

SVERIGES GEOLOGISKA UNDERSÖKNING

SER. C.

Avhandlingar och uppsatser.

N:o 444.

ÅRSBOK 36 (1942) N:o 1.

COPPER ORES OF  
THE "RED BEDS" TYPE FROM  
VISINGSÖ, SWEDEN

BY

O L O F H. Ö D M A N

*Pris 1.00 krona*

STOCKHOLM 1942

KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER

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## Introduction.

Copper ores in sandstone on the island of Visingsö — situated in Lake Vättern in South Sweden — have been known for at least 170 years. Thus there are in the collections of the Museum of National History in Stockholm and of the University of Uppsala a number of specimens of sandstone highly impregnated with chalcocite and bornite. The specimens represent loose boulders, the exact locality of which is not stated. The year when the specimens were found could not be ascertained, but they are mentioned in catalogues of the collections dated about 1780 and 1770, and must consequently have been found before that time.

In the summer of 1940 some boulders of copper ore were again found on the island and a claim was staked by some people from Gothenburg. The boulders were found on the beach on the western side of the island, NW of the village of Tunnerstad (Fig. 1). In the spring of 1941 the find became known to the Geological Survey and the author was sent down to make an investigation.

The original find consisted of loose boulders in the beach gravel but the

author soon found the ore *in situ* as concretions in sandstone. They were of the same shape and size as the boulders.

The ore indeed aroused great interest because of its high content of copper, three available analyses showing 13.1, 20.8 and 21.8 % Cu. In one

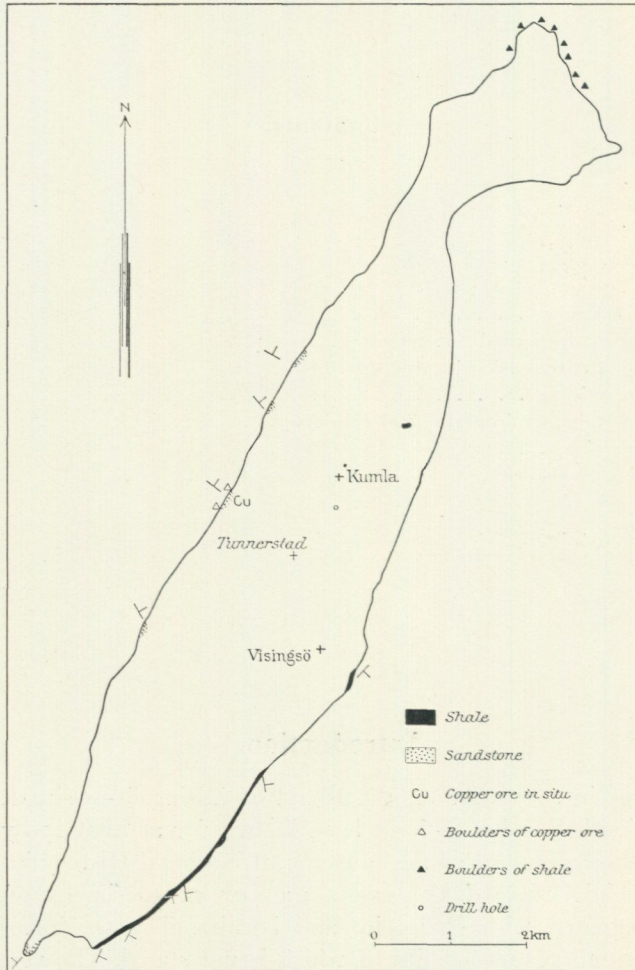


Fig. 1. The island of Visingsö, showing the distribution of rock exposures and the location of the copper ore at Tunnerstad (compiled from older maps and the author's own observations).

of the samples the silver content was 0.2 %. All the analyses were carried out on picked boulders of rich ore and cannot be considered average values of the copper content of the sandstone, for these rich portions, appearing as concretions, are scattered haphazard in the sandstone. Several samples of the sandstone collected within the claim showed only very small traces of copper.

Dr S. Landergren of the Geological Survey kindly undertook a prelimin-

ary spectrographic analysis of one of the ore concretions and of the sandstone, the results being shown in the table below.

Spectrographic analyses of copper ore (I) and sandstone (II).<sup>1</sup>

	I.	II.
Ag . . . . .	0.1—0.3 %	nil
Zn . . . . .	nil	nil
Sn . . . . .	0.03—0.1 %	presence proved
Pb . . . . .	0.1 %	»
As . . . . .	0.05 %	»
Sb . . . . .	nil	nil
Bi . . . . .	0.003 %	nil
Mn . . . . .	presence proved	nil
Co . . . . .	nil	nil
Ni . . . . .	0.01 %	nil
Cu . . . . .	not det.	presence proved

### Geological Setting.

The island of Visingsö is built up of sandstones, grits, and shales of the so-called Visingsö formation, a sedimentary series of rocks mainly distributed around the Lake Vättern basin. Its exact geological age has been and still is a much discussed problem. It can only be stated with some degree of confidence that the formation is younger than the late pre-Cambrian Jotnian sandstone series and older than the Peltura Zone of the Cambrian.<sup>2</sup>

The island is heavily covered with quaternary deposits and the bedrock is exposed in some isolated areas only along the shore. The best exposures are found in some sheer cliffs at the southern end of the island.

Fairly good exposures are also found at the site of the ore boulders at Tunnerstad. The rock is here a reddish brown or yellowish gray, well bedded, and sometimes gritty sandstone. Its general strike is NW—SE and it dips at low angles (10—30°) to the NE. Fissures are fairly uncommon but some were observed striking N 30° E or N—S and dipping steeply to the west. The sandstone may possibly be correlated with the upper yellow sandstone series in Brotzen's section through the Visingsö formation at Huskvarna (1).

The sandstone is superimposed by dark-green shales and shaly and gritty sandstones, exposed in a well at Kumla church and in a boring recently made S of Kumla (Fig. 1). The section obtained at the latter place runs as follows:

0.0—2.3 m: drift

2.3—17.5 m: dark-green shale

17.5—71.2 m: fine-grained, grayish green and gritty shale

71.2—150.1 m: alternating layers of gray or red bedded sandstones, sometimes gritty.

<sup>1</sup> The values are estimated.

<sup>2</sup> For literature see the recent publication by Brotzen (1).

### Occurrence.

The ore boulders are spread out along the beach at Tunnerstad for a distance of a few hundred metres and dozens of them have been collected here. In calm weather the boulders are easily discernible in the clear water of the lake because of the thin crust of malachite they are covered with.<sup>1</sup>

The ore occurs also *in situ* in the sandstone exposed on the shore at Tunnerstad. The abrasive action of the waves wears down the soft sandstone, leaving the concretions to accumulate on the beach.



