

THE MOUNT LYELL COPPER DISTRICT OF TASMANIA.

By CHESTER G. GILBERT and JOSEPH E. POGUE,
Of the Department of Geology, United States National Museum.

INTRODUCTION.

The present paper is based upon a study of a representative collection of rocks and ores received in 1910 by the United States National Museum from Robert Sticht, manager of the Mount Lyell Mining & Railway Co. (Ltd.). The geologic and technical information is derived largely from the writings of Gregory and of Sticht (see Bibliography), which embrace the most authoritative expressions on those subjects. Mr. Sticht has also generously assisted the undertaking by supplying copies of his papers and communicating unpublished data.

LOCATION.

The Mount Lyell mining district, comprising the Mount Lyell Mine, the North Mount Lyell Mine, the South Tharsis and Royal Tharsis Mines, and other workings of less importance, occupies an area of 9 square miles situated 18 miles inland from Macquarie Harbor on the west coast of the island of Tasmania. The field is reached over a railway 28 miles in length from Strahan, the harbor port, to Queenstown, the mining center. The region is wild and inhospitable, is covered with a dense undergrowth, and is scarcely penetrable except along streams and where cleared by man or forest fire. The colony is under British rule and lies off the southernmost point of Australia, from which it is separated by Bass Strait, about 150 miles in width.

HISTORY.

Discovered in 1642, but not settled until 1803, Tasmania attracted no mining interest until the early sixties of the nineteenth century, when gold was discovered in the western interior. In 1881 prospectors came across gold-bearing alluvium near Mount Lyell, and in 1883 the ferruginous outcrop of the Mount Lyell ore body was encountered.

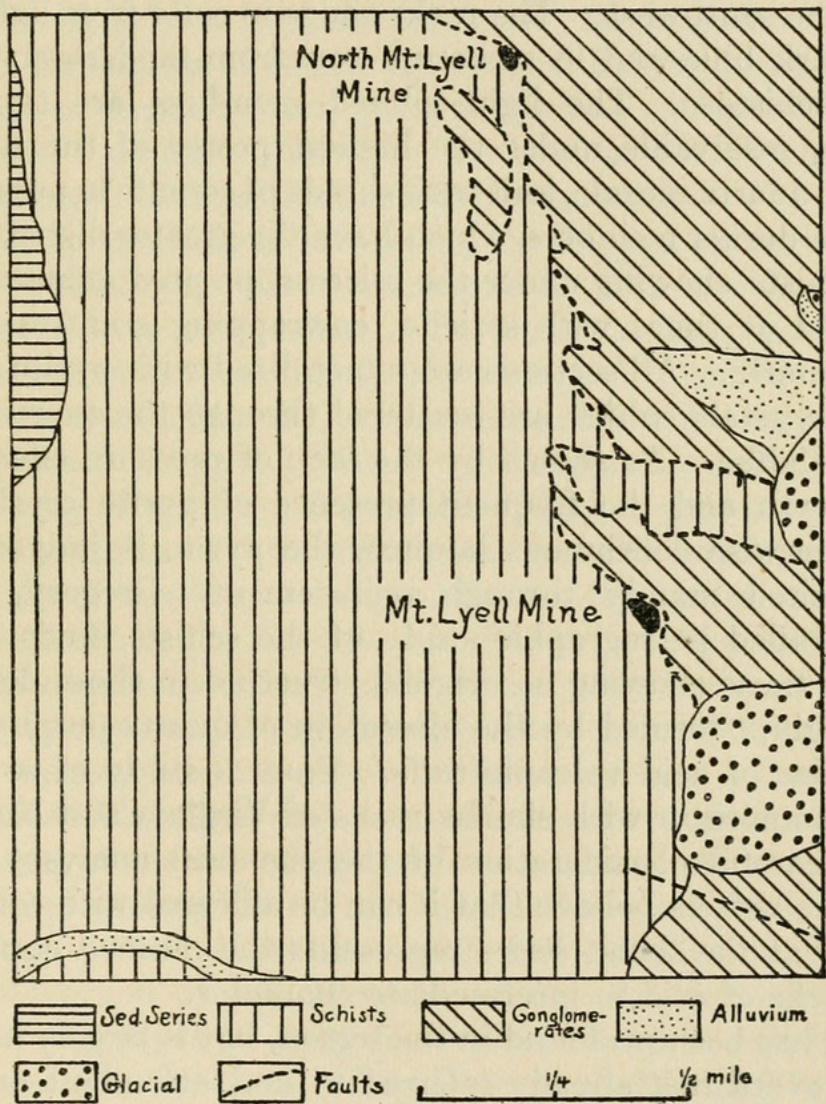
Good values in gold were found here and although the underlying pyritic mass was soon detected, its significance was not recognized, and attention was confined to the oxidized ore, the valuable portion of which was depleted within a few years. In 1891 lagging interest in the deposit was revived by the recognition of the copper potentialities of the pyritic mass, and a syndicate was organized for working the ore on a systematic scale. In 1893 the company was incorporated as the Mount Lyell Mining & Railway Co. (Ltd.), which to the present has retained control of practically the entire field. At its inception this company was fortunate in securing the services of an eminent metallurgist, E. D. Peters, whose favorable report and recommendations, coupled with a very timely find of rich silver-copper ore, insured the financial backing necessary for the success of the enterprise. Development work was at once actively prosecuted and a coast-to-mine railway projected and started. Robert Sticht, an American engineer, was engaged to direct the undertaking, and to his administrative ability and scientific skill the subsequent success of the company is largely due. In 1895 the open-cut system was adopted for working the ore body and a system of pyritic smelting was planned and inaugurated whereby the sulphur and iron of the ore served as fuel for its smelting, admitting of an economical recovery of copper and the precious metals. Success amply rewarded the introduction of this treatment, which at the time was little understood and had not been tested on a large scale upon regular copper ores.

