the breithauptite grain is bordered by gudmundite.

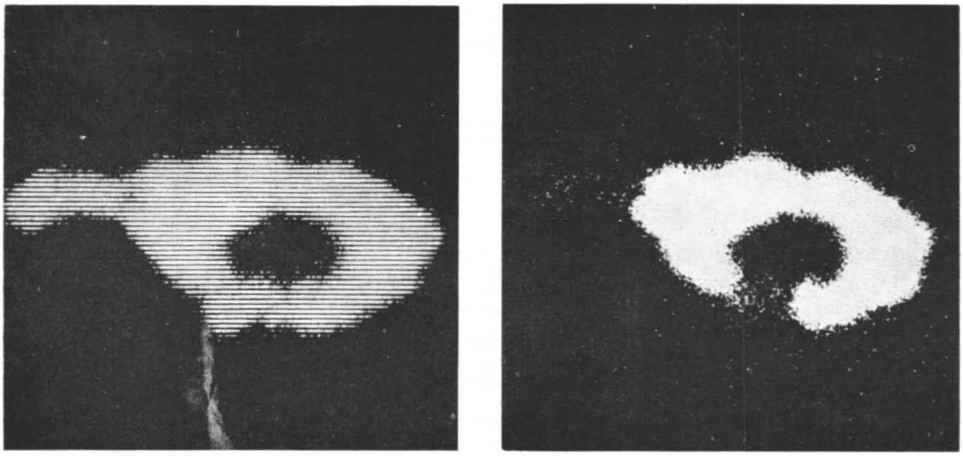
TABLE 10

Hardness and reflectivity values yielded by ore minerals from Törnävä, Seinäjoki. Determined by Lauri Hyvärinen.

		Pressure hardness [1] $H = \frac{1854 \cdot 4xP}{d^2}$	Reflectivity [2] $\frac{R\ green + R\ orange}{2}$ %
Native antimony	Sb	95	74
Stibnite	Sb_2S_3	95	40
Berthierite	$FeSb_2S_4$	200	35
Pyrrhotite	FeS	290	34
Gudmundite	FeSbS	570	57
Löllingite	$FeAs_2$	900	56
Arsenopyrite	FeAsS	1 050	51

[1]) Pressure P = 50 g; d = diagonal length of Vickers' diamond in μ.

[2]) Leitz Mikroskop-photometer für Reflexionsmessungen (Berek). E. Leitz Wezlar 346.



Sb Lα Ni Kα

FIG. 51. Scanning pictures of electron probe analyser showing distribution of antimony (striped area) and nickel (white area). The same polished section as Fig. 50 but magn. 750 x. Analyst: Jaakko Siivola.

In all probability breithauptite was formed during the reaction between pyrrhotite and native antimony and caused by the slight nickel content of pyrrhotite.

Because of the minute grain size (0.05 mm) the confirmation of breithauptite was carried out by »Geoscan» electron probe analyser (Fig. 51).

Ore grades and quantities

Investigation of the ore prospect of Törnävä has proved that the chief mineral contained in the deposit is native antimony. In addition, the antimony-bearing gudmundite and stibnite add noticeably to the antimony content of the ore. As a result, though the ore appears to be poor macroscopically, the antimony content

TABLE 11

Quantity of ore in holes drilled in the eastern part of the Törnävä field

Drill hole No.	Depth interval in meters	Ore thickness m	Sb % (mean value)	% m³ [1]	Au content g/ton (ppm)
10	62.53— 71.64	9.11	1.40	54 204	0.0—0.3
11	18.80— 21.02	2.22	0.85	3 680	0.2—0.4
13	85.74— 88.50	2.76	1.21	16 698	0.0—trace
14	69.85— 70.90	1.05	2.63	13 531	0.0
9	224.10—226.35	2.25	0.85	4 781	0.0—0.2
			Total	92 894	

[1]) % m³ = Sb-percentage x estimated volume

TABLE 12

Quantity of ore in holes drilled in the western part of the Törnävä field

Drill hole No.	Depth interval in meters	Ore thickness m	Sb % (mean value)	% m³	Au content g/ton (ppm)
15	64.25— 66.83	2.58	0.29	1 833	1.82
	74.20— 80.20	6.00	0.30	4 410	2.71
18	15.40— 19.20	3.80	0.58	3 085	0.0—trace
	30.20— 41.20	11.00	0.49	7 546	0.0—0.5
	43.65— 50.45	6.80	0.93	8 853	0.0—trace
19	48.50— 51.55	3.05	0.37	8 464	0.0—0.1
20	55.40— 56.50	1.10	0.38	1 045	1.0
	96.80— 98.50	1.70	0.46	1 955	1.8
21	121.09—123.75	2.66	0.66	15 960	0.0—0.5
23	63.90— 73.30	9.40	0.78	9 165	0.0
			Total	62 316	

rises in places to over three per cent. This content has, however, only been found in drill hole no. 10. The antimony content of the ore met with in the other holes varies mainly around one per cent, and only in exceptional instances does it exceed 2 %. The gold content of the ore-bearing rock in drill holes nos. 15 and 20 is over 1 g/ton, but elsewhere it is less than that and therefore insignificant. The same must be said of the very slight silver content. Tungsten is likewise present scantily and altogether sporadically.

