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# ARSENIC-COBALT-NICKEL-SILVER VEINS IN THE LINDSKÖLD COPPER MINE, N. SWEDEN

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*Pris 0,50 kr.*

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## Introduction.

The Lindsköld ore belongs to a group of copper deposits occurring within the altered Archaean volcanics of the Kuorbevare area which is situated in the north-western part of the Skellefte District in northern Sweden (*6*, p. 76). In the course of underground work preceding the mining operations proper a mineral paragenesis quite foreign to the general mineralization of the area was discovered. This paragenesis is characterized by the occurrence of arsenic-, silver- and at times also of Co-Ni-minerals. A more comprehensive description of the ores within the Kuorbevare area is under preparation, but the particular features of the As-Ag-Co-Ni paragenesis as compared with the Kuorbevare ores as well as with pre-Cambrian mineral deposits in Fennoscandia in general, call for a special description, even though the mineralization so far known is quite insignificant.

In several instances the microscopical studies of the minerals have been confirmed by X-ray investigations. Thanks to the courtesy of the Boliden Mining Company the majority of the powder photographs could be produced in the Boliden Laboratory at Stockholm. The author wishes to express his gratitude to Mr O. Alvfeldt C. E. and to Dr. F. Wickman for their kind assistance in the X-ray work. In one instance the powder photographs were produced at the Chemical Institute of the University of Stockholm, where the determinations of the lattice dimensions could be performed with a higher degree of accuracy.

The spectrographic analyses were performed at the Geochemical Laboratory of the Geological Survey by Dr. S. Landegren and Dr. O. Gabrielsson.

## Survey of the Minerals and their Mode of Occurrence.

The principal minerals of the Lindsköld copper ores are chalcopyrite, pyrrhotite and arsenopyrite. The sulphides occur as disseminations, breccias or massive masses, forming a flatly dipping ore zone in cordierite- and cummingtonite-bearing quartzose rocks which were formed through metasomatic alteration of acid volcanics. These ores thus belong to a characteristic type of sulphide deposits in Fennoscandian Archaean regions.

The silver- and arsenic minerals were encountered in two calcite fissure veins, one on the 100 m, the other on the 50 m level. Both veins dip about vertically. On the 100 m level the somewhat winding vein is 1—2 cm wide and cuts the main strike of the altered rocks at an obtuse angle. It was primarily encountered in a disseminated zone containing pyrrhotite, pyrite, sphalerite and chalcopyrite, situated about 15—20 m below the main ore body. The appearance of greyish lumps of native arsenic and red coatings of proustite immediately

attracted attention to this special type of mineralization. In addition, pale yellow sphalerite was visible to the naked eye. A microscopical investigation revealed the occurrence of another couple of minerals, *viz.* native silver, dyscrasite, löllingite, tetrahedrite, galena and chalcopyrite. The filling of the fissure consists essentially of a white, coarse-grained calcite matrix. In addition quartz, zeolites and fluorite were observed in small quantities.

The same calcite vein has been struck by cross-cuts at another two places on the 100 m level, about 75 m from each other. In one of these cases the calcite vein cuts a diabase dyke, which appears within the whole mine at a distance of 20—40 m below the main copper ore. This diabase is genetically closely related to the sulphide mineralization but crystallized before the sulphides. In the other case the vein appears in the copper ore proper. In both these cases native arsenic and proustite appear in insignificant amounts only. A calcite vein, most probably the same one, has been encountered also on the 75 m level. In this case, however, yellow sphalerite was the only ore mineral observed.

The arsenic-silver-bearing fissure vein on the 50 m level differs from the vein on the 100 m level by its lack of native arsenic and by the appearance of Co-Ni-arsenides (smaltite-chloantite and safflorite-rammelsbergite) in the calcite matrix. It runs approximately at right angles to the 100 m level vein. The vein is only a few cm wide but frequently ramifies. In swellings there were often found vugs containing a second generation of calcite (developed as beautiful transparent crystals), argentiferous tetrahedite, well-developed crystals of proustite, chalcopyrite and zeolites. Yellow sphalerite was megascopically visible in the white calcite matrix. Dyscrasite or native silver have been noticed only microscopically as insignificant spots within proustite.

## Mineral Description.

### *Ore minerals.*

The most startling feature of the mineralization in question is the comparatively great abundance of *native arsenic*, which mineral has hitherto been known in Sweden only from Boliden. In polished sections Ödman observed small spots of arsenic in falkmanite, formed at the decomposition of this mineral. According to a personal communication from Prof. Aminoff, however, arsenic has been found also in mineral assemblages from Långban.

The native arsenic from the Lindsköld mine occurs as spheroidal lumps or reniform masses close to the walls of the calcite vein. The separate arsenic spheroids may attain 1 or 2 cm in diameter, whereas the aggregates of spheroids form larger continuous lumps. Specimens of native arsenic 0.5—1 cm thick and 5 cm in diameter could be obtained, but in the walls of the cross-cut even larger dimensions were observed.

Fresh specimens of native arsenic display a white metallic lustre, which, however, after a month or two disappears and the specimens assume the sooty colour characteristic of native arsenic affected by air for some time. In fresh

specimens the arsenic spheroids display a spherolitic texture, the crystal individuals radiating from the centre. Concentric contraction cracks are frequently visible to the naked eye. A blow easily separated several concentric shells along these cracks.

A microscopical investigation reveals that the arsenic spheroids are built up almost exclusively of a homogeneous phase (Fig. 1). Between crossed nicols the radiated texture is conspicuous. Narrow twin lamellae in two systems are occasionally visible (Fig. 2). According to Schneiderhöhn-Ramdohr lamellae of this kind are to be explained as translation twins, an interpretation which seems to be very plausible in the present case in view of the general appearance of the lamellae. The concentric scaly development is generally not very conspicuous under the microscope and the crystal individuals extend without interruption through the different shells within the spheroid. The polished surface tarnishes but slightly even after some weeks in the air — the tarnish appears as small worm-shaped, black precipitations, visible only at high magnifications (see fig. 5).

Chemical investigation of the homogeneous phase disclosed it to consist mainly of arsenic with a minor content of antimony, as is shown by the following analysis, performed by Dr. G. Assarsson.

| | Weight-% | Mol.-% |
|---|---|---|
| As | 94.7 | 96.6 |
| Sb | 5.4 | 3.4 |

Ag, Cu, Bi, Zn, Pb $< 0.01$ %.

A spectrographic examination, however, disclosed the presence of Ag, Bi, Cu, Zn and Pb in small quantities. In order to get a view of the distribution of these minor constituents within the arsenic spherulites, examinations of six consecutive shells in one spherolite were performed. Small variations but no regular changes from the centre to the periphery were found.

