RECENT WORK ON ARCHÆAN SULPHIDE ORES IN FENNO-SCANDIA.¹

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Introduction.—The Swedish Archæan contains a considerable number of sulphide ore deposits which are mostly of rather insignificant size, but includes the Falun mine, for centuries the world's leading copper producer and still an important pyrite mine, and also the zinc deposits of Ämmeberg. Recent studies on Falun and some other districts by the author, and, somewhat earlier, by Dr. P. Eskola on the analogous Orijärvi district in southwestern Finland have yielded results that may perhaps deserve a brief review in this journal, particularly as these deposits represent a genetic type that previously has not been clearly understood.³

The sulphide deposits in the Archæan of central Sweden occur in the leptite formation, which also harbors the numerous iron ore deposits of this region. Referring for more details to a review published a few years ago in a paper dealing with some of the iron ore types,⁴ I will here repeat only the fundamental features of the general geology of the ore-bearing country.

General Geologic Features.—The leptite formation is of supra-

¹ The name Fenno-Scandia has been proposed by Prof. W. Ramsay, of Helsingfors, for the geologically well defined region comprising the Scandinavian peninsula and Finland, and is being increasingly used by the geologists in these countries.

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³ Dr. Eskola's report, "Petrology of the Orijärvi region," and a shorter paper discussing the relations between chemical and mineralogical composition of the metamorphic rocks at Orijärvi (in Swedish) are published as Bull. 40 and 44, respectively, of the Geol. Survey of Finland. The author's report on the geology and ore deposits of the Falun district is published in Swedish (with a summary in German) as Series C, no. 275, of the Geol. Survey of Sweden.

⁴ ECON. GEOL., vol. X., p. 299, 1915.

crustal origin, *i.e.*, consists of rocks formed at the surface. The leptites, its chief components, are very fine-grained gneisses, generally of a granitic composition. Where the formation is less metamorphosed, the grain is finer and the rocks are typical "hällefintas." Despite the strong metamorphism, volcanic rocks, both lavas and tuffs, can often be identified among the leptites. The remainder is probably also made up of volcanics and their detritus. Femic rocks of the same kinds of origin also occur, but are more subordinate. Limestones and quartzbanded iron ores (also other types) are not uncommon, but mica schists chemically corresponding to shales are rare. The leptite formation has no substratum of older rocks. It rests on younger granite masses. The older ones among these granites, mostly more or less gneissic, appear to have mainly risen along the anticlinal axes in the folded leptite formation, while the younger massifs show cross-cutting boundaries, shatter-zones, and usually the contact relations interpreted as due to magmatic stoping.⁵ Exactly the same conditions, both in the leptite formation and in the granites, are found in the Archæan of southwestern Finland, where Orijärvi is situated.

The first detailed geological examination of one of the sulphide deposits in question was Törnebohm's work at Falun, the results of which were published in 1893.⁶ Törnebohm found that the ore deposits were associated with a quartzose rock, containing cordierite and an orthorhombic amphibole (anthophyllite). He regarded this ore-bearing quartzite as the result of an alteration of the leptite, caused by diorite eruptions. This view was rather remarkable for that time, although Törnebohm apparently regarded the alteration as a rather "shallow" process, in accordance with his idea not only of the leptite formation but also of the granites. Later, it was pointed out by several authors⁷ that many sulphide deposits in limestones or dolomites

⁵ Compare a paper by the author "On the Intrusion Mechanism of the Archæan Granites of Central Sweden" (*Bull. Geol. Inst. Upsala*, vol. 15, p. 47).

⁶ "Falu gruvas geologi" (*Geol. Fören. i Stockholm Förh.*, vol. 15, p. 609).