Owing to the sparse network of diamond drillings, the amount of ore one might regard as commercially significant is exceedingly small. But considering the clear continuity of the deposit both in length and in depth, rough estimates of the ore content can be made. The calculations have been carried out by assuming the ore grade found in the drill holes to extend in length half way to the following hole and in depth the same distance as between the site of the ore zone found in the drill hole and the outcrop observed. On the basis of this assumption and the mean value of specific gravity determinations (2.75) the ore reserves in the eastern part of the Törnävä field are 200 000 tons (Table 11), by the mean value of the analysed

TABLE 13

Content of gold in drill hole 21, western part of the Törnävä field

Drill hole No.	Depth interval in drill hole m	Ore thickness m	Sb %	Au g/t	g/t m	Mean value Au (ppm)
21	60.82—62.41	1.59	0.06	2.2	3.5	
»	62.41—63.40	0.99	0.00	0.0	0.0	
»	63.40—65.20	1.80	0.12	2.2	4.0	
		4.38			7.5	1.7 g/t

antimony contents 1.37 per cent, and in the western part 300 000 tons (Table 12), by the mean value of antimony 0.51 per cent.

Also worth noting is a slight isolated enrichment of gold in drill hole no. 21, which has not been included in the overall count because it is very poor in antimony (Table 13).

The ore occurrence of Syrjämö

In connection with geophysical investigations carried out in the field, an antimony mineral occurrence was detected in the rock exposed in the bed of a stream near the Syrjämö farmhouse (Figs. 7 and 20), which stands some 600 m from the church of Törnävä toward the southeast. The deposit apparently represents an extension of the Törnävä ore body, which may be regarded as the chief ore occurrence; but since, according to both geophysical surveys and diamond drillings, there is a break or at least a noticeable weakening in the sequence, the ore deposit at Syrjämö may be considered as a separate occurrence.

In the light of outcrop specimens and the cores obtained from four diamond drillings, it must be stated that the Syrjämö ore is very much like that found at Törnävä. The antimony mineral content is here too principally associated with a sericitized and silicified mica gneiss zone. The chief minerals of the mica gneiss vary in most cases, according to the different layers: andesine-plagioclase (An_{30-40}), quartz with an undulating extinction and strongly oriented biotite. In smaller but also varying amounts, there occur muscovite, microcline and tourmaline. Sporadic accessory constituents are diopside, epidote, sphene, zircon and apatite. In spite of its strong metamorphism, the rock's original stratification appears both in the variability of the amounts of the minerals present and in the grain size which is between 0.001 and 0.1 mm. The bedding is disturbed by quartz veins of varying thickness, which occurs as layered dike-like or lenticular bodies consisting of grain sizes between 1 and 2 mm in diameter.

A fine-grained dissemination of pyrrhotite is common, but in the silicified zones the pyrrhotite grains grow sparser and conspicuously larger. Upon approaching the ore zone proper, one will notice antimony minerals, bound up with or in the proximity of pyrrhotite grains.

Quite within the ore belt the plagioclase is strongly sericitized, occurring in most instances only as sparse relics attended by prominently oriented sillimanite and biotite. There is an abundance of grossularite ($N = 1.748$) and more than an ordinary content of apatite, too. The thickness of the nearly vertical ore deposit proper is roughly five meters both in the exposure situated in the locality of the brook and in the holes drilled under the exposure in the same profile section (Fig. 52). But it narrows down and evidently weakens both toward the west and the east, for in the hole drilled 50 m farther to the east the ore content is very weak, being only 1 % Sb over a distance of 82 cm, and 100 m farther west the antimony mineral content can be detected only under the microscope. Owing to the lack of outcrops and the limited

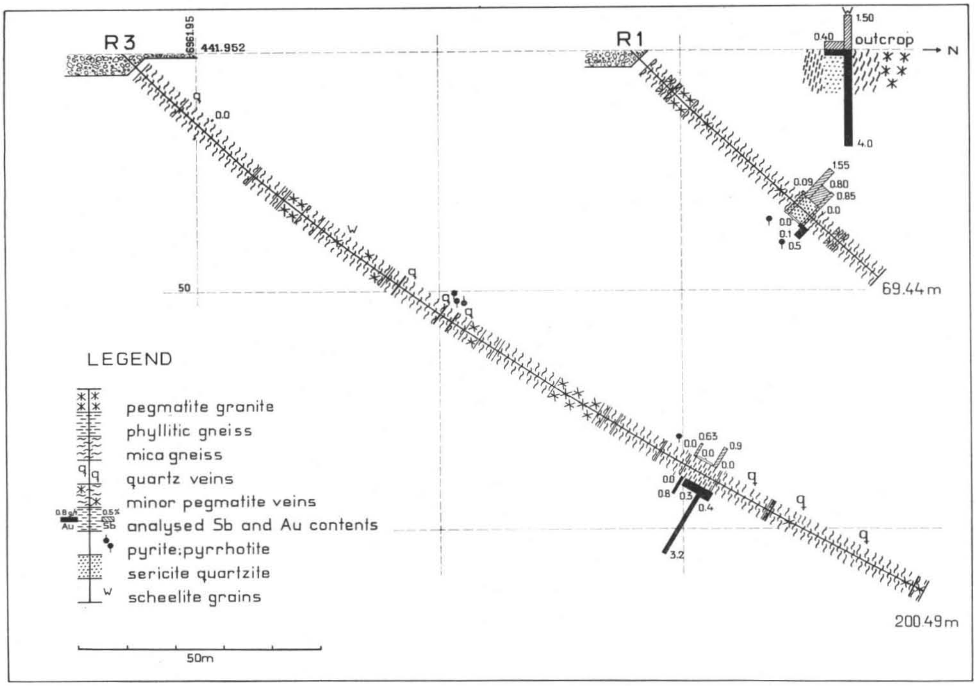


FIG. 52. Vertical cross section of the Syrjämö antimony zone.

ore occurrence for sure. But indications show that it can scarcely be of any significant number of the drill holes it is not, of course, possible to determine the extent of the size, although perhaps it continues sufficiently downward, as suggested by the weak occurrence of ore met with at a depth of about 100 m in drill hole no. 3. Despite the fact that the dip of the schistosity in the surface exposure is 85° S, the general dip of the ore body appears nevertheless to be about 65° S.