In the meantime an independent company was developing a property (the North Mount Lyell) to the north of the pyritic mass, but encountered little ore until, in 1897, a rich body of siliceous bornite was accidentally located. The treatment adopted, however, proved unsuccessful, and in 1903 the company was merged with the Mount Lyell Mining & Railway Co. (Ltd.)—a happy combination, for the ores of the two deposits were metallurgically complementary and were amenable to more economical treatment than could be applied to either alone. Many other mining companies have operated in the field, but all the important ones have been added by the principal company to the original holdings.

The history of the Mount Lyell district is unique and affords an example of notable success in the face of great natural obstacles. The profitable exploitation of a low grade deposit in a remote and isolated region, where labor costs and difficulties are at a maximum, is an important achievement. The secret of this success is to be sought in the application from the outset of the highest type of technical, scientific, and administrative ability to the problem.

GEOLOGY.

The geology of the Mount Lyell district is shown on the accompanying sketch map. A narrow belt of deeply dipping schistose rocks is bordered on the east by an area of quartzitic conglomerates, while to the west lies a sedimentary series of Silurian age, composed of sandstones, quartzites, and clay slates with limestone intercalations. The ore is confined to the schists, lying along their contact with the conglomerate, which is marked by an important overthrust fault. Igneous rocks, both acid and basic, are rather extensively developed near the western coast of the island and approach in bulk



SKETCH MAP OF THE MOUNT LYELL DISTRICT. (MODIFIED FROM GREGORY.)

to within 1½ miles of the deposits; dikes of diabasic character come nearer, though none are in contact with the ore. The region shows signs of glaciation.

The conglomerate is younger than the schists, containing inclusions of the latter, and normally overlies them except near the mines, where the relations are reversed by the overthrust fault. The formation is predominantly reddish in color and is composed of rounded to subangular pieces of quartz and quartzite, ranging from small

grains to boulders a foot or two in diameter, and consolidated by siliceous cement. Its lowest member is a typical quartzite, and other quartzite beds are intercalated through the series. The formation is unmineralized except in proximity to its schist contact, where it shows pyrite, chalcopyrite (in places some bornite and chalcocite), and hematite, all in unimportant amounts. Specimens near the fault plane show results of the fault pressure by a schistose tendency, and under the microscope by undulatory extinction and shattered condition of some of the quartz grains.