Photo C. Larsson.

Fig. 2. Layered concretion sending out protrusions into the sandstone (copper ore dark gray, sandstone light gray). Nat. size.

The ore concretions vary in size from mere grains no bigger than a pin's head to large cakes 0.5 m in diameter and 15—20 cm thick. They show a great variance in shape. The smaller ones are rounded and, occasionally, where they are fairly densely distributed in the rock, the ore resembles the "Knotenerz" from the German lead-mine in Triassic sandstone at Mechernich. The larger concretions are often cake-shaped and sometimes follow certain horizons in the sandstone. Irregular protrusions are seen to branch off from a flat concretion as in Fig. 2. The surface of the cake-shaped concretions is often knotty and irregular and it seems as if they were formed by the successive growth of the smaller, rounded concretions. Many of the cake-shaped concretions are, however, quite smooth. Figures 2—7 demonstrate the appearance of some of the concretions.

<sup>1</sup> Boulders were found at two other localities on the island but as they are of the same appearance as at the original locality no further mention will be made of them.



Fig. 3. Upper side of cake-shaped concretion.  $\frac{1}{3}$  nat. size.

Photo C. Larsson.

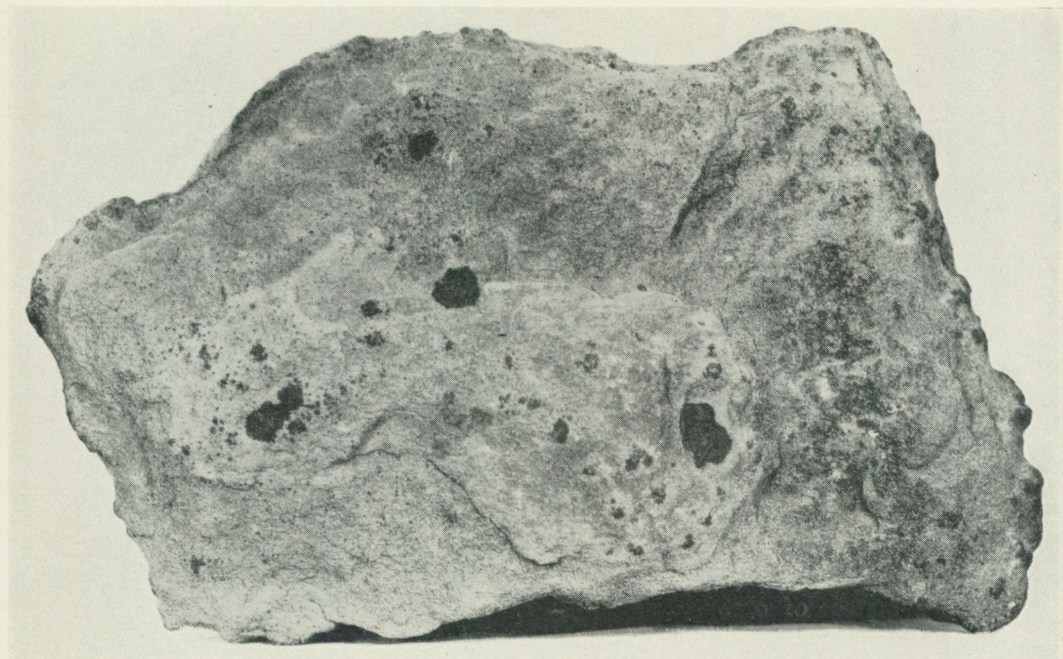


Fig. 4. Lower side of concretion in Fig. 3, showing small rounded concretions.  $\frac{1}{3}$  nat. size.

Photo C. Larsson.

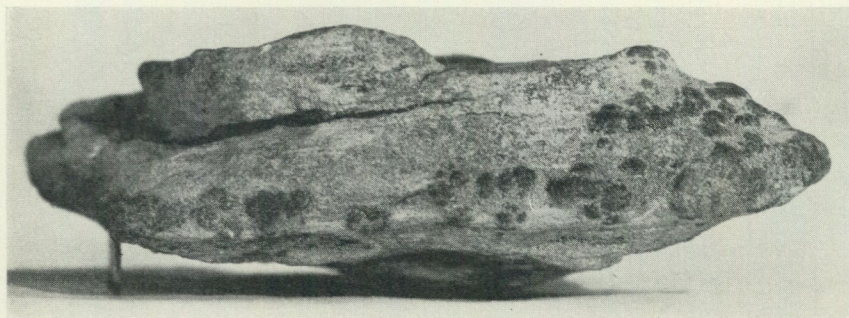


Photo C. Larsson.

Fig. 5. Side view of concretion in Figs. 3 and 4.  $\frac{1}{4}$  nat. size.

The concretions are sparsely scattered and only in one or two places are they so densely distributed that one might speak of a disseminated ore. It occupied only a very restricted space in the sandstone.

### Description.

#### Megascopical Features.

Even a superficial examination of the specimens indicates that the ore minerals in the normal concretions have more or less completely replaced

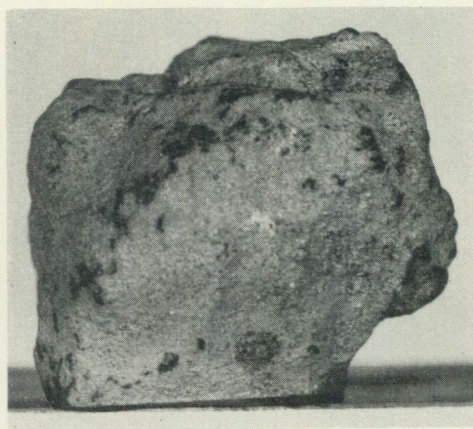


Photo C. Larsson.

Fig. 6. Massive concretion of fine-grained chalcocite and pyrite, covered with thin crust of malachite. Nat. size.

the groundmass in the sandstone, leaving the detrital grains embedded in a matrix of ore.

The megascopically most conspicuous ore minerals are chalcocite and chalcopyrite, but also pyrite, bornite, and covellite have been observed. Where chalcocite and covellite are the predominant constituents, the ore

gets a dark-bluish hue. As mentioned before, the loose ore boulders are surrounded by a thin coating of malachite, occasionally also of azurite.