Among the ore minerals primary attention is commanded by the native antimony in the exposure, occurring as it does as lumps half the size of a man's fist in association with quartz lenses. It has also been noticed at many points in the drill holes. The other chief mineral in the exposure and the drill holes is berthierite, which also occurs in conjunction with quartz bodies (Figs. 44 and 45). Gudmundite, arsenopyrite and stibnite are commonly present but in smaller amounts than the previously mentioned minerals. The content of pyrrhotite and sphalerite is trifling. Hematite, magnetite, pyrite, scheelite and gold occur only sporadically as tiny grains.

In a sample taken from the outcrop of Syrjämö a very small jamesonite grain (diameter 0.01 mm) is observed with the aid of an electron probe analyser

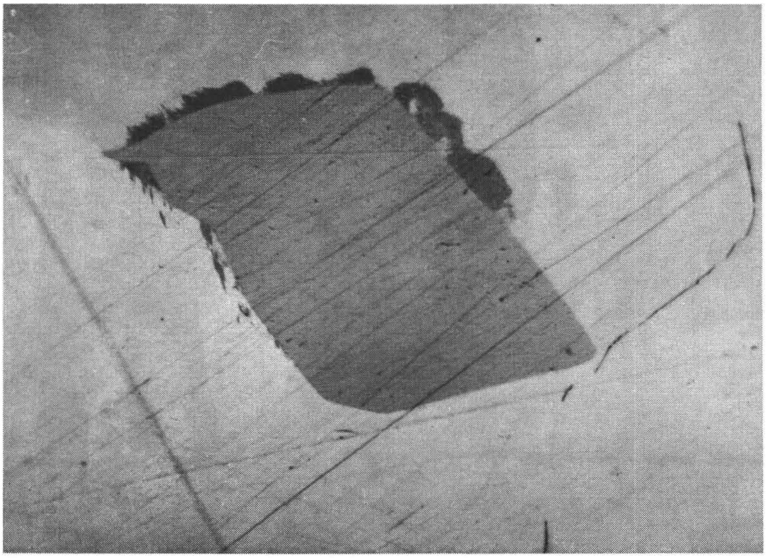


FIG. 53. The grey grain is jamesonite with darker tetrahedrite along its margins. The light mineral is stibnite. Syrjämö outcrop. Polished section. Nicols +. Magn. 900 x. Photo B. Lindmark.

(Geoscan). Situated between two larger stibnite grains (diameter 0.1 mm) the jamesonite grain is partly bordered by a tetrahedrite fringe with a width of 0.001 mm (Fig. 53, Table 14). The same sample contains abundantly native antimony, stibnite and arsenopyrite. Berthierite and sphalerite are met with in minor amounts.

Also in the samples taken from the Syrjämö outcrop, one can observe the alteration of pyrrhotite into gudmundite in varying degrees and especially the myrmekite-like appearance of the pyrrhotite in it.

Löllingite was met with as a few thin grains, 2 to 5 mm long, in the pegmatite occurring near the end of drill hole no. 3 (49.50 m). Vickers hardness is at right angles to elongation 585—649, and 894—900 parallel to it.

Fig. 52 reveals the modest content of precious metal in the ore body as well as the fact that the deposit is situated in the exceptionally strongly altered zone of sedimentogeneous schist penetrated by pegmatite veins.

The native antimony of the Syrjämö outcrop contains 3.26 % arsenic, 0.2—0.6 g/ton silver. According to the spectral analysis it contains 0.035 % bismuth and traces of Si, Al, Fe, Ca, Mg, Pb and Cu. In drill hole no. 1 (46.66—47.90 m) the content of antimony is 1.55 %, arsenic 0.17 % and silver 1.6 g/t. Only traces of gold have been detected.

8 7567—66

TABLE 14

Tetrahedrite $(Cu, Zn, Fe)_{12} Sb_4S_{13}$

Seinäjoki		B & T[1])		
I	d (Å)	I	d (meas)	hkl
vw	5.16	1/2	5.19	022
w	3.64	1	3.69	022
100	2.976	10	3.00	222
w	2.757	1/2	2.78	123
m	2.581	1	2.61	004
mw	2.425	1	2.46	033; 114
vw	2.315	1/2	2.33	024
vw	2.212			
vw	2.110	1	2.12	224
m	2.030	1	2.04	134; 015
m	1.889	1	1.895	125
s	1.828	6	1.831	044
vw	1.778	1/2	1.784	334; 035
		1/2	1.722	244; 006
m	1.681	1	1.687	235; 116
		1/2	1.647	026
s	1.562	3	1.563	226
		1/2	1.501	444
vw	1.494			
vw	1.463	1/2	1.467	055; 017; 345
		1/2	1.410	255; 127; 336
		1/2	1.386	246
vw	1.298	1/2	1.299	008
w	1.278	1/2	1.277	118; 147; 455
		1/2	1.258	446; 028
w	1.240	1/2	1.244	356
mw	1.204	1/2	1.204	138; 057; 347
mw	1.191			
w	1.119	1	1.189	266
		1/2	1.157	048
		1/2	1.116	167; 129; 556
mw	1.095	1/2	1.092	039; 158; 457
mw	1.072			
m	1.061	2	1.056	
vw	1.048			
w	1.028			
m	0.9998	1/2	0.996	
ms	0.9901	1/2	0.988	
m	0.9728			
		1/2	0.953	
		1/2	0.937	
		1/2	0.922	
		1/2	0.875	

I: 100 > s > ms > m > mw > w > vw

[1]) C. G. Berry and R. M. Thompson (1962)