The schist series forms a belt three-fourths to $1\frac{1}{2}$ miles wide, with north-south course. The strike is N. 50° W. to N. 60° W., with dip of $60-80^{\circ}$ to the southwest. The rocks range in color from light grayish green to dark blue and in structure run from moderately schistose to highly schistose. The light-colored members are typical sericite schists, resolvable under the highest power of the microscope into a dense quartz mosaic, knit with shreds of sericite in parallel alignment. The darker members, which have the greater distribution, are chloritic schists showing under the microscope predominant chlorite, accompanied at times with sericite, enwrapping grains and mosaic masses of quartz. All sections are mineralized with pyrite in minute grains and crystals, which are scattered through the quartz, chlorite, and sericite alike. As shown by the lack of pressure effects due to crystal growth and the frequent presence of pyrite crystals intercepting otherwise continuous laminae, the pyrite is judged to have been deposited mainly through replacement. Gregory, who has made a detailed petrographic study of the schists, finds that they grade from those showing no original structure to those definitely of igneous origin, "formed by the alteration of quartz-porphyrites and probably also of acid volcanic tuffs." From a study of several thin sections, comparison with similar rocks of Virginia and North Carolina,¹ and careful consideration of the chemical analyses given by Gregory, the writers believe that it can be affirmed with considerable certainty that the schist series represents the mashed equivalent of volcanic rocks of acid to intermediate character.

Faulting has been profound in the region, but is largely localized in the major overthrust already referred to and attendant cross faults of minor development. The ore deposits are confined to the fault zone, and the principal deposition has taken place in the angles formed by the intersection of the cross faults with the major fault. The latter may be traced along the surface and is marked by outcrops of hematite which, however, according to Sticht, bear no relation to the pyrite and is not its gossan.

¹ The sericite and chlorite schists of Mount Lyell are strikingly similar, both in appearance and in microscopic detail, to analogous copper-bearing schists of the Virgilina, Gold Hill, and Cid districts in Virginia and North Carolina, which have resulted from the dynamic metamorphism of volcanic rocks.

THE MINES.

Two mines only need be considered in detail, as these represent the major development of the field and embrace the features of interest shown by the minor deposits.

Mount Lyell mine.—This mine has opened up a pyritic mass of remarkable size, carrying a low copper content and values in gold and silver. The ore is fine-grained, homogeneous pyrite, bearing chalcopryite and including evenly distributed gangue of quartz and barite in extremely subordinate amount. The ore body lies entirely within deeply dipping schists, adjacent to and approaching on the foot-wall side within a few inches of the conglomerate fault contact. Its configuration is that of a horn-shaped body, tapering downward, with maximum dimensions of 270 by 660 feet at the 400-foot level. It has been mined *en masse* by the open-cut system, and in 1906 had been developed to a depth of 730 feet. At present the mining is carried on underground, the open cut nearing completion.

The body as a whole is low grade, the copper averaging from 0.6 to 0.75 per cent, with silver running from 1.10 to 1.75 ounces and gold from 0.06 to 0.08 ounce. The mass is singularly free from deleterious elements, containing only about 0.25 per cent arsenic, less than 0.17 per cent antimony, no bismuth, and traces only of selenium and tellurium. Along the contact and about the periphery the ore body is locally richer from deposition of higher percentage of chalcopryite and addition of tetrahedrite and enargite bearing areas.

North Mount Lyell mine.—This mine is the richest property and largest producer in the district. It differs from the Mount Lyell in that the predominant ore is bornite, which, together with subordinate chalcocite and some tetrahedrite, pyrite, and chalcopryite, forms lenticular masses in sericitic and chloritic schists. These minerals, with considerable silica and some barite, have been deposited as stringers and lenses following the lamination of the schistose rocks, forming impregnated zones or "fahlbands" of ill-defined limits, representing combined replacement and interlaminal deposition. The ore is worked by underground mining and the operations have penetrated to a depth of 1,100 feet. The values in copper run much higher than in the Mount Lyell mine, averaging from 5 to 7 per cent, though the precious-metal content is less. Owing to the siliceous character of the ore it forms an efficient flux for the pyritic ore of Mount Lyell, permitting the lowest grades of the latter to be profitably worked.