⁷ K. Beck, "Lehre von der Erzlagerstätten," 1901, and A. Bergeat in Stelzner and Bergeat, "Die Erzlagerstätten," 1904-1906.

of the leptite formation, as the argentiferous galena and zinc ores of Sala, are analogous to contact deposits. Further, H. Johansson showed⁸ that the association of sulphides with siliceous rocks high in alumina, ferrous iron and magnesia, as at Falun, is a widespread phenomenon in the leptite formation.⁹

The Orijärvi District.—Eskola's recent work in the Orijärvi district in southwestern Finland gave the following results: Around one of the numerous batholiths of gneissic oligoclase granite¹⁰ that invade the leptite formation, the latter has suffered intense metamorphism. This metamorphism has been of a metasomatic nature, and its products are characterized above all by the development of cordierite and anthophyllite. Feldspar-quartz rocks with these two new-formed minerals probably represent a less intense metamorphism of the leptite, while the combination quartz, cordierite, anthophyllite, or the two last-mentioned minerals with only small amounts of others indicate a more complete replacement. Where there are amphibolites within the metamorphic aureole, their hornblende has been changed to cummingtonite [monoclinic amphibole (Mg, Fe) SiO_3], but the plagioclase is intact. Limestones are changed to skarn consisting of tremolite or andradite. The porphyritic marginal phase of the granite is locally metamorphosed in the same way as the leptite. In the cordierite-anthophyllite-quartzite there are chalcopyrite deposits, the sulphide apparently having been formed contemporaneously with its gangue as a metasomatic product. In the tremolite skarn, there is galena and sphalerite. At one mine, free gold occurs, accompanied by lillianite (a sulphantimonide of lead and bismuth). Particularly noteworthy are the facts that the replacement of leptite by cordierite-anthophyllite-quartzite can be proved beyond doubt, and that the room relations and

⁸ *Geol. Fören. Förh.*, vol. 29, 1907, p. 157.

⁹ The zinc deposits of Ämmeberg have been described by H. Johansson (*Geol. Fören. i Stockholm Förh.*, vol. 32: 2, 1910, p. 1051, and as guide for the 11th internat. geological congress). As the author has only a very slight acquaintance with them, and it is doubtful whether they are genetically analogous to those of Falun and Orijärvi, they are not considered in this paper.

¹⁰ American petrologists would probably prefer to call this rock a granodiorite.

the metasomatic alteration of the granite margin point to the granite as the mother rock of the ores. However, Eskola has also found similar metamorphic rocks at great distances from any known granite.

The Falun District.—In the immediate neighborhood of Falun¹¹ in Sweden, the leptite formation is intruded by two great bodies of granitic rocks. One of these rocks is a granite gneiss with a metamorphic (grano-blastic) texture. This igneous body is a complex one, its dominant rock having the composition of a granite with predominant sodic feldspar. The other rock has suffered less textural rearrangements and may be called a gneissic granite. Chemically, it is characterized by its dominant oligoclase, and is very closely similar to the oligoclase granite of Orijärvi. Both differ from the Falun granite gneiss by their somewhat more calcic plagioclase.

Near a projecting point on the granite gneiss area, but about 2 or 2.5 kilometers from the oligoclase granite, the leptites grade into a cordierite-bearing mica schist, which in turn, without any sharp boundaries passes into the cordierite-anthophyllite-quartzite of the ore-bearing area. The ores at Falun are classed as "hard ores" and "soft ores." The "hard ores" are phases of the quartzite which contain chalcopyrite (and other sulphides) and thus constitute a copper ore. Törnebohm found that the ore minerals must have been formed contemporaneously with the quartzite. As already mentioned, the same relations have been found by Eskola at Orijärvi. Associated with the Falun hard ores are gold ore bodies, in which the free gold is accompanied by a bismuth-lead-selenium mineral, weibullite (compare lillianite at Orijärvi). The "soft ores" are pyrite bodies with some chalcopyrite, sphalerite and galena. These pyrite-masses are generally separated from the quartzite by a boundary "sköl," a mass of biotite or chlorite and talc. (Other "sköls" at Falun appear to be replacement veins of cordierite and anthophyllite.) Considerable parts of the pyrite stocks contain numerous lime-

¹¹ The author's work at Falun may be regarded as a revision and an enlargement of Törnebohm's detailed survey.

stone fragments, and show the relations typical of replacement deposits in limestone. A little tremolite and actinolite skarn accompanies the sulphides in these "soft ores." Other parts of the pyrite bodies do not contain any limestone fragments, nor any lime silicates, but quartz and a cummingtonitic amphibole. They cannot have replaced limestone, but probably leptonite.