The size of the unit cell in the system As—Sb has recently been determined by Ahlberg and Westgren (13). They found a continuous increase of the cell volume with increasing content of antimony in the alloys. Powder photographs of the As—Sb-phase from the Lindsköld mine rendered the following values:

Hexagonal cell: $a_0 = 3.77$ Å $\pm$ 0.02; $c_0 = 10.58$ Å $\pm$ 0.02.

Rhombohedral cell: $a_0 = 4.145$ Å, $\alpha = 54.^\circ 17$. Volume of the rhombohedral cell $= 43.4$ Å$^3$. According to the diagrams and tables of Ahlberg-Westgren, the following values might be expected for the alloy from the Lindsköld mine: $a_0 = 4.145$ Å; $\alpha = 54.^\circ 19$; $V = 43.5$ Å$^3$; these values are in very good agreement with those actually found.

*Native silver, dyscrasite, native antimony* (?). On polished surfaces running through the centre of the arsenic spherulites a yellowish spot with a high reflection power and about 1—1.5 mm in diameter is often visible — even to the naked eye — in the very centre. Under the microscope this spot is found to be made up of an aggregate of minor irregular-shaped spots (as a rule 0.05—0.1 mm) separated from each other by arsenic. The aggregate is surrounded by a

zone of extremely small particles (their size being about 0.005 mm) with the same high reflection power (fig. 3). The microscopical study discloses that the larger spots are composed of two minerals, and most probably a third constituent is present in the small particles of the outer zone. The two chief minerals turned out to be native silver and dyscrasite. Silver is the most abundant of these two minerals and looks somewhat yellowish in comparison with dyscrasite. In immersion the difference as regards reflection power is quite obvious (fig. 4). Dyscrasite is slightly harder than silver, but both minerals are distinctly softer than the surrounding arsenic. As the native silver showed a faint anisotropism, the microscopical diagnosis seemed somewhat questionable. In order to get a univocal determination of the mineral, pure material was bored out and examined by X-ray methods. The powder photographs disclosing the characteristic pattern of native silver, however, there can be no doubt about the diagnosis.

Dyscrasite, too, shows a faint anisotropism, occasionally making twin lamellae visible. It seems to be more abundant in the marginal parts of the silver aggregate than in the centre. In addition to its appearance in the centres of the arsenic spheroids, dyscrasite has also been encountered separately in marginal shells of löllingite surrounding arsenic. In both cases the diagnosis has been confirmed by powder photographs.

When examined two weeks after polishing, the native silver had tarnished in iridescent colours. Also dyscrasite had tarnished but to a smaller degree than silver. The small, light particles surrounding the silver-aggregates were also tarnished next to the aggregate, and they therefore most probably consist of native silver or dyscrasite. At some distance from the silver-dyscrasite aggregate the spots were quite unaffected by tarnish and appeared perfectly white in comparison with silver and arsenic. The grains were too small to permit of a distinction of anisotropism or a boring out of pure material for powder photographs. Spectrographic examinations of native arsenic including these minerals showed no increase in the silver content as compared with the homogeneous arsenic phase, which implies that the white spots are no silver minerals. In view of the paragenesis native antimony seems to be most probable. Similar small white particles are also found in the native arsenic in the vicinity of other ore minerals (see below). It is noteworthy that the small worm-like precipitations appearing on the polished surface of native arsenic some time after polishing are absent within areas containing the minute antimony particles.

*Löllingite.* The native arsenic is generally surrounded by a thin crust of löllingite separating the arsenic from adjacent calcite or sulphides (figs. 1, 2, 5).

Sporadic small löllingite crystals or aggregates of crystals also occur separately in the calcite matrix in the vicinity of the arsenic lumps. Besides, löllingite is frequently found as crusts around sphalerite crystals or sometimes even as veinlets within the sphalerite.

The microscopical diagnosis has been confirmed by microchemical tests of sulphur and spectrographic tests of cobalt and nickel, which elements were found to be absent, while iron and arsenic were found to be abundant. The crust of löllingite is generally about 1 mm thick and is composed of aggregates

of small well-defined crystals, their dimensions varying between 0.003 × 0.01 and 0.05 × 0.1 mm. Occasionally skeleton textures are encountered. As was mentioned above, dyscrasite sometimes appears in pores or »druses» in the löllingite aggregates.

*Co-Ni-arsenides.* The calcite matrix of the fissure vein on the 50 m level contains sporadic small accumulations of a mineral with white metallic lustre. The microscopical investigation disclosed these accumulations to consist of two minerals, their optical properties indicating one mineral of the *smaltite-chloantite* series and one mineral of the *safflorite-rammelsbergite* series.[1] Powder photographs of the two minerals yielded patterns that were in comparatively good accordance with Harcourt's determinations of smaltite and safflorite presented in a survey of the interatomic spacings $d_{hkl}$ and the intensities of the lines (4). In order to get a conception of the proportions between Co and Ni, microscopical quantitative analyses of these elements were performed by Dr. S. Assarsson. Separation between the smaltite and safflorite minerals being impossible, the results represent the bulk composition of the two arsenides together. In two samples the following values were obtained:

| | % Co | % Ni | |
|---|---|---|---|
| 1..... | 9.0 | 5.7 | (20 mg substance) |
| 2..... | 8.2 | 5.8 | (50 » » ) |

Iron is present in considerable amounts — on the basis of the theoretical formula (Fe, Co, Ni) $As_2$ the iron content can be calculated to be approximately 13 %.

Under the microscope smaltite appears as rounded grains 0.5—1.5 mm in diameter. They are frequently accumulated to aggregates of varying shape, sometimes forming garlands or scaly textures. The mineral is generally completely isotropic, but in solitary crystals a faint anisotropism was visible within the central parts, making boundaries between minor grains discernible. Etching with conc. $HNO_3$ discloses the beautiful zonal texture characteristic of the smaltite-chloantite minerals. The central parts of the crystals were far more easily attacked than the marginal zones, and etching during a few seconds completely spoiled the polished surface. By choosing a suitable time for etching this difference can be demonstrated perfectly (fig. 6, 7). Schneiderhöhn-Ramdohr distinguish three various components of smaltite, one of which is far more resistent to etching with $HNO_3$ than the two others. The composition of this »main component» is thought to approach the three-arsenide, skutterudite. Judging from the results of the etching of the Lindsköld smaltites, the »main component» occurs in the uttermost zones of the crystals only, while the central parts are made up of components I and II (according to the terminology of Schneiderhöhn-Ramdohr). This result is also in accordance with the appearance of a faint anisotropism in the central parts of some crystals. Before etching, on the other hand, no variations in colour or hardness suggesting a zonal texture could be detected within the crystals. Hoehne (5) has described a very

[1] In the following description the minerals are called smaltite and safflorite for short.

similar development of smaltite from veins in the Riesengebirge, characterized by mineral assemblages very like those in the Lindsköld veins.