THE ORE MINERALS—MOUNT LYELL MINE.¹

The ore minerals at the Mount Lyell mine, in the order of their observed prominence, are pyrite, chalcopyrite, enargite, tetrahedrite, sphalerite, galena, bornite, and chalcocite.

Pyrite.—The Mount Lyell ore is dominantly pyritic and the average ore specimen appears to consist purely of densely granular pyrite with accessory quartz. Where the development of quartz is sufficient to be conspicuous its distribution is not uniform, but tends toward segregation into bands. In polished sections the banding becomes more apparent and presents a plicated and distinctly schistose aspect. (See fig. 1, Pl. 48.) Under magnification the pyrite appears characteristically granulated and is not intergrown with other sulphides. Its bearing toward quartz is both that of contemporaneous and of later development.

Chalcopyrite.—The copper content of the Mount Lyell ore is largely due to the presence of chalcopyrite, which permeates the pyritic ore in the most intimate fashion. It is imperfectly distinguishable in hand specimens, but under the microscope is seen to traverse the pyrite in stringers and form a network enmeshing grains and cementing fractured individuals. (See fig. 3, Pl. 49.) Its development is especially marked along the quartzose bands, and the inclosing filaments decrease outward from such areas, in some instances leaving the denser pyrite of the section entirely free from observable chalcopyrite. Such pyrite, free from visible chalcopyrite even at a magnification of 200 diameters, however, was found to react for copper.

Enargite.—The occurrence of this mineral is highly localized. Where present it does not permeate the ore after the fashion of chalcopyrite, but occurs as relatively large, irregular, confluent areas inclosing breccialike pieces of pyrite. (See fig. 2, Pl. 48.) Its most interesting microscopic feature is an ever-present impurity in the form of chalcopyrite, which is disseminated throughout the enargite in minute patches, networks, stringers, and disconnected points. (See

¹ The microscopic work was done on polished sections with a metallographic microscope using vertical illumination from an acetylene light, at magnifications ranging from 30 to 200 diameters. The minerals were identified by noting their characteristics, such as color, hardness, structure, tarnish, and etching effects, upon areas sufficiently large to furnish fragments for blow-pipe tests; by which means criteria were obtained for the identification of these minerals even where microscopically developed. In making the photographs it was found desirable to increase the color contrasts by developing tarnishes by brief treatment with acid; for this purpose nitric acid was most useful.

A useful hardness test, applicable to the determination of the relative hardness of adjacent grains in opaque sections, was developed during the course of the study, and may be applied as follows: Having centered the microscope tube on the contact between two mineral grains, place a small metal straightedge on the section and move until its edge intersects the two grains; then remove the section from the microscope stage, holding firmly the straightedge in place, and, by means of a knife point, draw a line across the two grains, being careful to press uniformly throughout. Replace the section under the microscope and note the size of the channel as it passes from one grain to the other. The larger channel, of course, will lie in the softer mineral. This method is sensitive to within a half degree of hardness in the customary scale and is applicable to grains as small as 0.5 mm. in diameter.

figs. 1 and 2, Pl. 50.) A noteworthy feature of this included chalcopyrite is that it is everywhere richer toward the margin of the enargite areas and is not infrequently strongly concentrated close to or at the border. It nowhere crosses into the pyrite, nor does it seem to be related to the chalcopyrite already referred to as disseminated through the pyrite ore.

Bornite, chalcocite, tetrahedrite.—These minerals, while important as correlating the Mount Lyell ores with those from North Mount Lyell, are exceedingly limited both in quantity and in extent, and since their mode of occurrence is analogous to that observed in ore from North Mount Lyell they may be reserved for discussion under that head.