Porphyritic body of Satamo

The rock at Satamo (Figs. 19, 20 and 22) forms a zone extending eastward. It had previously (Saksela 1935) been designated as basic leptite. Due to its proximity and parallelism with the ore deposit the rock seems to have had an effect on the antimony ore formation. Antimony-bearing minerals were, in fact, first detected in the rock, in association with separate bodies of quartz. The chief mineral component of the rock is a small-grained (less than 0.5 mm) and in many instances zoned plagioclase (An_{25-30}). It also occurs as larger (5—10 mm), frequently zoned phenocrysts or clusters of phenocrysts and the zoning is often oscillatory in character. The amount of quartz in the rock is small, but there is an abundance of biotite and in spots also ragged hornblende or, as an alteration product of it, considerable amounts of pennine with numerous small inclusions of ilmenite grains. Accessory constituents are sphene and apatite, in some instances, tourmaline. Carbonate occurs sporadically as small pockets or fissure veins. Owing to its general metamorphosed and partial mylonitized nature and due to its rather gentle metamorphism which has resulted in the preservation of the phenocrysts of plagioclase and because of its intermediate composition, the term porphyrite would be more descriptive for the rock. The hornblende also appears to have been originally as phenocrysts, though in spots reduced to tatters or totally altered to chlorite containing inclusions of ilmenite grains. In conjunction with dynamometamorphism, metasomatic mineralization seems also to have occurred. The previously mentioned pockets of quartz have a slight ore mineral

TABLE 15

Chemical composition of porphyrite, Seinäjoki. Analyst: A. Heikkinen.

	Weight per cent	Molecular proportion	Weight norms		or: ab: an
SiO_2	64.62	10 759	Q	5.11	
TiO_2	0.60	75	or	13.29	15.39
Al_2O_3	15.80	1 550	ab	55.99	64.83
Fe_2O_3	0.49	31	an	17.09	19.78
					100.00
FeO	4.76	662	en	3.38	
MnO	0.08	11	fs	3.32	
MgO	3.00	744	cor	0.34	
CaO	3.99	711	mt	0.33	
Na_2O	3.66	590	il	0.51	
K_2O	1.24	132	ap	0.09	
P_2O_5	0.12	8		99.45	
CO_2	0.21	5	$CaCO_3$	0.01	
H_2O+	1.03				Sb = 0.00 (5) %
		611	H_2O	0.24	
H_2O-	0.07				
Cu	0.02		Cu		
		4		0.01	
S	0.02		S		
	99.71			99.71	

content. The same phenomenon is met with in the porphyrite itself. A scattered occurrence of ilmenite, especially, is fairly common, but also small-grained pyrrhotite and chalcopyrite occur as scattered groups and isolated grains of varying size. Frequently in conjunction with clusters of chalcopyrite grains, one is likely to run across tetrahedrite crystals, either separately or in intergrown bunches, the largest of the grains being 0.3 mm in diameter. Here and there one sees a few small grains of arsenopyrite, löllingite and sphalerite or on rare occasions native antimony flakes measuring less than 0.05 mm in diameter and sometimes bordered by stibnite.

In the light of chemical analysis (Table 15), the composition of the rock approaches that of quartz diorite, but with respect to its structure it could be of hypabyssal origin and, more than anything else, trachyandesitic vein rock.

Calcite occurs not only as narrow carbonate veins and phenocrysts but also as slightly larger bodies filling cavities, whose middle portion is calcite but whose margins consist of grossularite and epidote as well as spots of quartz with a partly undulating extinction. Furthermore, a slight splash of scheelite and scattered apatite grain may be noticed here and there. Slight crushing action appears to have occurred even after the formation of the garnet, for epidote and, to some extent, calcite are present as filling in the garnet's cracks.

Upon investigating the contents of the pocket of sulfide mineral found in the macadam quarry of Satamo, Saksela (1952) discovered pyrrhotite, fahlerz, chalcopyrite, arsenopyrite, cobaltite, sphalerite, gudmundite, breithauptite, linneite, berthierite and argentopyrite (Silberkies) embedded in the quartz veins, which in turn occur in a variety of rock designated by him as basic leptite. After describing the minerals, their mode of occurrence and the amounts in which they are present, he also treats their age sequence. The minerals of the parent rock, he reports, are quartz, carbonate and colorless amphibole. In connection with the first brecciation, the chief minerals of the ore material evolved: arsenopyrite, cobaltite, gudmundite, pyrrhotite, fahlerz, sphalerite and chalcopyrite. In connection with the second brecciation, there would have occurred a partial dissolution of the fahlerz, whereupon gudmundite, breithauptite, chalcopyrite and sphalerite would have formed. During the late facies there would have occurred a further dissolution of the fahlerz and the introduction of additional material, creating gudmundite, pyrrhotite, chalcopyrite, pyrrhotite-chalcopyrite-myrmekite and chalcopyrite-linneite-myrmekite bound up with sphalerite as well as berthierite and argentopyrite. As regards the genetic process, Saksela primarily favors the concept that the vein formation is associated with hydrothermal phenomena, in which case the ore solutions would have derived from the complex pegmatites abundantly in the region. He considers as a second possibility that the fahlerz-rich vein components might be the enriched products of some process acting upon a previously poor sulphide ore occurrence. He ventures the prediction, subsequently proved correct, that larger sulphide ore deposits would be discovered in the vicinity. Finally, he deems it possible that the volcanogenic leptite itself might have influenced the genesis of the fahlerz-bearing quartz veins.

Later investigation of the macadam quarries at Satamo brought to light, in conjunction with the quartz veins, numerous small chalcopyrite-pyrrhotite pockets which also contained sphalerite; but neither fahlerz nor other less common minerals listed by Saksela were to be found in them. On the other hand, one specimen taken from a pocket investigated by Saksela proved also to contain native antimony both as small inclusions in the fahlerz grains and as narrow border and fissure-fillings. Under these conditions, the antimony appears even more conspicuously white and bright than the gudmundite, weakly anisotropic and softer even than the chalcopyrite. In addition to these minerals ullmannite (Ni (Fe, Co) SbS) is seen as myrmekitic inclusions in chalcopyrite bordering on tetrahedrite in the same specimen. The electron probe analyses revealed arsenopyrite containing a small amount of cobalt and nickel.