The ore-bearing rocks are cut by a number of igneous dikes, consisting of a somewhat recrystallized oligoclase granite porphyry (the felsite of Törnebohm), flanked by amphibolites ("trap"). There are also independent amphibolite dikes. In their original character, these "mixed dikes" were apparently entirely analogous to those, for instance, that accompany the granite of the Kristiania region in Norway, and are closely connected with contact deposits of sulphides.¹² In the outer zones of the amphibolite bodies, or sometimes throughout them, the amphibole is cummingtonite, otherwise an ordinary green hornblende. One of the porphyry dikes is faulted by a "sköl," in this case consisting almost exclusively of anthophyllite, and probably a replacement vein. Next to it, the dike rock is altered to a cordierite-anthophyllite-quartzite of the usual type, only the quartz phenocrysts of the porphyry remaining as proofs of the original character. The author's interpretation of this fact, and of the cummingtonite of the amphibolites, is that the metasomatic action continued also after the intrusion of the dikes. It cannot, however, have been entirely later, or the dikes should have been completely replaced.¹³ A connection between the mixed dikes and the ore deposits is also suggested by the fact that the dikes are exclusively found within the ore-bearing area or its immediate neighborhood. Therefore, it is highly probable that the dike rocks and the ore-forming solutions came from one source. It is known that dikes of this character are closely connected with granites. At Falun, the chemical composition points to the gneissic oligoclase granite as the prob-

¹² Compare V. M. Goldschmidt, "Die Kontaktmetamorphose im Kristiania-gebiet."

¹³ There is a certain analogy between this relation and the garnetization of dikes at their intersection with faults, which has been studied by Dr. Knopf in the Yerington district, Nevada (U. S. Geol. Survey, P. P. 114).

able mother rock of the dikes, and therefore also of the ores. The position of the ore-bearing area near the granite gneiss might suggest a genetic relation to the latter, but is more probably due to structural causes.

Other Districts in Sweden.—In connection with the work at Falun, a survey was made of a great number of other sulphide deposits in central Sweden, including Garpenberg, Ryllshyttan, Väster-Silvberg, Saxberget (Rävåla), Kallmora, Yxsjö, and many others. In this way, a somewhat clearer picture than before was obtained of the geological relations of the sulphide ores of Central Sweden.¹⁴ These ores may be divided into two chemical-mineralogical groups, one characterized by a lime-magnesia-iron-silicate gangue and occurring in association with limestone and dolomite, and the other by siliceous rocks, high in alumina, magnesia and ferrous iron. The former are clearly the products of a metasomatic replacement of carbonate rocks. Like the skarn iron ores of the same region, their geological relations and paragenesis are those of contact deposits. The gangue minerals (skarn) are pyroxenes (diopside or hedenbergite), amphiboles (mostly tremolite or actinolite), lime-iron-garnet (andradite), chondrodite, fluorite. The sulphides are chalcopyrite, pyrite, sphalerite, galena, pyrrhotite, arsenopyrite, molybdenite. One deposit (Yxsjö) also contains rather much scheelite. Magnetite also occurs, but the relations between the sulphides and the skarn iron ores are not yet clearly proved. The siliceous sulphide ores are often found in an intimate connection with such of the former group, as at Falun (and also at Orijärvi). It is apparent that the replacement of leptitic rocks has resulted in siliceous ores, cordierite-anthophyllite-quartzite, etc., while the interstratified limestones have been replaced by sulphides with skarn minerals. The general character of the siliceous ores and associated rocks have everywhere been found to be essentially the same as at Falun and Orijärvi. The ore mineral is generally chalcopyrite, but also pyrite, sphalerite and galena may occur in