Sphalerite and galena.—These minerals represent highly localized phases of the ore and are nowhere prominently developed. They are confined to the pyrite and were in no place observed in association with the copper sulphides. Sphalerite is much more prevalent than galena and wherever the latter does occur it is in intimate association with the former. Occasional sections show both together, or sphalerite alone, as disseminated grains in the pyrite ore; but commonly their occurrence is as veinlets traversing the section.

THE ORE MINERALS—NORTH MOUNT LYELL MINE.

In the North Mount Lyell workings the same minerals are to be found as at Mount Lyell, but in relative proportion so different as to produce ores of entirely divergent character. Here the minerals, in order of their importance, are bornite, chalcopyrite, chalcocite, tetrahedrite, and pyrite; and these form mineralized zones in the schists and not a great sulphide body as at Mount Lyell, where pyrite is dominant.

Bornite.—The ore mineral of widest development and greatest significance at North Mount Lyell is bornite. It occurs alone, in association with pyrite, and admixed with other copper sulphides. (1) Where occurring alone it forms lenses within the schists and presents no microscopic features of note. (2) In association with pyrite it is confined to quartzose patches and channels of megascopic proportions within a pyrite-quartz rock similar to the typical ore of Mount Lyell. (3) The third type of occurrence is the dominant one. The bornite is in close association with chalcopyrite, or chalcocite (with or without tetrahedrite), or both, and the ore forms lenticular areas and stringers within the inclosing schists. In polished sections scattering pyrite grains show up in ore and gangue alike, and in places granular pyrite aggregates are visible. Toward chalcopyrite, bornite has a varied bearing. While the two are often developed in intimate association, as if intergrown (fig. 2, Pl. 51), there is in other sections a distinctly noticeable tendency for the chalcopyrite to associate itself with granular pyrite aggregates where such occur in the section, and for the bornite in a general way to envelop the association as a whole. In

one section the bornite grains, when examined at 200 diameters, are seen to be bordered by chalcopyrite, or by tetrahedrite, or both. (See fig. 3, Pl. 51.) The relation between bornite and chalcocite is often that indicative of contemporaneity; the boundaries are ordinarily intricate and clear-cut, and good examples of graphic intergrowths were observed. (Figs. 3 and 4, Pl. 50.)

Chalcopyrite.—In addition to the associations with bornite just described, and minor interstitial development in pyrite, chalcopyrite at North Mount Lyell occurs alone inclosed in sericitic or chloritic schists. In polished sections under the microscope the chalcopyrite shows in every proportion from the merest development (fig. 1, Pl. 49) to a solid opaque body with only a scattering of gangue (fig. 2, Pl. 49).

Chalcocite.—So far as studied chalcocite is a rather minor constituent of the ore and is always in close association with bornite. In sections across such specimens the bornite occupies relatively large areas, with the chalcocite occurring here and there in smaller patches either as sharply defined individuals but with marginal lines variously embaying, and embayed in, bornite in the most completely intimate fashion, or rarely as graphic intergrowths. (See fig. 4, Pl. 50.)¹ Such chalcocite is clearly of contemporaneous development with bornite. Sections of this chalcocite, when etched by immersing a few minutes in dilute nitric acid, develop characteristic cleavage lines, as shown in figure 4, Plate 49. In two of the sections studied relatively large areas of bornite were found which assumed a granular character toward their margins, and were encased in pure chalcocite. This structure is suggestive of secondary chalcocite, but no further examples were found and even the ones in question were destroyed when the sections were repolished preliminary to more detailed study. It may be safely said that chalcocite deposited by descending surface waters is an unimportant constituent of the North Mount Lyell ore.

Tetrahedrite.—This mineral is somewhat analogous to enargite at Mount Lyell in that its development is highly localized. Like enargite, too, it is intimately associated with extremely fine chalcopyrite discernible only under high magnification. On the section tetrahedrite appears both as irregular patches up to 10 mm. in diameter, and as sharply defined, exceedingly narrow, marginal zones surrounding bornite grains. In many instances the bounding zone will consist in part of chalcopyrite, the two alternating and together forming a beautifully sharp, irregular zone completely encasing the bornite area. (See fig. 3, Pl. 51.) This mode of occurrence for chalcopyrite is confined absolutely to tetrahedrite-rich areas, and its relationship to bornite is totally different from that in the conventional tetrahedrite-free ores of the North Mount Lyell mine.