Besides the pockets of antimony mineral met with in the quarries, it has also been encountered in the outcrops farther south at point x = 6961.39, y = 441.97, in which the rock is not porphyritic but more prominently schistose and fine-grained. In these rocks the plagioclase is, to be sure, partly zoned, though, after the fashion of metamorphic rocks, very indefinitely. The rock also contains considerable amounts of biotite and shredded chlorite, which evidently represent the remnants of amphibole. Accessories are apatite, sphene and, in some abundance, small scatterings of the ore grains. Coarser plagioclase occurs here and there as lense-shaped clusters conforming to the bordering texture. The ore grains are chiefly situated in dense fine-grained bands that have undergone silicification. Pyrrhotite and arsenopyrite occur in somewhat greater abundance in the form of disseminated ore, while chalcopyrite, gudmundite, stibnite, native antimony and, in some instances, also pyrite are present more sporadically. Chalcopyrite and pyrrhotite sometimes occur as ragged inclusions in gudmundite, while in some cases tiny chalcopyrite grains are found in association with arsenopyrite or pyrrhotite. In the outcrops the ore mineral content is far below the significant amount and only serves to indicate the distribution of antimony mineralization over a fairly broad area.

As far as the regional occurrence of the antimony minerals is concerned it is sure that more of them can be discovered in the surroundings of the investigated area. This assumption is supported by the several occurrences of the intermediate rocks such as the porphyrite of Satamo in the neighborhood. Likewise the tectonic circumstances and the similar metamorphic sedimentary rocks characteristic of the Törnävä area occur largely in the surroundings. Bearing this possibility in mind diamond drillings nos. 24, 25 and 26 were carried out in the so-called Pentinneva area, into which the magnetic and electromagnetic indications of the Törnävä — Syrjämö zone extend (Fig. 9). The anomalies proved, however, to be caused by a weak scattering of pyrrhotite and graphite in phyllite. To be sure, the core of drill hole no. 24 yielded an antimony content of 0.15 per cent between the depths of 43.80 m and 45.40 m, which could be traced to arsenopyrite and löllingite contained in silicified phyllite.

TABLE 16

The ore minerals identified in Seinäjoki

Drill hole no.	Sb	Sb_2S_3	FeSbS	$FeSb_2S_4$	FeAsS	FeS	FeS_2	$CuFeS_2$	ZnS	Au	Fe_2O_3	$FeAs_2$	$CaWO_4$	C
22 ..	+		+		+	+	+	+	+			+		
16 ..						+	+							
17 ..					+	+	+	+	+					
23 ..			+		+	+	+					+		
18 ..	+	+	+	+	+	+	+	+	+				+	
15 ..	+	+	+		+	+	+	+		+	+			
19 ..	+		+		+	+	+							
21 ..	+	+	+		+	+	+				+			
20 ..	+	+	+		+	+	+	+		+				
11 ..	+	+	+		+	+				+	+	+		
14 ..			+			+	+	+	+		+			+
13 ..	+	+	+			+	+	+			+			+
9 ..	+		+	(NiSb)	+	+	+	+						+
10 ..	+	+	+		+	+	+							+
12 ..	+		+		+	+	+	+				+		+
4 ..	+	+	+		+	+	+							
2 ..	+	+	+			+	+				+			
1 ..	+	+	+	+	+	+		+						
3 ..		+	+	+	+	+	+	+		+		+	+	
6 ..						+		+						
24 ..					+	+	+	+	+			+		
25 ..						+	+		+					+
26 ..						+								+
27 ..						+	+	+						+
29 ..						+	+	+	+					+
a ..	+	+	+	+	+	+	+	+	+	+	+		+	+
b ..	+	+	+	+	+	+	+	+	+				+	
c ..							+		+					+
M ..	+	+	+		+	+		+						

Drill hole nos. 1—4 Syrjämö occurrence
» » » 9—14 Easter part of the Törnävä field
» » » 15—23 Western part of the Törnävä field
» » » 24—29 Outside the ore zone
a = Syrjämö outcrop (jamesonite, tetrahedrite)
b = Satamo » (tetrahedrite, cobaltite, ullmannite)
c = Törnävä » (graphite zone)
M = Ore boulder of Malinen

According to Ödman (1942) antimony may also be present in arsenopyrite. This anomalous content of arsenic and antimony in the schists may however point to the further but possibly deeper extension of the ore zone.

In Table 16 the ore minerals found in the drill cores and in the rocks of the outcrops are listed. It is to be seen that pyrite and pyrrhotite occur generally in the schists but the antimony minerals only in the ore zone proper.

Chalcopyrite occurs generally in minor amounts but in the silicified inclusions of the porphyrite area it is more common and as abundant as tetrahedrite.