Smaltite is frequently surrounded by a border of safflorite. Under the microscope the safflorite is easily recognized on account of its distinct anisotropism. It is also slightly harder than smaltite. Etching with conc. $HNO_3$ reveals also in this case an inhomogeneous composition, the centre and and the parts of the crystals close to the smaltite individuals being far more easily attacked than the outer parts. Repeated narrow zones with different reaction power to $HNO_3$ as in smaltite do not emerge, however. Fig. 7 demonstrates the acicular shape of the more intensely attacked component.

Besides the occurrence as crusts around smaltite crystals, safflorite has also been found as small separate crystals or skeleton-shaped aggregates in calcite in the vicinity of tetrahedrite and proustite. Occasionally multiple twins were observed.

*Proustite* and *argentiferous tetrahedrite* (*freibergite*) frequently appear in close association with each other. In the Co-Ni-bearing vein on the 50 m level both these minerals are visible to the naked eye. Proustite often forms beautiful crystals with reflecting crystal faces, their shape being determined by the prism $(11\bar{2}0)$ and the scalenohedron $(21\bar{3}1)$. Striation parallell to the edge of intersection of these faces is common (figs. 8 and 10). The proustite crystals in the vugs are generally associated with zeolites. Frequently they have grown on tetrahedrite. Under the microscope, on the other hand, the central parts of tetrahedrite crystals are often found to be replaced by proustite. In some proustite crystals there were observed wery small interpositions of a mineral with high reflection power. Their size renders definite determinations impossible — the insignificant tarnishing in air makes dyscrasite more probable than native silver.

In the vein from the 100 m level containing native arsenic the proustite always appears in a very fine-grained form, generally as coatings on the boundaries between arsenic and löllingite or on the walls of the vein. Besides, coatings of proustite occur separately on calcite faces within the calcite matrix. In a few cases an orange-yellow mineral was noticed which seems to be closely associated with, or possibly grade into proustite. Sufficient material could not be obtained for a close investigation of the mineral; its relation to proustite might favour the suspicion that the mineral is *xanthokonite*(?)

At high temperatures Sb and As can substitute each other completely in the proustite-pyrargyrite series. In nature, however, there seems to be a clear division into As-dominant and Sb-dominant members. In order to get an idea of the As : Sb proportions in the Lindsköld proustites the minerals were tested by spectrographic analyses. In the idiomorphic crystals from the 50 m level vein the As : Sb-proportions were: 7—8: 3—2; in the coatings from the 100 m level vein the corresponding values were 19 : 1. Among the coatings, members with higher Sb contents have also been encountered, the scarcity of material, however, not permitting more exact determinations.

Powder photographs of material of proustite crystals disclosed a pattern

which in the main agrees with Harcourt's values of proustite and pyrargyrite. There are also a few conspicuous differences, however. The following table gives Harcourt's values (4) as compared with the values of the Lindsköld proustite:

| Pyrargyrite (Harcourt) | | Proustite (Harcourt) | | Proustite The Lindsköld mine | |
|---|---|---|---|---|---|
| d | I | d | I | d | I |
| 3.35 | 2.0 | | | 3.26 | w |
| 3.20 | 5.0 | 3.20 | 6.0 | 3.16 | w |
| 2.79 | 7.0 | 2.75 | 2.0 | 2.74 | m |
| 2.55 | 6.0 | 2.53 | 4.0 | 2.54 | m |
| | | | | 2.47 | m |
| 2.26 | 1.0 | 2.27 | 0.5 | 2.22 | w |
| 2.12 | 1.0 | 2.08 | 0.5 | | |
| 1.960 | 1.0 | 1.94 | 1.0 | 1.92 | w |
| 1.865 | 1.0 | | | 1.85 | w |
| 1.750 | 1.0 | 1.73 | 0.3 | 1.72 | w |

The most conspicuous difference between the Lindsköld mineral and Harcourt's minerals is the appearance of a comparatively distinct reflection with d = 2.47, which cannot be due to foreign material. In addition, there is some disagreement with regard to the intensities. An exhaustive discussion of the signification of these differences does not belong here; the author will on some other occasion discuss some of the problems of the crystal structure met with during the investigation.

Similar to proustite, the argentiferous *tetrahedrite* in the 50 m level vein appears generally in association with zeolites on the surfaces of transparent calcite crystals. A microscopical investigation discloses that the mineral has been intensely replaced by proustite, the two minerals frequently forming intricate intergrowths. On the other hand, there also exist homogeneous, generally hypidiomorphic tetrahedrite crystals (0.5—1 mm) quite free from other minerals. In polished sections tetrahedrite has been observed also in the 100 m level vein, appearing at the boundary between löllingite and native arsenic and probably formed in the decomposition of the native arsenic phase. The colour in polished sections is pure gray; in comparison with proustite it appears to have a faint yellowish hue. The olive-green tint characteristic of normal Cu-Sb-tetrahedrite was never observed.

On account of the intimate intergrowth between tetrahedrite and proustite it was impossible to gain pure material for a complete chemical analysis. In order to gain an idea of the proportions between the main constituents small grains of the mineral were subjected to spectrographic analyses, the grains having been controlled to be homogeneous under the microscope. The quotients Sb : As and Cu : Ag could be determined at least approximately. Quite contrary to what might have been expected in view of the paragenesis, antimony was decidedly predominant. In two different crystals the following values were obtained: Sb : As = 1) 85 : 15, 2) 95 : 5. The quotient Ag : Cu varies between 3 : 7 and 5 : 5. Calculating with the ideal tetrahedrite formula these results

involve a mineral with 15—25 % Ag and should thus properly be termed freibergite.

The crystal structure of the tetrahedrite minerals has been investigated and discussed by Machatschki (8) and Pauling (12). Machatschki shows that the unit cell increases by As being substituted by Sb and Cu by Ag. A survey of several tetrahedrites published by Machatschki contains values of $a_0$ from 10.189 Å (Ag-free As-tetrahedrite) to 10.400 (argentiferous Sb-tetrahedrite). An extremely high $a_0$-value ($a_0$=10.555) is believed by Machatschki to be caused by an abnormal Bi-content (4.94 % Bi). The highest Ag-percentage among the analyses presented, however, is 8 % Ag, no especially argentiferous members thus being included. Powder photographs of material from two different specimens from the Lindsköld mine rendered $a_0$-values distinctly higher than the highest values in Machatschki's table of the Cu-Ag-Sb-As-tetrahedrites, *viz.* $a_0 = 10.44 \pm 0.03$ Å and $a_0 = 10.48 \pm 0.03$ Å. These results are consequently in good agreement with the high Ag-contents of the mineral.

*Chalcopyrite* has been found in both of the veins. In the vein on the 100 m level, however, it is observed only under the microscope. Generally it appears together with proustite and tetrahedrite but it has also been found in association with galena as small interpositions in dark sphalerite. It may be questioned, however, if the chalcopyrite and galena were really formed at the arsenic-silver-mineralization. The dark colour of the sphalerite makes it probable that at least the sphalerite, and perhaps also the interpositions, belong to the primary mineralization of the quartzose wallrock.