In a few concretions there were observed irregular "veinlets", some mm wide and about 5—10 mm long (Fig. 7), of a dark-blue colour, evidently mainly composed of chalcocite and covellite. An appreciable amount of pyrite is seen under the microscope. Malachite was occasionally present in small pockets. As the "veinlets" have never been encountered *in situ*, it is impossible to ascertain their field relations. In one of the cake-shaped

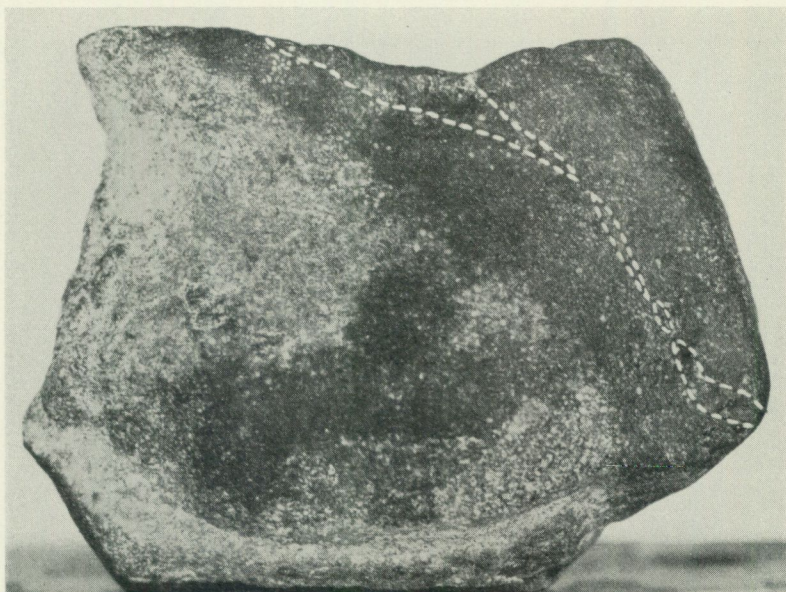


Photo C. Larsson.

Fig. 7. Concretion with "veinlet" of chalcocite (retouched). Nat. size.

concretions a "veinlet" was found standing at right angles to the bedding. The "veinlets" here and there contain large detrital grains which sometimes accumulate to large masses. In doing so they cause the "veinlets" to peter out and disappear.

On one occasion there were found some nut- or egg-sized and irregularly rounded concretions of compact ore (Fig. 6), which only occasionally carried detrital grains on the surface or in the interior. They occurred as boulders in the beach gravel. The ore is very fine-grained and has a bluish gray colour on a fresh surface. It is mainly composed of chalcocite and pyrite. The concretions were covered with a thin crust of malachite which also appears in fissures within the concretions.

Similar in appearance was a small nut-sized pocket of pure chalcocite and pyrite which occurred inside a normal concretion.

### Microscopical Features.

The microscopic study of the ore discloses the presence of the following ore minerals, *viz.* pyrite, chalcocite, bornite, chalcopyrite, and covellite. There are also small grains of a white isotropic mineral which may be galena. This supposition is strengthened by the comparatively high percentage of Pb in the ore (cf table on p. 5). The presence of malachite and azurite has already been mentioned. Finally, limonite has been found to be fairly abundant in some specimens.

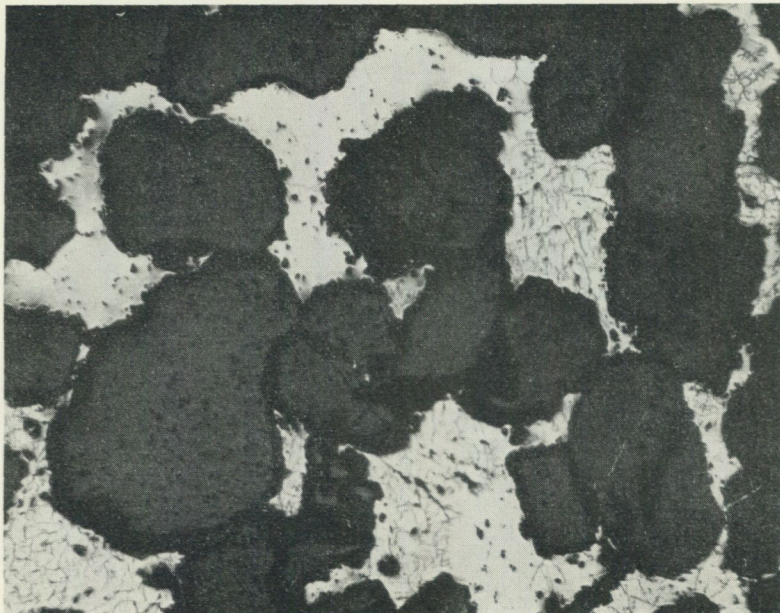


Photo C. Larsson.

Fig. 8. Chalcopyrite as matrix in sandstone. Fine network of limonite. Pol. sec., ord. light, 50 ×.

Minerals of the groundmass of the normal concretions. — The groundmass of the normal concretions is mainly built up of the minerals enumerated above. Only rarely is the primary, sandy matrix preserved.

In two concretions chalcopyrite is the predominant mineral of the groundmass (Fig. 8). It does not occur here only but is also found to corrode or to cut the detrital grains of the sandstone in narrow veinlets and fissures. Covellite and blue chalcocite are only rarely present. Limonite, on the other hand, is fairly common, occurring in veinlets or wart-shaped formations. One of the concretions is surrounded by a narrow and irregular zone of malachite. The surrounding sandstone is coloured green by the malachite even at some distance from the concretion.

In most of the concretions the paragenesis and structure of the ground-

mass are far more complicated. Pyrite to a large extent formed the primary ore mineral. As in the case of the chalcopyrite, also the pyrite veins the detrital sand grains. The pyrite is very extensively replaced by later copper sulphides, mainly bornite but occasionally also chalcocite. The latter may in some cases be absent. In the initial stages of replacement the later sulphides form a net-work in the pyritic groundmass (Fig. 9), but where the process is more advanced the pyrite remains only as dust-like particles. The surface of bornite and chalcocite then takes on a scarred appearance in polished sections.

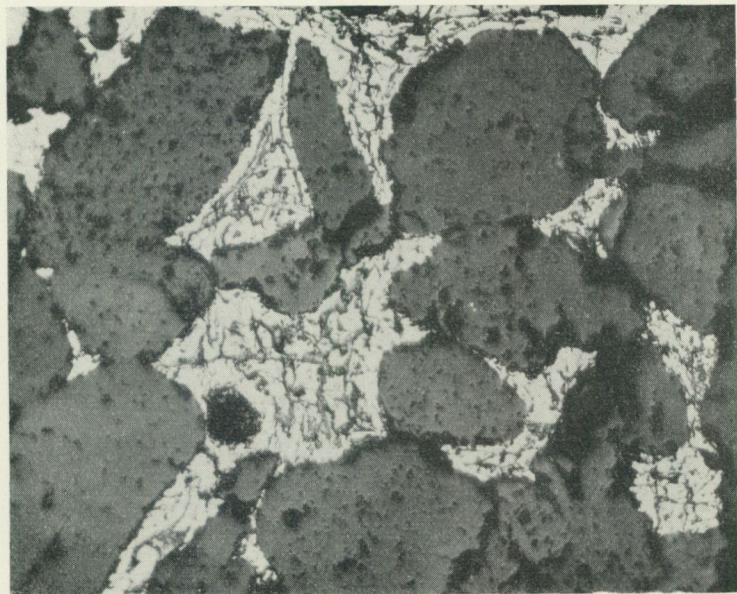


Photo C. Larsson.