COMPARISONS AND DISCUSSION ON THE GENESIS OF THE ANTIMONY ORE OF SEINÄJOKI

Of the few antimony occurrences so far met with in Finland the Törnävä find is the most noteworthy. The most important of those previously known, it may be said, is the occurrence in the Ylöjärvi locality, Järvenpää, which has been found to contain gudmundite, bournonite, boulangerite and copper-antimony-fahlerz (Saksela 1947). These antimony-bearing minerals also occur only as rarities in silicified and sericitized schists in association with intermediate volcanics in addition to pyrrhotite, pyrite, chalcopyrite and arsenopyrite as well as sphalerite and galena. Scheelite too occurs at Ylöjärvi but not in the Järvenpää district, though in association with the nearby copper ore of Paronen with its considerable content of arsenopyrite. Besides a number of other ore minerals, the Paronen occurrence also includes galena, matildite, native bismuth, bournonite, boulangerite, tetrahedrite and gudmundite (Himmi 1959, Clark 1965). Included in the varied mineral assemblage of the Pyhäsalmi ore (Pyhäjärvi Ol.) there are two antimony-bearing minerals known as andorite ($AgPbSb_3S_6$) and geocronite (Pb_5AsSbS_8) (Helovuori 1964). According to the archives of the Geological Survey, stibnite has been reported to occur also at Uiherla, in the commune of Eräjärvi, jamesonite at Taljala, Kalvola and at Pakila, Helsinki, pyrargyrite at Aijala, Kisko, boulangerite at Pakila and gersdorfite at Sarvikainen, Lempäälä, but all as mineralogical rarities. Gudmundite, boulangerite, jamesonite and pyrargyrite have been met with in association with the zinc ore of Vihanti (Mikkola 1963).

The abundance of native antimony in the Törnävä occurrence makes it so nearly unique that finding a sister type is difficult. Of the roughly one thousand other antimony occurrences known to exist on earth (Quiring 1945), only seventeen have been reported to contain native antimony (Table 17) and most of them very little. Only in the Busan Hills of Borneo is the native antimony reported to occur in commercially significant amounts; there it has been found in gravel and in the cavities of limestone, sometimes in bodies weighing as much as 300 g (Posewitz 1892). Nevertheless, the principal antimony mineral occurring in the Busan Hills is stibnite. The reason for the rarity of the known deposits of native antimony may, it is true, be inadequate investigation in cases where the presence is very scanty. It also seems that very special conditions are required for antimony to exist generally in a native state. The primary reason is probably the great lack of sulfur in delivering magma and in the new host rock.

The most usual companion minerals of native antimony are stibnite and arsenopyrite, which in most instances have migrated together with quartz into acid schists. The majority of antimony ores have a predominance of stibnite. Frequently associated with the antimony minerals are gold and tungsten (scheelite). In most cases the former have enriched, however, in different zones or are obtained as by-products of the mining of gold, silver and tungsten ores. A case in point are the tungsten, antimony

TABLE 17
Occurrences of native antimony

Place	Mode of occurrence	Paragenesis
Australia, New South Wales, Broken Hill (Andrews 1922)	Enclosed in calcite	Stibnite
Australia, New South Wales, Hillgrove (Kenny 1924)	In veins of quartz	Stibnite
Bolivia, Bueno Vista (Ahlfeld 1927)	In an oxidation zone of sandstone and quartzite	Cervantite, stibiconite
British-Borneo, Busan Hill (Posewitz 1892)	Veins and pockets in limestone	Stibnite, arsenic, copper, realgar, gold, cinnabar
Canada, Hants County, Nova Scotia (Askwith 1901/02)	In an oxidation zone of lime and clay slate	Kermesite, valentinite
Canada, New-Brunswick (Quiring 1945)	In a quartz-antimonite vein of clay slate and quartzite	Stibnite
Canada, Quebec, South Ham (Quiring 1945)	In pockets with quartz of a Pre-cambrian formation	Stibnite, kermesite, senarmontite, valentinite
China, Chang-Sha (Quiring 1945)	In paleozoic limestone	Stibnite
Czechoslovakia, Böhmen, Pribram, Bohutin (Quiring 1945)	In an oxidation zone with siderite and sphalerite	Kermesite, valentinite, stibnite, allemontite
France, Dauphine, Les Chalanches (Ramdohr 1960)		Arsenic, breithauptite, niccolite, safflorite, kermesite
Germany, Brandholz, Fichtelgebirge (Quiring 1945)	In a vein with quartz, limestone, barite	Stibnite, valentinite, kermesite, stibiconite
Norway, Sulitelma (Ramdohr 1938)	In sulfide ore deposits	Fahlerz, arsenopyrite, gudmundite, galenite
Portugal, Caës de Sobreira (Ramdohr 1960)		Stibnite
Sweden, Sala (Quiring 1945)	In a vein of limestone	Stibnite, galenite
Sweden, Varuträsk (Ödman 1941)	In veinlets in stibiotantalite of pegmatite	Stibnite, microlite
U.S.A. California, S. Emigdio (Quiring 1945)	In a vein in granite	
U.S.A. Nevada, Oreana Lawrence (1963)	In a pegmatite vein	Scheelite, beryl

and gold deposits near Stibnite in Idaho (Cooper 1951). This area in its general features bears a resemblance to the Törnävä occurrence with its intermediate dike rocks (quartz monzonite) and acid cataclastic schists but nevertheless deviates from it by reason of its lack of native antimony and its abundance of stibnite.

»It is thought that the ores near Stibnite were formed in a single period of complex mineralization related to the Tertiary igneous activity of the region. The ore-forming solutions rose from below in three surges, each preceded and followed by fracturing and brecciation. During the first stage, sericite, fine-grained quartz and feldspar, pyrite, arsenopyrite, and gold were formed. During the second stage, carbonates, quartz, and scheelite were formed. The metallic minerals of the first stage were soluble in the solutions of the second stage and were partly leached from the tungsten ore bodies. A small part of the gold thus leached may have been deposited around the sides of the tungsten ore bodies, but probably most of it was deposited above the tungsten and later removed by erosion. In the final stage stibnite, accompanied by silver, quartz, pyrite, and carbonates, was formed. The initial fracturing was very extensive, but these fractures were sealed by the first, or gold, stage of mineralization. Intense but local fracturing near the center of the gold ore body then took place. The second, or tungsten, stage of mineralization was practically confined to this central area. The fractures along which the tungsten was introduced were reopened and extended prior to the final, or antimony, stage.» (Cooper 1951).