In the Co-Ni-bearing vein on the 50 m level chalcopyrite is found in close association with tetrahedrite and proustite and seems to have developed at least in part at the decomposition of tetrahedrite. In the vugs it appears together with zeolites as idiomorphic crystals grown on the faces of calcite. Repeated twinning often gives the crystals very intricate forms (fig. 9).

Sphalerite is a comparatively plentiful mineral in the 100 m level vein, forming crystals on the walls of the vein. The colour is yellow to light brown. Under the microscope the yellow sphalerite appears as well-developed crystals. When native arsenic is present, there is generally a shell of löllingite at the border between arsenic and sphalerite, but löllingite also occurs as separate »veinlets» between the sphalerite crystals. In view of the appearance of the internal reflections with crossed nicols, it seems probable that the sphalerite is more ferriferous when it borders on the iron sulphides of the wall rocks. A dark sphalerite being a frequent constituent of the impregnated zone formed at the principal copper-iron mineralization, it may often be questioned whether a dark sphalerite was formed at the arsenic-silver vein mineralization, or whether it belongs to the disseminated zone. The light sphalerite lends itself more easily to a good polish than the dark type and is entirely free from interpositions of other minerals, whereas the dark sphalerites generally contain small grains of galena, chalcopyrite and occasionally pyrrhotite.

Besides in sphalerite, galena has been found as insignificant veinlets and as fillings of the interstices in the skeleton-shaped löllingite aggregates.

*Gangue minerals. Calcite* is by far the preponderant constituent of the fissure veins. In both veins coarse white calcite forms the main filling. A second generation of calcite is found in the vugs of the 50 m level vein, appearing as beautiful, transparent, scalenohedral crystals, their habit being regulated by the rhombohedron $(10\bar{1}1)$ and the scalenohedron $(21\bar{3}1)$. Both these types are very »pure» calcite, as is seen from the following chemical analyses:

| | % FeO | % MgO |
|---|---|---|
| White calcite | 0.25 | 0.28 |
| Transparent calcite | 0.18 | 0.00 |

*Quartz* is found in the 100 m level vein only, and even there in very small amounts. It appears close to the native arsenic, forming small hexagonal prisms, terminated by the positive and negative rhombohedrons $(10\bar{1}1)$ and $(01\bar{1}1)$ in practically equal development. The prisms are generally up to 1—2 mm in length and 0.5—1 mm in diameter. They have grown from the walls of the vein, their c-axes being approximately perpendicular to the walls.

*Fluorite* has been noticed erratically in the vein on the 100 m level, forming light green or uncoulored, transparent crystals, about 1 mm in size.

*Zeolites.* Several zeolites have been identified. In the 100 m level vein zeolites are comparatively scarce and occur erratically; in the vugs of the 50 m level vein, on the other hand, they are a characteristic constituent. In this latter case they have grown on the faces of the transparent calcite crystals.

*Laumontite* has been found in both veins. In the 100 m level vein it forms fibrous aggregates appearing together with quartz and calcite at the border to the löllingite crusts around native arsenic. A determination of the extreme indices of refraction gave the following results: $\alpha_{(Na)}$ 1.505, $\gamma_{(Na)} = 1.516$, 2 $V_\alpha$ is moderate.

The crystal aggregates in the vugs of the 50 m level contain well-developed prismatic crystals of laumontite, generally 1—4 mm in size (see fig. 11). The indices of refraction of these crystals are $\alpha_{(Na)} = 1.507$, $\gamma_{(Na)} = 1.517$.

*Stellerite.* The most frequent zeolite in the 50 m level vein appears as transparent well-developed prismatic or tabular crystals (Figs. 9, 10, 11). Occasionally they attain 1 mm in length; in most cases, however, they do not exceed 0.5 mm. The crystals are accumulated to bundles or irregular aggregates forming crusts around the calcite individuals. The crystal habit is in perfect agreement with that of desmine, as it is illustrated in »Atlas der Kristallformen» ((3) Tabl. 25, figs. 4, 7, 12 and 28). Generally the faces (010), (100), (001) and (111) determine the shape of the crystals. The essential optic properties are: $\alpha_{(Na)} = 1.492$, $\gamma_{(Na)} = 1.503$, $\gamma - \alpha = 0.011$ (determined); $2V_\alpha = 36°$; X = c; the optic plane is (010). The two last facts demonstrate the mineral to be stellerite, even though the refringence is more in accordance with epidesmine or stilbite as given by Winchell (19). In epidesmine, however, the optic plane is (100) and in stilbite X forms a small angle with c (3°—12°). Stellerite has been regarded as a very rare mineral, but recently it has been found at Kongsberg (9) in a mineral assemblage which in several respects is very similar to the paragenesis of the

Lindsköld veins. In several instances the crystals are inhomogeneous and contain kernels characterized by a lower refringence ($\alpha$ = about 1.487), thus a value which agrees better with the refringence of the previously described stellerites.

*Chabazite* is often found together with stellerite and laumontite, forming transparent cubes about 1 mm in size (fig. 11). Solitary crystals with the characteristic penetration twins have been observed. Chabazite occasionally contains small stellerite crystals as inclusions.

One more zeolite mineral has been met with in the 100 m level vein, but it has been observed only in one single specimen and in insignificant quantities. The optic properties of this mineral do not agree with those of any zeolite known: $\alpha = 1.528$, $\gamma = 1.538$, $2V_\alpha = 73-76°$. The mineral appears in intergrowth with quartz and proustite at the border between löllingite and calcite. On account of the scarcity of the material no chemical analysis could be obtained. A spectrographic test revealed Si, Al and probably Na to be the chief constituents. In thin sections it appears as fibrous aggregates with a flamy undulatory extinction.

## Discussion on the Origin of the Veins.

It has been shown above that there are very great resemblances between the two veins, but on the other hand we have also noticed certain conspicuous dissimilarities. As the two veins never meet, we are not able to determine whether they are contemporaneous or whether they represent different stages in a continuous mineralization. In order to get an idea of the order of the precipitation of the minerals, we consequently have to consider each vein separately. In both veins it is possible to distinguish certain stages in the development of the mineralization.

In the vein on the 100 m level quartz was the first mineral to crystallize. Then followed coarse white calcite, and probably yellow sphalerite crystallized in close association with this calcite. In a third stage native silver and dyscrasite precipitated on the walls of the vein, and these minerals then acted as precipitants of arsenic. In fact, crusts of native arsenic around silver minerals seem to be a fairly common phenomen in silver-arsenic parageneses. Schneiderhöhn and Ramdohr, for instance, have illustrated very similar textures from Andreasberg ((16) fig. 107). In some cases also pyrite (from the adjacent wallrocks) and sphalerite have acted as precipitants of native arsenic.