¹⁴ As mentioned above, Ämmeberg and certain other ore fields are not considered here.

commercial quantities. The ore-bearing rock is never sharply defined against the surrounding leptites. The transitional phase is often a quartz mica schist, with cordierite or andalusite. The chief components of the ore-bearing rocks are quartz, cordierite, anthophyllite, andalusite, iron-alumina garnet (almandite,) biotite. Anthophyllite and andalusite are as a rule not found together, but otherwise these minerals are combined in various ways. Also gahnite (zinc spinel) and staurolite sometimes appear as important constituents. Cordierite, andalusite, garnet and staurolite are mostly developed as big poikilitical grains, enclosing quartz, while the anthophyllite appears as beautiful stellate aggregates. The grain is coarse, sizes up to several inches being nothing exceptional. The quartz grains, however, invariably are much smaller.

Although the chemical composition of these rocks is often that of a shale, the geological relations very clearly indicate their metasomatic origin (compare above description of Orijärvi and Falun).

Discussion of Origin.—While the sulphide ore deposits in limestone exactly correspond to the well-defined group of the contact deposits, those accompanied by siliceous rocks have no counterpart in younger geological systems. A review of a number of important monographs on various contact-metamorphic deposits has failed to reveal anything fully corresponding to this type. Where the limestones carry ore deposits identical to our skarn sulphide ores, the metamorphism of quartz-feldspar rocks has resulted in the development of quartz, sericite and pyrite. The only thing that hints at something corresponding to our ore-bearing "quartzites" with alumina silicates is the occurrence of an andalusite-bearing rock in the San Francisco district, Utah. According to Butler,¹⁵ this rock is a metamorphosed lava rock, probably a quartz-latite, and now consists of 26 per cent. andalusite, 56 per cent. quartz, and sericite. A certain analogy may

¹⁵ U. S. Geol. Survey, P. P. 80.

also be traced in the occurrence of anthophyllite with galena in the Cœur d'Alene¹⁶ and Kootenay¹⁷ districts.

The metamorphism of the leptite formation was undoubtedly caused by the older granites. Both at Orijärvi and at Falun the evidence points to a certain granite as the mother rock of the ores. In other districts, no such connection can be proved, but general considerations show that other intrusions cannot have had this effect, the hypabyssic intrusives among the leptites being too insignificant, and the younger granite group decidedly younger than the ore deposits. Thus the sulphide deposits in question, both those with skarn in limestone, and the siliceous ones, must be interpreted as products of igneous metamorphism under abyssal conditions—in the strips of leptite formation engulfed among the granitic magma masses. This origin explains several remarkable features of the ores. One is the distance from any possible mother rock, which at least horizontally in most cases stretches several kilometers. That such relations must be expected at deposits formed at great depths has been realized by several authors.¹⁸ Observations by F. E. Wright and Ch. W. Wright in the Ketchikan and Wrangell districts, Alaska,¹⁹ show the increase in distance with increase in depth. Another region, where this is illustrated, is Nautanen in Swedish Lapland (compare below). Probably, the physico-chemical conditions determined by depth and stress have also determined the development of the characteristic gangue minerals of our siliceous ores. It is true that these minerals are common as recrystallization products in hornfelses formed at moderate depths and under static conditions, but their development through replacement processes in feldspar-bearing rocks is apparently not possible under these conditions. The absence of veins is probably also due to the same causes.

Similar Deposits Elsewhere.—Among deposits in Europe out-

¹⁶ F. L. Ransome and F. C. Calkins, U. S. Geol. Survey, P. P. 62.

¹⁷ S. J. Schofield, Geol. Survey of Canada, Summ. Rep. 1911, p. 158, and Mémoir 76.

¹⁸ Compare W. Lindgren, "Mineral Deposits," 2d ed., pp. 655 and 750.