It has been difficult to trace the delivering rock of many of the antimony occurrences described in the literature. In several cases the antimony ore material — usually stibnite — has penetrated both metamorphic and unaltered sediments forming veins, pockets or scatterings and chiefly in conjunction with quartz veins, having evidently originated from delivering magmas consolidated deep in the crust.

In most cases the antimony minerals have shown to be consolidated in the ore rock after the other sulphide minerals during the cooling process of the formation. In connection with the Seinäjoki deposits it is clearly seen that the idiomorphic grains of arsenopyrite occur as inclusions in antimonite and in native antimony. Both of these also fill the very small fissures evidently caused by cooling of the wall rock. Because the native antimony of Syrjämö contains 3.2 per cent arsenic the mineralizing temperature may have been about 630° C, which is the liquidus-solidus point of this composition when the pressure varies between 1 and 100 atm. (Skinner 1965).

Utilizable antimony ores are generally gangue formations or are associated as pockets or dissemination zones with quartz veins formed in fracture fissures during tectonization. In this respect the Seinäjoki antimony ore occurrence does not appreciably deviate from the others. Still, the general rarity of antimony — or rather its generally small content in rocks — justifies focussing closer attention on its origin and the possibilities of its becoming enriched into ore bodies. Judging by the majority of the examples presented in the literature, the association of antimony with hypabyssal rocks as pneumatolytic-hydrothermal deposits is apparent (Quiring 1945). Even in the case under consideration it appears highly probable that the arsenic- and antimony-bearing exhalation material had, after separating from the magma, seeped into veins of quartz to produce pockets and scattered occurrences of the minerals or had become impregnated into the schistose country rock. Owing to the low melting point of arsenic and antimony as well as their sulfides, the migratory distances may have been fairly long, as a consequence of which the point of departure cannot always be determined. The prevalence of silicified formations resembling stratiform dikes in the schists of sedimentary origin in the Seinäjoki district and the very low antimony content of these rocks does not adequately support the view of a lateral origin for the antimony enrichments. Rather, their material should be regarded as having migrated from some nearby magma. True, the copper schist of Mansfeld contains 0.001—0.05 % antimony, which is a substantially greater content than the general millionth part geochemical figure for antimony (Rankama and Sahama 1950). At Törnävä graphite phyllites occur in which pyrite enrichments had formed as early as the sedimentation stage (Marmo and Mikkola 1951). But they have not exhibited any distinct antimony content and it is scarcely possible that such slight graphite schist beds could have yielded the quantities of antimony observed in the antimony mineral enrichments under consideration.

Associated with the pegmatites of the Seinäjoki district are quartz veins, but they have not been observed to contain antimony, although they have also been met with in the antimony-bearing schist zone. The gold content is even less than in the antimony- and arsenic-bearing silicifications. A quartz vein associated with pegmatite is recognised by the fact that it is either glasslike in its clearness or has the appearance of milky quartz, whereas antimony follows the veins of very clear but smoky quartz. The only ore minerals met with in the pegmatites of the Törnävä area are löllingite and pyrrhotite, which likewise are quite sporadic in their occurrence. It cannot be stated that the presence of antimony is connected with pegmatites, even though pegmatitic penetrations might be found in extensions of the antimony-bearing zone. Rather it would seem as if the penetrations of pegmatite has had the effect of scattering the antimony-bearing schist zone and thereby destroying previously formed ore deposits. Therefore the porphyrite of Satamo, which runs parallel to the observed antimony-bearing ore occurrence at a sufficiently close distance remains the most probable source of the antimony. The reliability of this supposition is supported further by the small antimony mineral content of the porphyrite itself and its quartz-rich inclusions. It would, indeed, be only natural that more mobile components would boil over out of the intermediate intrusive rock, as it intrudes between schist folds during the synorogenic stage, and which components would then migrate to the zones of weakness created in the country rock. Evidently, these vapors generated during the boiling stage, were extremely poor in sulfur, in view of the fact that a large proportion of their antimony content has remained in the form of native antimony and only part of it combined with the pyrrhotite of the country rock to produce antimony-iron sulfides. There was probably nevertheless enough sulfur for some of the antimony, enabling it to migrate as antimony sulfide, to form stibnite in the country rock.

$$FeS_2 \underset{1\ \text{atm}}{\overset{570^\circ\ C\ [1]}{\rightleftarrows}} FeS + S; \quad 3\ S + 2\ Sb \rightarrow Sb_2S_3$$

It is nevertheless possible that it too might have taken its sulfur from the pyrrhotite in the schist. Likewise arsenic appears to have migrated in metallic form and produced arsenopyrite only after coming into contact with pyrrhotite in the schist and combining with it.

As for the reaction between native antimony and pyrrhotite, there seems to be no obstacle to the formation of gudmundite or the appearance of arsenopyrite through its genesis from arsenic and pyrrhotite. On the other hand, there seems to be an obstacle to the formation of stibnite and berthierite through the union of native antimony and pyrrhotite on account of the affinity of sulfur in metallurgical process to iron rather than to antimony, so that according to the formula

$$3\ Fe + Sb_2S_3 \underset{\text{temp.} < 517^\circ\ C}{\overset{\text{temp.} > 517^\circ\ C\ [2]}{\rightleftarrows}} 3\ FeS + 2\ Sb$$

the end products are iron sulfide and antimony. The reaction, however, is reversible and it thus depends only on the prevailing conditions which direction it will take. Apparently, the pneumatolytic stages of the temperature and the higher pressure cause the displacement of the equilibrium of the reaction.

The same sort of phenomenon is reported by Maucher (1938) to have happened in a bravoite-bearing fragment of serpentine rock embedded in a vein of stibnite in which the bravoite appears to have altered to gudmundite as a consequence of stibnite having invaded the rock.