After the precipitation of arsenic, löllingite was formed by reaction between arsenic and the iron content of the remaining ore solution or possibly of the adjacent iron sulphides. Obviously silver was still contained in the solution, which is evident from the appearance of dyscrasite in cavities in the löllingite crusts. Tetrahedrite crystallized later than both arsenic and löllingite but is in part replaced by chalcopyrite. As regards galena we can only ascertain that it was precipitated later than löllingite.

The last stage of the mineralization is characterized by the crystallization

of proustite and zeolites, which minerals at least in several instances appear in close association.

In the Co-Ni-bearing vein on the 50 m level we can discern two principal stages of mineralization. The first stage begins with the crystallization of coarse, white calcite. The cobalt-nickel-arsenides, too, belong to this stage, even though they are unmistakably later than the calcite. Among the arsenides smaltite was evidently the first to crystallize, as it is frequently surrounded by a shell of safflorite. The yellow sphalerite was in all probability formed during this stage, too.

The second stage represents the formation of the minerals in the vugs. The first mineral to crystallize was also in this case calcite (forming transparent, scalenohedral crystals); then followed tetrahedrite, which in turn was replaced by chalcopyrite and proustite. In close association with the two last-mentioned minerals the zeolites appear. The proustite crystals were, however, at least in part formed before the crystallization of the zeolites. This is evident from the fact that solitary zeolites are found to have grown on the crystal faces of proustite (see *e.g.* fig. 10). The minute particles of dyscrasite (or possibly native silver) very likely originated in the decomposition of proustite. A survey of the order of crystallization in the two veins is given in Table 1:

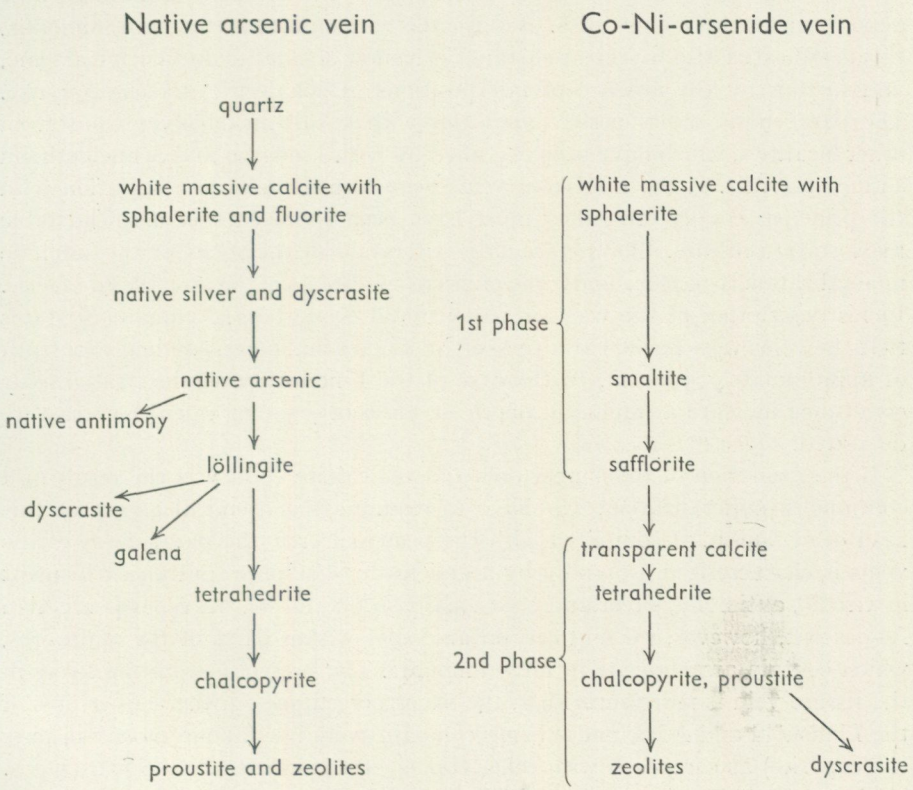


Table 1.

As regards the origin of the veins certain minerals, such as native arsenic, silver and proustite, could be taken as an evidence of a supergene origin. Again the presence of Co-Ni arsenides, chalcopyrite, and tetrahedrite strongly indicate a hypogene mineralization and in all probability the veins were formed by ascendent liquids. Another question is whether the veins are genetically related to the principal copper-sulphide mineralization within the area or whether they were formed during an isolated, later epoch of mineralization. No direct proof in favour of either of these possibilities can be obtained within the mine, but the appearance of the veins in close vicinity to the copper ores may be taken as an argument for a genetic relationship between the veins and the copper ores. No traces of a later mineralization of the vein type have ever been discovered in the surroundings of the mine.

As regards the physical conditions attending the formation of the veins it is difficult to get exact information from the mineral assemblages only. The low Sb percentage in the native arsenic phase (3.4 atomic %) makes it impossible to use the equilibrium diagram of the system As-Sb (published by Wretblad, [20]) as a geologic thermometer, as the homogeneous phase with up to 5 % Sb is stable also at normal temperatures.

However, even the initial temperatures during the formation of the veins must have been considerably lower than were the temperatures during the deposition at the copper ores. Besides the evidence of the gangue minerals, this is indicated also by the appearance of yellow sphalerite and native arsenic, and further by the absence of interpositions in sphalerite and chalcopyrite. The paragenesis shows perfect analogies with cobalt-nickel-silver veins from other localities, which have been classified by both Lindgren and Schneiderhöhn as mesothermal. If the Lindsköld veins were formed in close association with the principal copper ores, they must have been formed under a considerable hydrostatic pressure. The metasomatic alteration of the rocks at the sulphide mineralization took place under the physical conditions of the amphibolite facies. In his description of the very similar veins at Kongsberg, Neuman (9) states that the veins were formed at a pressure of 1 000 atm., corresponding to a depth of approximately 3 700 m. In the case of the Lindsköld ores the stratigraphic conditions indicate a minimum depth of 3 000 or 3 500 m when the ores were deposited.