Fig. 9. Pyrite as groundmass in sandstone, replaced by a network of bornite and chalcocite. Pol. sec., ord. light, 130  $\times$ .

The chalcocite is as a rule light grayish blue and weakly anisotropic and may consequently be interpreted as rhombic or "white" chalcocite. This "white" variety contains small spots or even lamellae (Fig. 10) of a considerably darker blue and isotropic chalcocite, which very likely is comparable to the "blue" chalcocite considered to be a mixed crystal between  $\text{Cu}_2\text{S}$  and  $\text{CuS}$ . Similar phenomena are mentioned *e. g.* by Geijer (2, p. 9) and in Schneiderhöhn-Ramdohr's handbook (3, p. 279), and are explained to be due to a changing intermixture of  $\text{CuS}$ .

Where bornite and chalcocite together replace pyrite, the former mineral readily replaces chalcocite, using its contacts to residual grains of sand or fissures as starting points. The structure clearly speaks in favour of a replacement. Similar structures were recently described by Scherbina (4, pp. 400 and 436) from Glava in W. Sweden and were by him also

interpreted as replacement. Between the bornite and the chalcocite there are developed two microscopically narrow zones (0.01 mm or less): next to the bornite a zone composed of a mixture of "blue" chalcocite and bornite, almost undissolvable under the microscope, followed by another zone composed of the "blue" chalcocite only.

Chalcopyrite is common in the bornite-rich portions of the groundmass and replaces the bornite in the shape of sword- or bayonet-shaped grains. They evidently follow the (111) cleavage of the bornite (Fig. 11). Chalcopyrite also occurs in a zone between the bornite and detrital sand grains. Also in this case there is evident proof of a replacement.

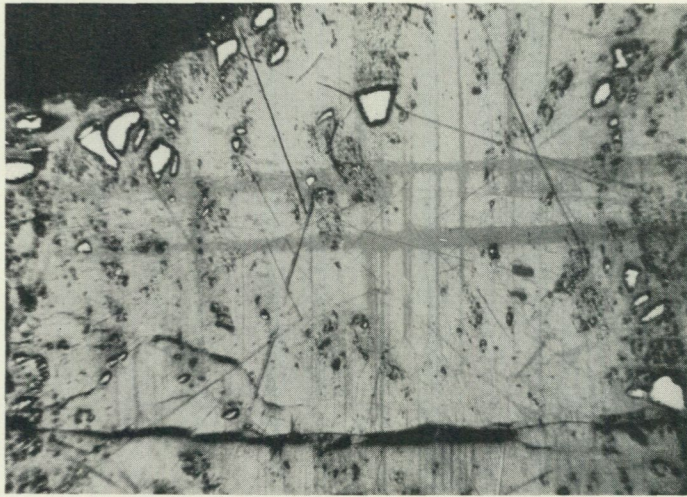


Photo C. Larsson.

Fig. 10. Lamellae of "blue" chalcocite in "white" chalcocite. Pyrite remnants in white grains and small particles. Pol. sec., ord. light, 230  $\times$ .

In several samples covellite is common in bornite or chalcocite, when it occurs as small rosette-shaped or coarser, scaly aggregates. Fringes of covellite needles are common, growing out at right angles from fissures filled with limonite. In the exterior bornite-rich portion of one ore concretion the aggregates of covellite were unusually large and tabular, containing narrow lamellae of limonite which were oriented parallel to the cleavage of the covellite (Fig. 12). The formations now mentioned are related to the veinlets described on p. 14.

The copper sulphides, however, not only replace the pyrite in the matrix but in some cases they also extensively replace the detrital grains, as is shown in Figs. 13 and 14. Bornite and chalcopyrite are the most common replacing minerals. The contours of the replaced grains are irregular and between them and the replaced pyrite of the matrix there is developed a zone of copper sulphides which lacks the dust-like pyrite remnants typical of the replacing copper sulphides in the pyritic matrix.

This replacement process is rather curious in view of the fact that the replaced minerals — mostly quartz and some felspar — are soluble only with difficulty and that the replacing solutions evidently had a low temperature (see p. 23).

"Veinlets" of pyrite, chalcocite, and covellite. — Also in these formations pyrite is found to be the oldest mineral in the ore paragenesis. It is extensively cut and replaced by a network of chalcocite veins. The pyrite remnants are often elongated and arranged in subparallel



Photo C. Larsson.

Fig. 11. Bornite (dark gray) replaced by chalcocopyrite (white). Pol. sec., ord. light, 130  $\times$ .

streaks, running parallel to the "veinlets" (Fig. 15). Detrital grains of sand embedded in the "veinlets" are often corroded by the chalcocite. The pyrite remnants are often so densely distributed that one is forced to believe that the "veinlets" were originally composed entirely of pyrite.

Chalcocite sometimes forms areas one or two mm wide (although always more or less contaminated by dust-like pyrite particles) in the veins cutting the pyrite, and here a well marked cleavage parallel (001) is noticeable. The mineral is light bluish gray and anisotropic and is probably the "white" rhombic chalcocite form. In one of the "veinlets", as in the surrounding normal sandstone ore, the chalcocite was of the "blue", isotropic variety. On etching it showed the same structure as the "white" chalcocite (see p. 20). Plenty of covellite was developed around fissures and cleavage planes.

Covellite is common also in the "white" chalcocite and occurs in scaly aggregates, often to a large extent replacing the chalcocite. The mineral

may also grow out from fissures (Fig. 16), sometimes filled with limonite (see p. 15).

Bornite occurs but rarely in the "veinlets".

**Massive concretions.** — These only rarely contain detrital grains, often corroded by the copper sulphides. Pyrite is again the oldest ore mineral and is as usual extensively replaced by a network of rhombic chalcocite (Fig. 17). Judging from the structure, the concretion was originally very likely composed entirely of pyrite.



Photo C. Larsson.

Fig. 12. Covellite (light to medium gray) showing pleochroism and containing dark-gray lamellae of limonite. Detrital grains black. Pol. sec., ord. light, 130  $\times$ .