Vei Diu-Yin and Saukov (1961) assume that antimony occurrences have evolved out of the hydrothermal solutions of alkaline sulfides because such occurrences are ordinarily close to the earth's surface and in association with carbonate rocks.

In conclusion it may be stated that magma containing arsenic and antimony considerably in excess of the normal, lost these elements pneumatolytically after which they seeped into the country rock and lodged there in zones determined by the temperature. Crystallization either as native antimony or as compounds was dependent on the amount of pyrrhotite present. The arsenic was evidently even more likely to combine with the pyrrhotite, but there seemed to be enough of it left over to form mixtures with native antimony, as the analysis shows.

Evidently the ore forming process has happened during the mountain folding connected with the subvolcanic activity. It is apparent that the following pegmatite granite intrusion process has caused alterations in the ore zone.

[1] Equilibrium (Ramdohr 1960).

[2] Liddell (1945).

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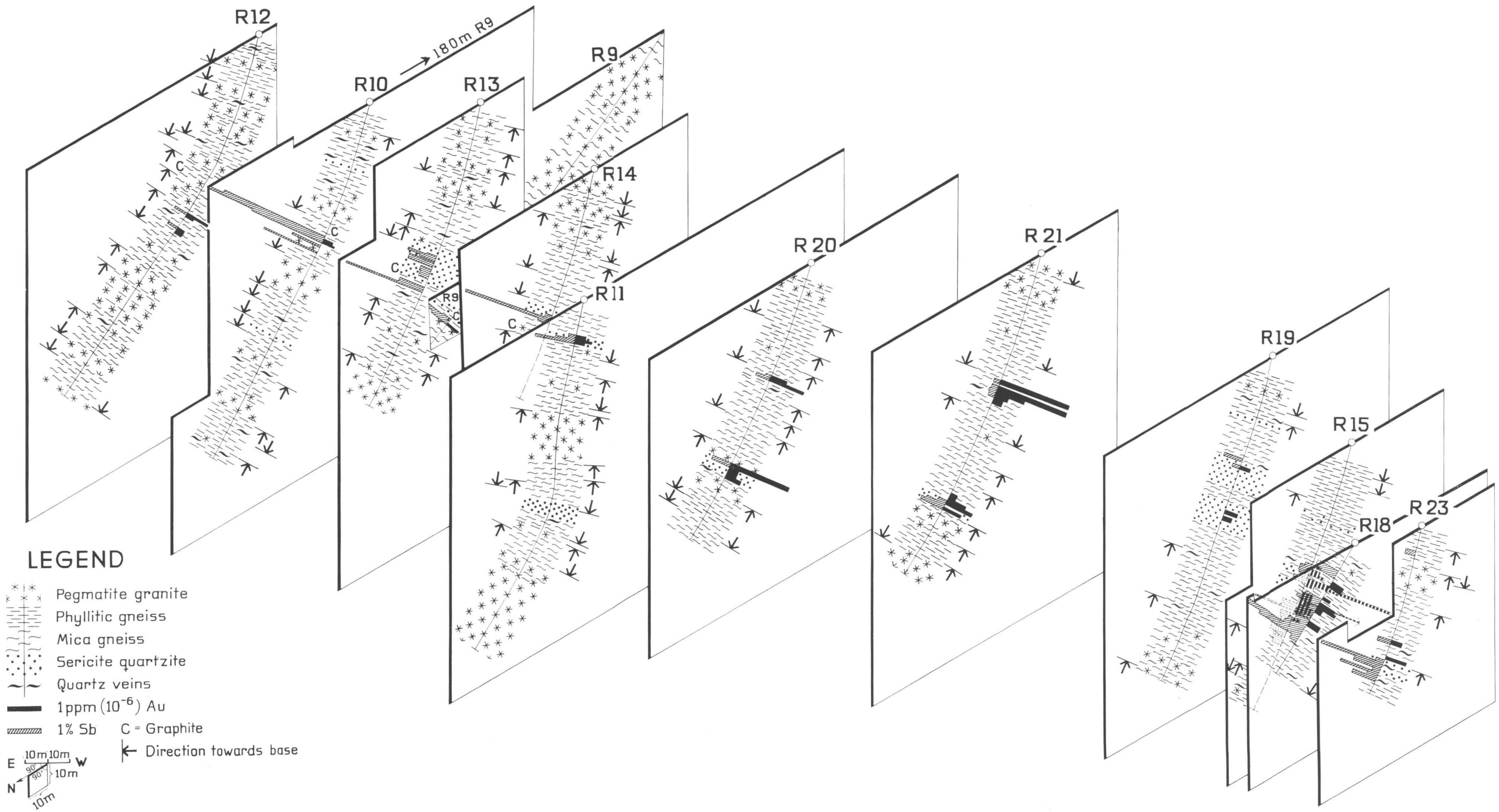
Twelwe drill hole profiles viewed from the northwestern side of the ore zone. They are shown in such a way that the starting points of the holes are correctly placed in relation to each other. The plane of the curve illustrating each drill hole, the lengths of which are on scale, is turned 60° to E around the vertical line running through the starting point of the drill hole. The view is nearly the same as if looking at a true spatial model from a NW direction. Drill hole no. 9 shows only the middle part and the significant lower end, and it too has been placed almost in its right place. However, deviating from the aforesaid rule, its projection plane has been turned around the same vertical line as drill hole no. 10.


R12
R10
180m R9
R13
R9
R14
R11
R20
R21
R19
R15
R18
R23
C
R9
LEGEND
Pegmatite granite
Phyllitic gneiss
Mica gneiss
Sericite quartzite
Quartz veins
1ppm (10^-6) Au
1% Sb
C = Graphite
Direction towards base
E
W
N
10m
10m
10m
10m
90°
90°