If the formation of the copper ores and the calcite veins was the result of a continuous mineralization, we have to examine the chemical aspect of this kind of evolution. If compared with the principal ores, the paragenesis of the veins is characterized especially by a deficiency of sulphur and an enrichment in arsenic, antimony, silver and occasionally in Co and Ni. As regards the high As-content, however, we find certain analogies within parts of the main ores, which contain arsenopyrite in large amounts. The presence of native silver in the fissure vein is more surprising, the silver percentages in the copper ores of the Lindsköld and Adak mines being comparatively low (about 140 g/t in pure chalcopyrite) as compared with other copper ores in the Skellefte District (*e.g.* in the very similar Laver ores). The copper ores of the Adak and Lindsköld

mines contain Co and Ni only in very small amounts (generally $< 0.1$ % Co + Ni), but according to spectrographic analyses of sulphide minerals from several ore deposits in the Skellefte District the Co- and Ni-percentages are comparatively high in the Adak ores. In comparison with the other ore minerals arsenopyrite is always found to be enriched in Co and Ni. In the Adak mine Co greatly preponderates over Ni. In the Lindsköld mine the quotient Co : Ni varies between 3 : 1 and 1 : 1. The Co : Ni ratio in the smaltite-safflorite minerals being approximately 1.5 : 1, there is consequently nothing in the Co-Ni ratio to contradict a genetic relationship between the copper ores and the Co-Ni-bearing calcite veins. It might be questioned whether the constituents of the vein-forming liquids were brought into solution by a selective mobilization of the »primary» ore minerals or whether they are residual components after a continuous course of crystallization of the sulphides in the copper ores. If the hypothetic mobilizing agents are thought to have derived from the ore solution proper, this question is of no importance, however. There must always have been a certain redissolution of previously precipitated minerals also in a continuous course of mineralization, as is shown by the frequent textures indicating replacement in sulphide parageneses.

## Comparison with Similar Mineral Deposits.

The quite insignificant fissure veins now described are chiefly of interest for comparisons of the parageneses with similar mineral assemblages. Considering first the ore minerals, we find great similarities among the mineral deposits of the Co-Ni-Ag-type, their typical representatives being *i.a.* Andreasberg, the Riesengebirge, Schwarzwald, the Erzgebirge in Germany, Kongsberg in Norway, Cobalt in Ontario. Exhaustive surveys of this type of ore deposits have been presented by Bastin (2) and Schneiderhöhn (17). Hoehne (5) has described a paragenesis from Schmiedeberg in the Erzgebirge, which is of particular interest in the present case on account of the relative abundance of native arsenic in some veins. Lumps of arsenic up to 30 cm thick are reported. Co-Ni-arsenides, native silver and other silver minerals are further essential constituents in certain veins. Among the gangue minerals calcite is predominant. A difference as compared with the Lindsköld veins is that among the Schmiedeberg deposits there also appear veins with bismuth and uranium minerals.[1]

Considering the Lindsköld Co-Ni-Ag-As-mineralization as a whole, the lack of Bi and U and the predominance of calcite and zeolites among the gangue minerals must be looked upon as characteristic features. We then find the greatest resemblances with Andreasberg and Kongsberg, where in both cases the principal gangue minerals are calcite and zeolites. In the Andreasberg veins Steltzner-Bergeat distinguishes the following phases:

[1] An investigation of the radioacitivity in specimens from the Lindsköld vein, performed at the Boliden Laboratory, showed a uranium content « 0.001 %.

1st phase: *Grey calcite*, containing: *Native arsenic, native antimony, dyscrasite*, breithauptite, niccolite, *smaltite, löllingite, light-couloured sphalerite, galena;* rare minerals are *chalcopyrite*, pyrite, pyrrhotite.

2nd phase: *Quartz, fluorite, argentiferous tetrahedrite, chalcopyrite, galena, red sphalerite, native silver*, millerite.

3rd phase: Alteration of silver with the formation of stephanite, *pyrargyrite-proustite*, miargyrite, xanthoconite, polybasite, stibnite, argentite, argentopyrite.

4th phase: Native silver, realgar, *calcite as transparent crystals*, apophyllite, analcime, gmelinite, *chabazite*, heulandite, brewsterite, harmotome, desmine, natrolite, thomsonite, younger fluorite and *chalcopyrite*.

The minerals in italics are those noticed also in the Lindsköld mine. Uncertain comparisons have been denoted in spaced-out type. Comparisons with minerals occurring at Andreasberg in more than one phase are of course more or less uncertain, but as regards the development of calcite in two separate phases the resemblance between the Lindsköld and the Andreasberg veins is quite conspicuous.

As is seen from the survey practically the complete mineral list of the Lindsköld veins is recovered (only two zeolites are lacking) and this list includes all minerals that contribute to characterizing the Andreasberg vein type. In view of the scanty material obtained for investigation from the Lindsköld veins this must be considered quite a remarkable result.

The silver-bearing veins at Kongsberg also display very great similarities to the Lindsköld veins. The paragenesis at Kongsberg has recently been described by Neuman and his mineral list includes all the species from the Lindsköld mine now described. Several minerals of the Kongsberg paragenesis have not been recovered in the Lindsköld veins, but in view of the insignificant extent of the Lindsköld mineralization this is by no means surprising. The most conspicuous difference is the scarcity of native arsenic and the abundance of silver minerals at Kongsberg.

Until recently the type of mineralization now described was quite unknown within the Skellefte District. Shortly after the discovery of the Lindsköld As-Ag-Co-Ni-veins, however, a very similar find was made at the Laver copper mine. This paragenesis has been described and discussed by O. Ödman (11 a). The Ag-Co-Ni-minerals appear at Laver in a fault zone at a distance of about 100 m from the main ore bodies. Ödman mentions the following minerals: Native silver, argentite, pyrargyrite, polybasite, safflorite, tetrahedrite, chalcopyrite, sphalerite and pyrite in a gangue matrix of calcite (predominating), quartz, apophyllite, and zeolites. The most conspicuous resemblances between the Lindsköld and the Laver veins are: The occurrence of silver minerals associated with Co-Ni arsenides, a gangue matrix of calcite and zeolites, and further the appearance of the veins in the vicinity of copper-iron sulphide ores, which are very much alike in the two cases. The most palpable dissimilarities between

the two parageneses are: The predominance among the ore minerals of native silver at Laver and of native arsenic at the Lindsköld mine. Ödman concludes that the paragenesis at Laver is of a hypogene origin for the same reasons as did the author when considering the Lindsköld veins, and the mineralization is thought to be closely related to the formation of the principal copper ores.

As was mentioned before, the Ag-Co-Ni ore type is a wide-spread and very characteristic type of mineralization all over the world. It must now be considered a very significant fact that this type has occasionally been recovered as a last phase of a high-temperature iron-copper sulphide mineralization of a regional character, even though this late mineralization has produced only quite insignificant veins. From a genetic point of view it is of importance that we have been able to establish that the special physico-chemical conditions necessary for the origin of the characteristic Ag-Co-Ni-ore type could be realized at the time of the sulphide mineralization within the Archaean regions here in question.