Chalcocite is the most prominent replacing mineral but along veins and in irregular formations also bornite, chalcopyrite, covellite, limonite, and malachite are developed. Where bornite replaces rhombic chalcocite, a narrow zone of "blue", isotropic chalcocite is often developed between the two minerals. Bornite does not seem to replace the pyrite any further and attacks the chalcocite exclusively. The bornite is later replaced by chalcopyrite and covellite.

The massive pocket found within a normal concretion, mentioned on p. 9, is of a similar nature. The replacement sequence is: pyrite  $\rightarrow$  rhombic chalcocite  $\rightarrow$  (bornite + chalcopyrite + covellite). The latter group of minerals invades the pyrite-chalcocite concretion from the surrounding normal sandstone ore.

**Veinlets of bornite, chalcopyrite, and limonite.** — These veinlets, frequently found to cut chalcocite, are symmetrically built and often developed around fissures. Outermost, bordering the chalcocite,

there are bands of bornite which towards the centre of the veinlet pass over into narrow bands of chalcopyrite. The latter mineral sometimes cuts into the bornite in the shape of swordlike grains of the appearance described above (p. 12). The evidence of replacement is quite distinct. The central portion, finally, is occupied by limonite, or, in some broader veinlets, by malachite. Fig. 18 demonstrates one of the veinlets. Limonite may also appear in separate veinlets, sometimes surrounded by fringes of covellite. Two

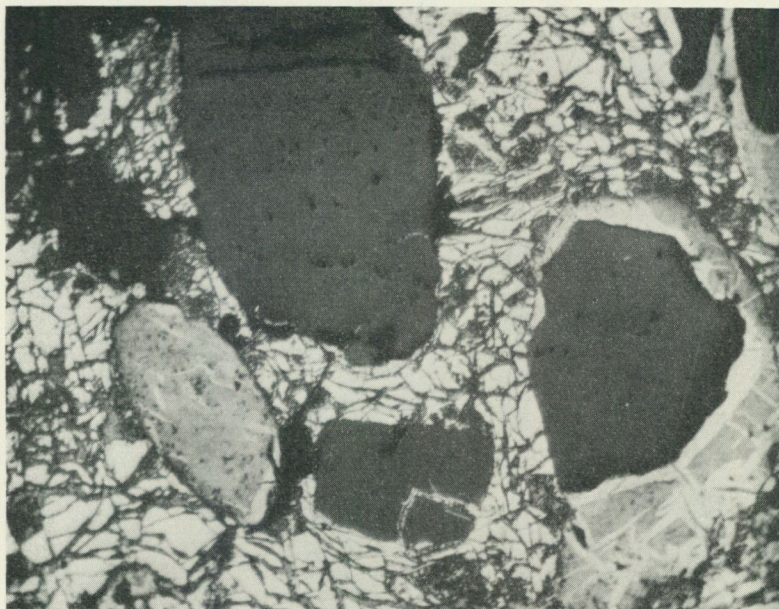


Photo C. Larsson.

Fig. 13. Detrital grains in matrix of pyrite, partly replaced by a network of bornite (medium gray) and chalcopyrite (white). These minerals also replace the detrital grains. Pol. sec., ord. light, 130  $\times$ .

slightly differently coloured types of limonite have been observed. In some of the broader veinlets the limonite shows a distinct banding.

These veinlets seem in general to be connected with and to emanate from the large areas of bornite, chalcopyrite, and covellite which in the ground-mass of the normal concretions replace the chalcocite.

**Zonary concretion.** — In a cake-shaped concretion, found *in situ*, the following five zones could be observed under the microscope in the ore-bearing groundmass: 1) Kernel with chalcocite and remnants of pyrite, 2) zone with mainly bornite, 3) zone with remnants of pyrite and an unknown mineral, 4) zone with mainly chalcopyrite, and 5) an outer zone with malachite.

The kernel is similar to the normal chalcocite-bearing concretions and is composed of "white" chalcocite, only to a comparatively small degree

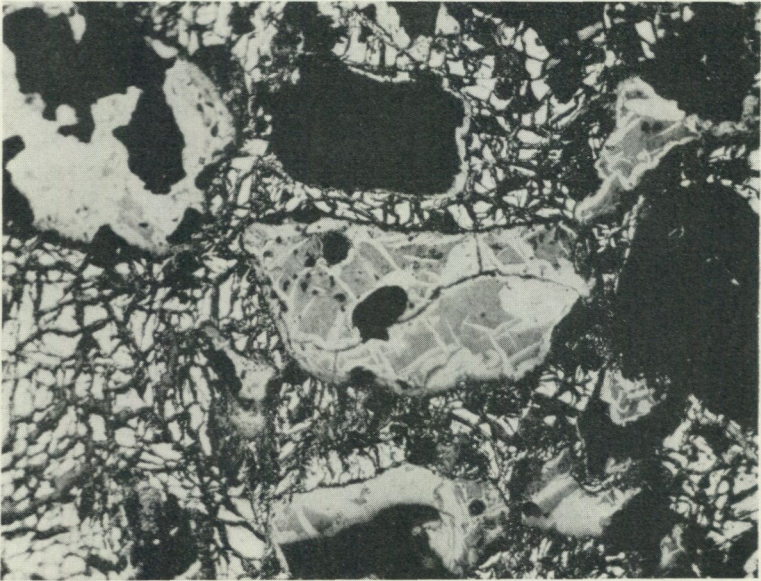


Photo C. Larsson.

Fig. 14. Same as Fig. 13. Pol. sec., ord. light., 130 X.

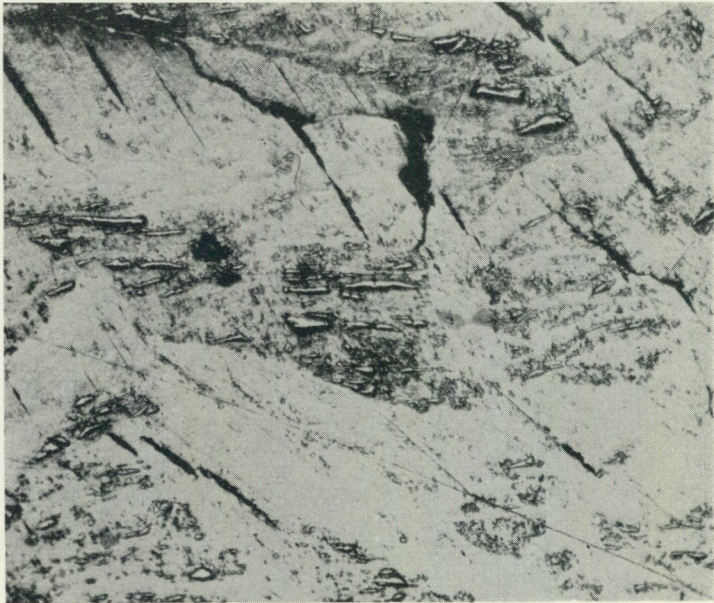


Photo C. Larsson.