¹⁹ U. S. Geol. Survey, Bull. 347.

side Fenno-Scandia, that of Bodenmais in Bavaria seems to be very nearly related to the siliceous Falun-Orijärvi type. It is generally cited as an example of injected sulphide ores. The similarity to Falun has caused several writers to class the latter deposit in the same group. This classification, however, is now known to be wrong as far as Falun is concerned, and the question may be raised whether the geology of the ore bodies of Bodenmais cannot be interpreted as due to such processes as are now known to have been in operation at Falun and Orijärvi. Also the great Broken Hill lode in New South Wales apparently exhibits features that point to a certain similarity in origin to the Falun-Orijärvi type. In North America, deposits of this siliceous type seem to be lacking. The paragenesis cordierite, orthorhombic amphibole, and garnet, was observed by Adams and Barlow²⁰ in Harcourt township, Ontario. No sulphide minerals are reported, however.

Deposits of deep-seated origin accompanied by skarn silicates are more common. The pyrrhotite ores of Ducktown are a well-known example.

The Nautanen Type.—Finally, mention may be made of a different copper ore type, that of the Nautanen district, east of Gellivare, in Swedish Lappland. These ore bodies are not of any economic importance—they are rather small and of a very low grade, and mining in the district has proved a failure—but they represent a new genetical type: chalcopyrite with scapolite and tourmaline. They also illustrate the occurrence of high-temperature replacement deposits at a long distance from their igneous mother rock.

In the Nautanen district,²¹ a formation of leptitic rocks with subordinate mica schists and quartzites (also the two latter rocks certainly of a sedimentary origin) is intruded by great granite batholiths. The whole complex is pre-Cambrian, and probably to be classed as Archæan. The granite is accompanied by

²⁰ "Geology of the Haliburton and Bancroft Areas," Geol. Survey, Canada, Mem. no. 6.

²¹ The district was surveyed by the author in 1916. The report is published in Swedish as Series C, no. 283, of the Geol. Survey of Sweden.

numerous pegmatites, intruded in the surrounding leptytes. In the outer part of this intrusion zone, the pegmatites are rich in tourmaline. The ore deposits lie at several kilometers' distance from any known granite, and generally not even a pegmatite dike is observed within the ore fields. Various ore types occur close together. In highly scapolitized leptyte with some tourmaline, chalcopyrite and magnetite are developed. Some of the best ore bodies were replacement veins of various silicates (garnet, hornblende, biotite) with magnetite and chalcopyrite. Further, there are zones of schistose leptyte, impregnated with garnet, chalcopyrite, magnetite, and tourmaline; replacement bodies of quartz, magnetite, chalcopyrite, pyrite and tourmaline, quartz veins with chalcopyrite and accompanied by an intense tourmalinization of the wall rocks, quartz veins with bornite, veins of hornblende and apatite with magnetite and sulphides, impregnations of apatite, etc. Zeolites, notably stilbite, have often been the last minerals to form. Particularly interesting is one occurrence of quartz veins with calcite, chalcocite, specular hematite, biotite, stilbite and some free gold and accompanied by the development of scapolite and tourmaline in the immediate wall rock.

The observations at Nautanen have established a connection between the great granite masses of northeastern Lapland and the regional scapolitization of the older, supracrustal rocks. This scapolitization has been studied by Sundius²² in the country south and west of Kiruna. In part of this district, the metamorphism has taken place at comparatively moderate depths, the finer textures of the igneous rocks are preserved, and the scapolite has formed mainly along joints, in the interstices between the pillows of ellipsoidal basalts, and similar places. In another part, however, the supracrustal rocks are recrystallized to leptytes and amphibolites, and the scapolitization has been contemporaneous with the recrystallization. Scapolitization is known from points that lie many kilometers from any exposed granite.

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²² "Beitr. z. Geologie d. südl. Teils d. Kirunagebietes." Uppsala, 1915 (in the series "Scientific and practical research in Lapland, arranged by the Luossavaara-Kiirunavaara Company").