## Summary.

In two small calcite veins in the Lindsköld copper mine, N. Sweden, a mineral paragenesis has been encountered which is quite foreign to the regional mineralization of the area. This paragenesis is characterized by the occurrence of As-Ag-Co-Ni-minerals. The comparatively great abundance of native arsenic in one of the veins is of special interest. The arsenic-bearing vein further contains native silver, dyscrasite, proustite, löllingite, tetrahedrite, galena, sphalerite, and chalcopyrite. The gangue matrix consists chiefly of calcite; besides quartz, zeolites (laumontite and one unknown species), and fluorite occur in small amounts. The other vein contains Co-Ni-arsenides (smaltite and safflorite), sphalerite, proustite, argentiferous tetrahedrite, chalcopyrite, and dyscrasite. The gangue minerals are calcite (appearing in two generations), laumontite, stellerite, and chabazite. Perfect analogies to these parageneses are found among the so-called silver-cobalt-nickel veins, the most conspicuous similarities being encountered in the Andreasberg and Kongsberg veins. The origin of the veins is discussed, and in view of their relation in space to the copper ores they are thought to have originated from residual ore solutions, which had previously deposited the copper-iron sulphides. Very similar conditions are encountered in the Laver copper mine, where an Ag-Co-Ni-bearing calcite vein was recently discovered. The mineralogy of that vein has been described by Ödman, who concludes that also in that case there was a close relationship between the low-temperature (mesothermal) Ag-Co-Ni-mineralization and the high-temperature (hypothermal or pyrometasomatic) copper-iron sulphide mineralization.

2—452360. *S. G. U. Ser. C. N:o 469.*

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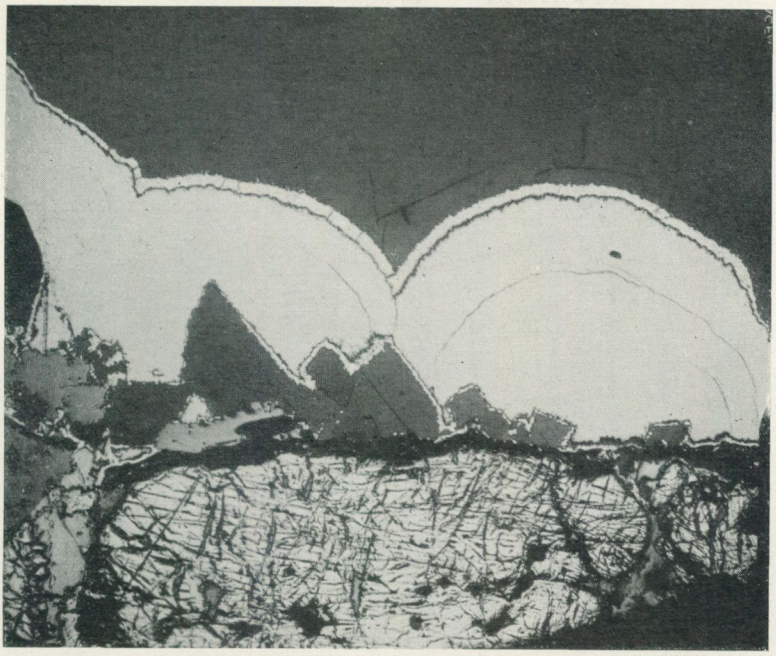

Fig. 1. Reniform masses of native arsenic (white) surrounded by a crust of löllingite (white, relief against arsenic). In the lower part of the figure a large pyrite crystal. Calcite dark grey, sphalerite light grey. Ord. light, 12 ×.

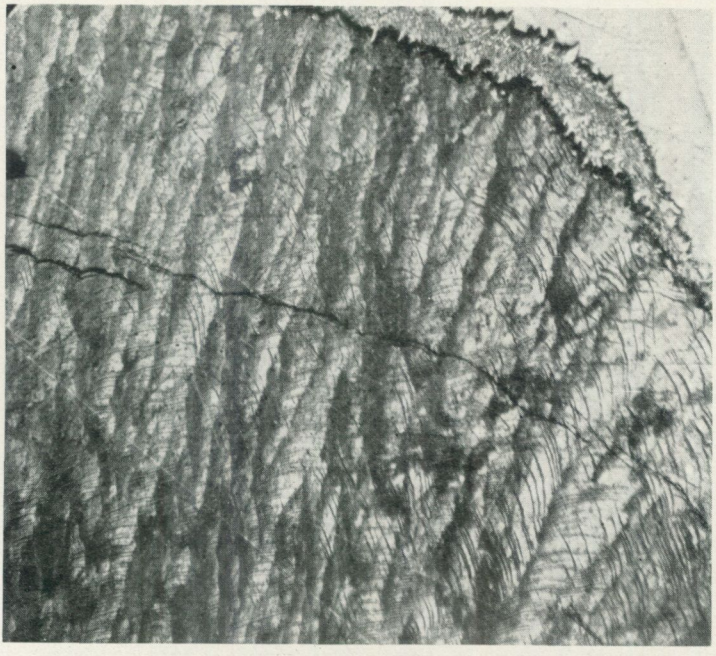

Fig. 2. Subparallel aggregates of native arsenic, radiating from the centre of a spheroid. Twin lamellae in two systems. In the right hand top corner a crust of löllingite. Nic. +, 50 ×.

Fig. 3. Native silver and dyscrasite (white) in native arsenic (grey). Ord. light, 65 ×.

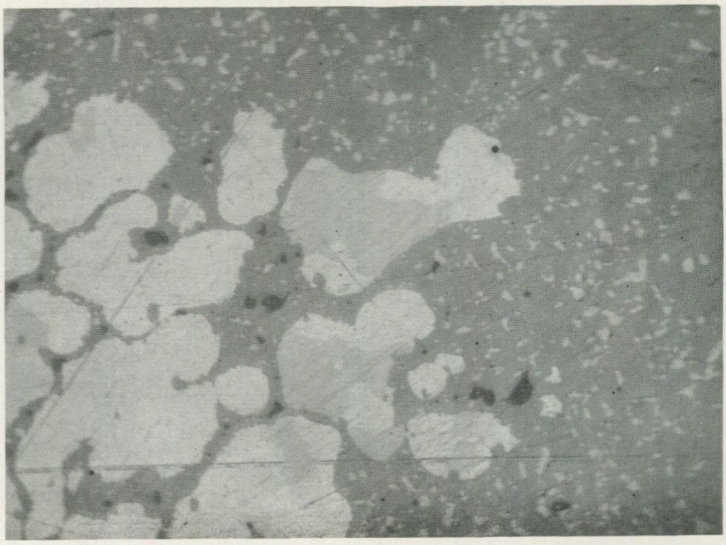

Fig. 4. Native silver (white) and dyscrasite (light grey) in arsenic (dark grey). Ord. light, immersion, 180 ×.