Fig. 15. "White" chalcocite (showing cleavage) replacing pyrite (white grains and dust-like particles). Pol. sec., ord. light, 130 X.



Photo C. Larsson.

Fig. 16. Covellite (dark-gray needles) replacing chalcocite (light gray) from fissure. Chalcocite cuts and replaces pyrite (white with relief). Pol. sec., ord. light, 130  $\times$ .

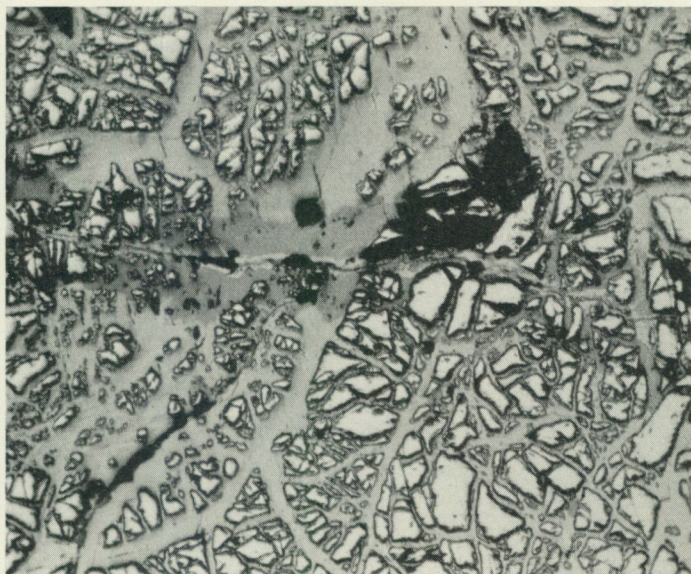


Photo C. Larsson.

Fig. 17. "White" chalcocite (medium gray) replaces pyrite (white with relief). In the middle symmetrical veinlet of bornite (dark gray), chalcopyrite (white), and limonite (in centre of veinlet). Pol. sec., ord. light, 130  $\times$ .



Photo C. Larsson.

Fig. 18. "White" chalcocite with remnants of pyrite (grains with relief). In lower half and upper left veinlets of bornite (dark gray), chalcopyrite (white), and limonite (in centre of veins). Pol. sec., ord. light, 130  $\times$ .

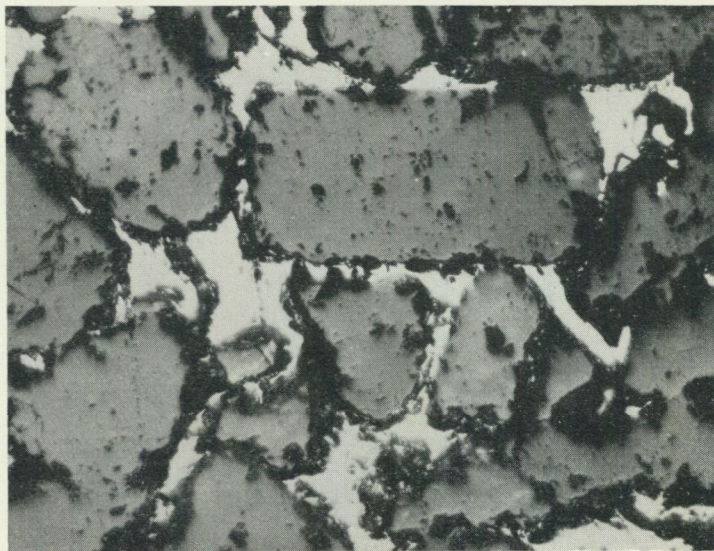


Photo C. Larsson.

Fig. 19. Pyrite as matrix in sandstone. Pol. sec., ord. light, 130  $\times$ .

replaced by bornite and covellite. The following zone is indistinctly developed. Bornite is the most common component but also chalcopyrite, covellite, and limonite are present, all these minerals being later than and replacing the chalcocite.

The following zone is composed of remnants of pyrite and a grayish, in polished sections soft, mineral which could not be identified. It is very likely an oxidation mineral and may be tenorite ( $\text{CuO}$ ). The mineral in question seems, however, to lack pleochroism and anisotropism, qualities which are quite typical of tenorite. This deficiency may depend on the extremely fine-grained state of the mineral which renders the observation of optical features almost impossible.

Next there follows a zone in which chalcopyrite dominates, occurring in the groundmass but also cutting the detrital sand grains. Only traces of other copper sulphides are present. The chalcopyrite is cut by veinlets of limonite. This zone to some degree resembles the chalcopyrite concretions described above.

In the outermost zone only minor traces of sulphides appear and the groundmass is mainly composed of malachite and some limonite.

**Pyrite-bearing sandstone.** — South of the locality of the ore concretions at Tunnerstad, the author found on the beach local boulders of a yellowish gray sandstone which contained knotty concretions of pyrite, the size of a pea. Similar but somewhat larger concretions were also seen in the sandstone in the drill hole at a depth of 121 m.

Under the microscope the matrix in the sandstone is seen to be more or less completely replaced by pyrite (Fig. 19), the same kind of structure being produced as in the normal concretions, where the pyrite now has been replaced by various other minerals.

### Nature of the Chalcocite.

Two modifications of chalcocite have been distinguished, the isometric high-temperature form which at  $91^\circ \text{C}$ . passes over into the rhombic, low-temperature form. This inversion point has until quite recently been considered a reliable geologic thermometer. In the January 1941 issue of *Economic Geology* N. Buerger (5) has published an X-ray study of the system  $\text{Cu}_2\text{S}-\text{CuS}$ , and he arrives at the conclusion that the conditions are more complicated than previously thought. According to Buerger no isometric modification exists, the high-temperature form having an hexagonal structure. At  $105^\circ \text{C}$ . this form passes over into the rhombic low-temperature chalcocite. A now discredited compound, earlier described as a distinct mineral species, digenite  $\text{Cu}_9\text{S}_5$ , is by Buerger found to enter into the system. The rhombic phase is capable of dissolving up to 8 atomic %  $\text{CuS}$ , while the high-chalcocite can dissolve only 2 atomic %. Buerger warns

not to state the temperature of origin of a chalcocite ore without undertaking an investigation according to the procedure used by him (controlled-temperature X-ray camera). In the case of the Visingsö chalcocite it may be shown with comparatively good evidence that the low-chalcocite is present.