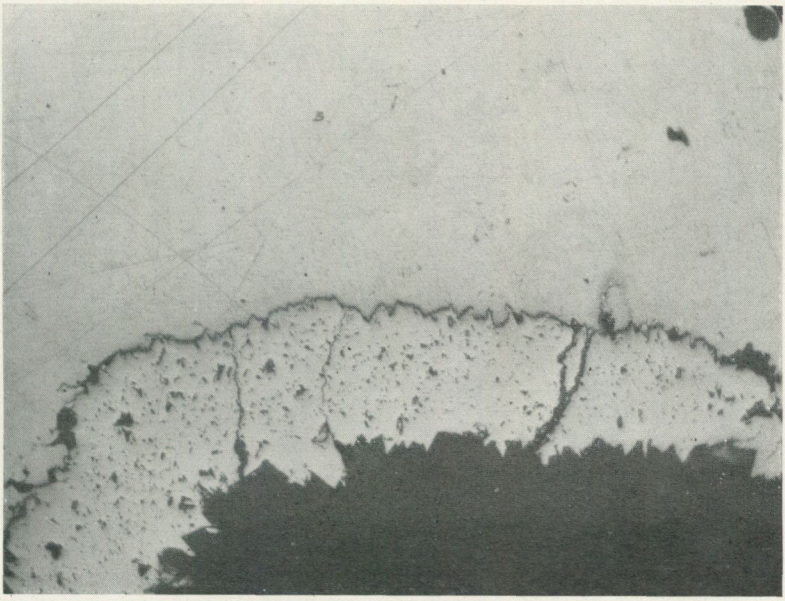

Fig. 5. Löllingite (white, hard crystals) between native arsenic and calcite (black). On the arsenic small black precipitations. Ord. light, 140 ×.

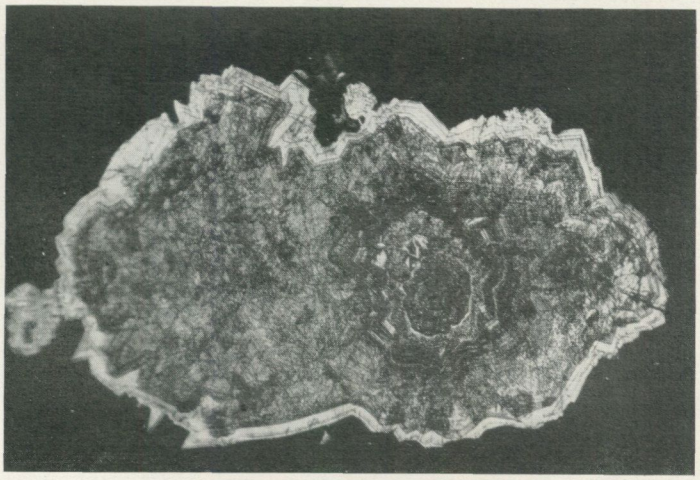

Fig. 6. Zonal texture in smaltite. Etched with conc. $HNO_3$. Ord. light, 100 ×.

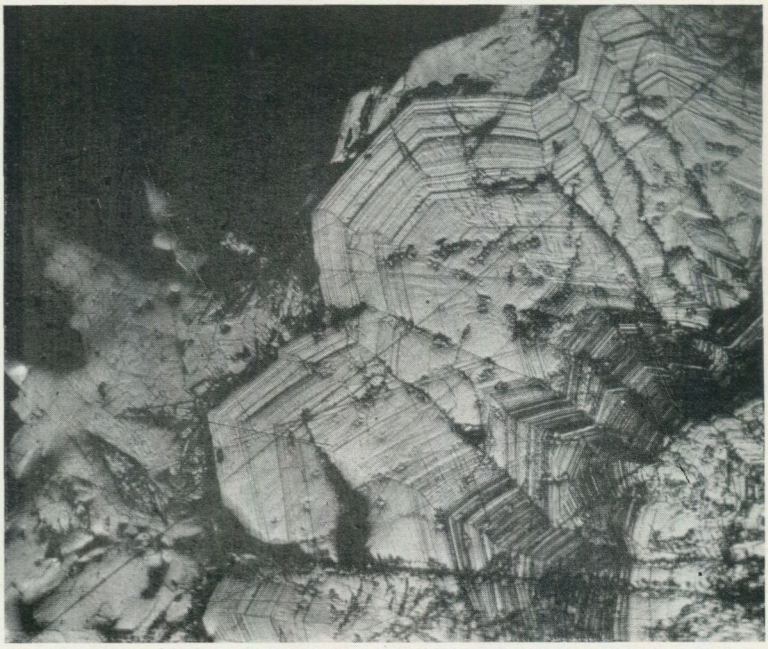

Fig. 7. Zonal texture in smaltite. To the left safflorite, its innermost parts being strongly affected by etching. Etched with conc. $HNO_3$. Ord. light, 280 ×.

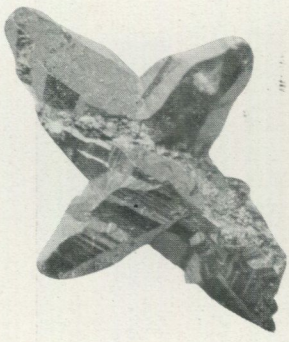

Fig. 8. Multiple twins of proustite. 8 ×.

Fig. 9. Intricate twins of chalcopyrite and transparent crystals of stellerite, 20 ×.

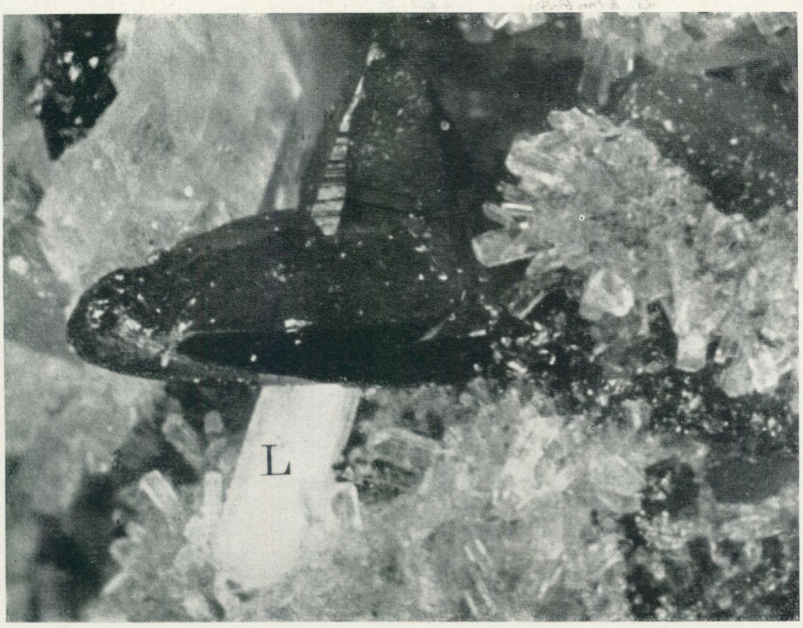


Fig. 10. Proustite crystals (black) surrounded by laumontite (L) and transparent stellerite crystals. 20 ×.

Fig. 11. White columnar crystals of laumontite, transparent »cubes» of chabazite and small transparent stellerite crystals. 9 ×.

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