According to the classification of Schneiderhöhn-Ramdohr (3, pp. 277—291), one may under the microscope distinguish four types of chalcocite, namely 1) rhombic chalcocite, 2) lamellate chalcocite, forming a rhombic paramorphose after high-chalcocite, 3) so-called "blue", isotropic chalcocite, a mixed crystal of  $\text{Cu}_2\text{S}$  och  $\text{CuS}$ , and 4) reddish gray chalcocite, a mixed crystal of  $\text{Cu}_2\text{S}$  and  $\text{Cu}_5\text{FeS}_4$  (bornite).

The "white" or rhombic chalcocite plays a dominant part in the Visingsö ore. It often shows a comparatively distinct cleavage, probably along (001). The grains attain a maximum diameter of 1.5 mm. Some sections were etched for 5—10" in concentrated  $\text{HNO}_3$  and the chalcocite then showed two well developed cleavage directions at right angles to each other. The resulting structure is rather similar to the one shown in Fig. 132 in Schneiderhöhn-Ramdohr's handbook (3, p. 283), representing cementative chalcocite from the Tsumeb Mine in SW Africa. On the other hand some grains show an etch-structure which is almost identical with the so-called "crackled porcelain structure". Both these related structures are looked upon as typical of low-chalcocite and it is concluded that the chalcocite occurring in the Visingsö ore was formed at a low temperature — whether by descending or ascending solutions will be discussed in the next chapter.

As to the "blue", isotropic chalcocite it is evident by its presence as intermediate zones between chalcocite and later bornite that it was formed during the replacement of the rhombic chalcocite. The isotropic variety may also form lamellae in the "white", but it cannot in this case be said whether its formation is connected with the replacement.

The chemical nature of the "blue" chalcocite is not known but it may be suggested that it is composed of  $\text{Cu}_2\text{S}$  with a certain amount of  $\text{CuS}$  in solid solution.

### Origin of the Ore.

It is evident from the description above that the Visingsö ore has undergone a long and complicated history of development. The study shows beyond doubt that pyrite is the oldest ore mineral and it seems just to assume that its formation is a process without any direct connection with the formation of the copper ore. It should here be kept in mind that pyrite also occurs in the sandstone as separate concretions. Usually the pyrite occupied the matrix of the sandstone but it must also have occurred in compact concretions and in the so-called "veinlets". The irregular appearance of the latter indicates that they very likely do not represent any real veinlets but rather some form of concretion, possibly a fissure filling.

The presence of pyrite in sediments is by no means of a rare nature, and,

*e. g.*, the Swedish Palaeozoic and Mesozoic sandstones often contain pyrite in the form of concretions or as a matrix. The iron sulphides (pyrite, marcasite, melnikovite, and hydrotroilite) in sediments may in many cases be considered formed during or shortly after the sedimentation. Later chemical transport of material and recrystallization during the diagenesis produce structures which veil or destroy the primary features. The sulphides are precipitated from iron solutions by hydrogen sulphide, formed by the decomposition of organic matter. Often bacteria may be active in the process (6, p. 397). The author considers it likely that some process of the kind now related brought about the formation of pyrite in the Visingsö sandstone. The fossil content of the Visingsö series is still under discussion but remnants of organic life have been established beyond doubt.

The question of the origin of the copper minerals is more complicated. The microscopic investigation has produced the evidence that the "white" chalcocite is oldest in this paragenesis and that it is extensively replaced by bornite, chalcopyrite, covellite, limonite, and malachite.

In the first place it may be asked whether this succession is the result of one continuous process, or whether it was formed in stages. In view of the fact that the replacing minerals enumerated often appear on distinctly younger veinlets and fissures, and of the difference in chemical composition between the chalcocite and the replacing, later minerals — implying the action of solutions of different character — the latter alternative would seem the most likely one. The first stage would then include the formation of chalcocite, implying an addition of copper only to the pyritic sandstone. This process is cementative in nature and is comparable to the formation of chalcocite in supergene enrichment ores. During the next stage the iron-bearing copper sulphides,  $\text{CuS}$ , and hydroxidic and carbonatic minerals were formed. This process is different to the first one and we must assume that it took place during oxidizing conditions.

It should be pointed out that the replacement sequence chalcocite  $\rightarrow$  bornite  $\rightarrow$  chalcopyrite  $\rightarrow$  (covellite + limonite + malachite) is reverse to the one generally taking place in the cementation zone, where, as is well known, the process leads from minerals poor in copper to minerals successively richer in that metal. This so-called "inverse cementation" (German "umgekehrte Zementation") has been defined by Ramdohr, who described it from a number of localities (3, pp. 282 and 292; 7, p. 173; 8, p. 16). Ramdohr interprets some of the cases as formed by supergene processes during fluctuations in the water table.

The next question concerns the source of the solutions that produced the copper ore. The problem is a rather intricate one and no definite solution can be offered as the evidence at present is rather scanty. Two possibilities can be considered: 1) formation by supergene cementation, and 2) formation by low-temperature ascending solutions.

As pointed out earlier, the chalcocite is in all probability deposited at a low temperature and its etching structure and relation to the pyrite indicate

that it was formed by cementation by descending meteoric waters in more or less the same fashion as Lindgren assumes for ore deposits of the "Red Beds" type (9, pp. 403—409). The resemblance between the Visingsö ore and ores of this type, widespread over large parts of the world but particularly known from the southwest of the United States, is rather striking and the author believes that there is also a concordance as to mode of origin. There also exists a resemblance between the continental Visingsö sediments (1, p. 258) and the sediments of the "Red Beds", the formation of which is summarized by Twenhofel (6, p. 318) as "deposited in a subaerial environment with warm and relatively dry climate and that fluvial processes played a large part in the deposition...".

As to the source of the copper, it must be pointed out that no copper deposits are known from the immediate surroundings of the Vättern basin, the nearest deposits known occurring at considerable distances (100—140 km) SE and NW from Visingsö. Although these distances in themselves do not prohibit a transport of soluble copper salts by running water into the Vättern basin, it seems more likely that weak and local disseminations of copper sulphides in the vicinity delivered the metal.<sup>1</sup> During a long erosional epoch even fairly weak disseminations should have ample time to form such insignificant ore concentrations as are present on Visingsö.

Oxidizing surface waters dissolved the ore minerals, and the copper, in the form of soluble salts, was transported with the solution down through the sandstone where, on striking suitable precipitating agents — mainly pyrite concretions and pyritic matrix — the copper was precipitated as chalcocite. It is also possible that the sandstone contained cupriferous detritus which was brought into solution by percolating surface waters, copper being later precipitated in pyritic parts of the sandstone.

The process is, as mentioned above, comparable to the process of supergene enrichment and the precipitation took place below the water table. The process began after the diagenesis of the sandstone and probably after the close of or during intervals in the sedimentation.

The possibility of a formation by telemagmatic ascending solutions can, however, not be completely excluded, the more so as the latest and most low-temperature manifestations of a hypogene mode of origin are likely to be similar to those of a supergene enrichment (9, p. 828). It should be noted, though, that in the deposit itself no features indicating a magmatic origin are to be found. Eruptive rocks are not known in the Visingsö formation.

An interesting observation in this respect was made at the southern end of the island of Visingsö. Greenish shales and grits are here outcropping in sheer cliffs and at the foot of one of them the author found a boulder, evidently deriving from the cliff above, which was composed of a gritty shale and contained an approx. 10 cm thick vein of coarse, drusy calcite with scattered crystals of chalcopyrite. It can hardly be doubted that this

<sup>1</sup> Much erosion has taken place since the deposition of the Visingsö sandstone and the surrounding bedrock may have contained copper deposits, now completely obliterated.

vein was formed by ascending, low-hydrothermal solutions and that consequently magmatic solutions at least locally have circulated through the Visingsö series. It is, however, rather unlikely that there exists any genetic connection between this mineralization and the entirely different copper ore concentrations in the sandstone.

The origin of the "inverse cementation" now remains to be discussed. The solutions acting here had a different character to those forming the chalcocite and, as pointed out above, Fe, H<sub>2</sub>O, and CO<sub>2</sub> have been added, while Cu was partly leached out. Experiments carried out by Schouten (10, p. 646) prove that the reversed order of cementation is caused by solutions with a high concentration of ferrous and ferric sulphates. The latter is a strong oxidizing reagent and the former, a powerful reducing agent, easily changes to the ferric salt and limonite. The presence of the latter mineral and malachite indicates that the "inverse cementation" took place under oxidizing conditions above the water table. There is no reason to doubt that the oxidizing solution consisted of percolating surface waters, although there is no obvious source of the iron sulphate content of these waters. It is close at hand to assume that pyrite in overlying strata, not consumed during the earlier copper mineralization, or, else, iron-bearing water from the surface, yielded the solution.

This mineralization may be considerably later than the formation of the chalcocite and it probably took place at a time when the Visingsö series had achieved its present-day position. As to the crusts of malachite surrounding the boulders on the beach, they probably form as the concretions are being freed from the enclosing sandstone.

In two concretions the matrix was mainly composed of chalcopyrite. The question is, whether the mineral is primary or if it was formed by "inverse cementation" of primary chalcocite. The evidence is not sufficient to allow a decision on this point, but the latter alternative seems likely in view of the fact that chalcopyrite is sometimes formed as a distinct zone at the replacement of chalcocite and that it further enters into the paragenesis of the "inverse cementation" as a common constituent.

### Comparison with Similar Deposits.

As mentioned above, the Visingsö ore is rather similar to ores of the "Red Beds" type as regards environmental rocks, general appearance, and paragenesis. Dissimilarities are, for instance, the absence at Visingsö of coaly matter in connection with the ore, a very common case in many ores of this type, and the more complicated paragenesis of the Visingsö ore.

The literature on this type of ore is quite voluminous and only a short summary will be given.

The ores generally occur in sandstones of Upper Carboniferous, Permian, Triassic, or Jurassic age. The rocks are of terrigenous or shallow-water

character and are often of a reddish colour. The ore minerals — mainly chalcocite but also chalcopyrite, bornite, covellite, and pyrite — occur in concretions or as disseminations, often in close connection with carbonaceous matter.

The origin of the "Red Beds" ores has been much discussed but the general opinion (9, pp. 403—409; 11; 12; 13; 14) seems to be that the ores were formed as concentrations from percolating meteoric waters which leached the strata of their content of cupriferous detritus or dissolved copper from older deposits, later depositing them in the sediments. Coaly matter, kaolin or pyrite generally served as precipitating substances. Only a few students, *e. g.* Graton (9, p. 407), Blanchard and Boswell (11, p. 387), believe that at least in some cases ascending magmatic solutions acted as ore carriers.

### Summary.

Copper ore was found as boulders on the beach on the western side of the island of Visingsö in Lake Vättern, S. Sweden. The author's survey disclosed copper ore also *in situ* in the sandstone, outcropping on the shore NW of Tunnerstad (Fig. 1). The ore appears as rounded or cake-shaped concretions, more rarely as disseminations erratically spread in the bed-rock.

Under the microscope the following minerals were identified: pyrite, chalcocite, (galena?), bornite, chalcopyrite, covellite, limonite, malachite, and azurite. They form the matrix of the sandstone, sometimes even replacing its detrital grains. Occasionally irregular "veinlets", most likely to be interpreted as some kind of concretions or possibly fissure fillings, and composed of mainly pyrite and chalcocite, are seen in the normal concretions. Some of the rounded concretions are composed of very fine-grained and compact sulphides, practically without any detrital grains of sand.

Pyrite is the oldest mineral in the ore paragenesis. The "veinlets" and the compact concretions were in all probability originally composed of this mineral exclusively. It was extensively replaced by chalcocite of the rhombic, low-temperature type. On etching the latter showed structures characteristic of a supergene mode of origin. Chalcocite was later extensively replaced by bornite, chalcopyrite, covellite, limonite, and malachite, sometimes along fissures.

The formation of pyrite took place in close connection with the deposition of the sandstone and before the entry of the later sulphides. It was presumably precipitated from iron solutions by hydrogen sulphide along with decomposition of organic matter.

The chalcocite is believed to have been deposited by percolating surface waters which derived their cupriferous contents from disseminations in the continental area surrounding the sedimentary basin. The solution seeped down through the sandstone and on encountering the primary pyrite con-

cretions and the pyritic matrix, copper was precipitated in the same way as in the supergene enrichment zone. The process took place below the water table.

The possibility of a formation by ascending low-hydrothermal solutions can, however, not be altogether excluded. Solutions of this kind have at least locally circulated through the rocks of the island, as indicated by the find of a local boulder with a vein of calcite with some chalcopyrite at the southern end of the island.

The minerals replacing the chalcocite form a so-called "inverse cementation" series, as here, contrary to the general rule, the minerals become successively poorer in copper. Oxidizing surface waters here acted as the replacing agent. The process probably took place much later than the chalcocitization, when the sandstone already had more or less achieved its present-day position.

The ore may be classified as belonging to the "Red Beds" type, widely distributed in many parts of the world but particularly in the southwestern states of the United States.

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