¹ These figures closely resemble crystallographic intergrowths of bornite and chalcocite in the copper ores of Virgilina, Virginia. See Laney, Proc. U. S. Nat. Mus., vol. 40, 1911, pl. 68.

PARAGENESIS OF ORE MINERALS.

The one mineral whose genetic relationships are everywhere sharply defined is pyrite. Its bearing toward the other sulphides is clearly that of a mineral of prior development. In most sections, however, there are certain examples of interassociation which suggest that the sulphide development from pyrite onward was one of sequential stages rather than of distinct isolated periods.

Among the copper minerals proper there is nowhere any sharply defined order of sequence such as exists between the group as a whole and the pyrite. Indications point strongly, however, to chalcopyrite as having been the first to follow the lead of the iron sulphide. Its wide diffusion, the intimacy of its occurrence everywhere with the manifestly earlier pyrite, and the frequency with which it is to be found inclosing and enmeshing pyrite clusters with the whole engulfed in bornite, by themselves would be conclusive. Elsewhere, however, chalcopyrite and bornite occur intimately intergrown (see fig. 2, Pl. 51) as if of contemporaneous development. From these two types of relationships the inference would be that a period of chalcopyritization passed into one productive of chalcopyrite and bornite together.

Of the rich copper minerals bornite shows itself not only the one most extensively developed, but the one most intimately associated in order of continuity with chalcopyrite. In some instances it is intergrown with chalcopyrite (fig. 2, Pl. 51); in other instances it is intergrown with chalcocite (fig. 4, Pl. 50); there are also numerous intermediate examples of its occurrence independently of chalcopyrite or chalcocite. These associations point strongly to a period of bornite development that was inaugurated while chalcopyrite was still forming, continued through a period of its own, and closed with simultaneous precipitation of bornite and chalcocite. Certain relations of the latter mineral tend further to indicate that it continued to form for a while after bornite ceased depositing.

Tetrahedrite, occurring as replacement rims to bornite grains, is distinctly later than that mineral. Though never associated with chalcocite so as to indicate relationship, tetrahedrite is judged to be subsequent to it also, since chalcocite is in part contemporaneous with bornite. With tetrahedrite occurs chalcopyrite, in minute proportions, having analogous bearing toward bornite; this chalcopyrite is of course also later than bornite and represents a second generation of chalcopyrite. This chalcopyrite and the tetrahedrite show every indication of synchronous deposition. Their formation is due either to descending waters or is the result of further changes in the primary ore-bearing solutions, dependent upon some specialized condition.

Tetrahedrite at North Mount Lyell is paralleled by enargite at Mount Lyell. Both minerals are of localized occurrence and are

characterized by a close association with chalcopyrite, of specialized development. The enargite forms an apparent fracture-filling in massive pyrite and incloses microscopic ramifications of chalcopyrite. These inclosures do not pass into the adjacent pyrite, nor do they possess any arrangement suggestive of subsequent penetration of the enargite by chalcopyrite-bearing solutions. On the contrary, they present rather strong evidence of simultaneous development along with the enargite, as a kind of a residual crystallization as a result of the molecular adjustment forming enargite. As the enargite has not been affected by the other mineralizing processes it may be inferred that its formation represents a late stage of the depositional epoch.

The microscopic study points unmistakably to the formation of the ores through replacement of the minerals of the schists; and the sericitic and chloritic components have been the first to be attacked and substituted. Gradual transitions from unmineralized rock to solid ore are often seen. In many places a schistose pattern delineated by residual quartzes has been inherited by massive pieces of ore. (See fig. 1, Pl. 50.) In most sections unreplaced shreds and fragments of the original schists may be detected. One section disclosed a hexagonal quartz crystal with embayments filled with pyrite and enargite, showing in striking manner the corrosive effects of sulphide solutions even upon that mineral. (See fig. 1, Pl. 51.) Accompanying dominant replacement a certain amount of interlaminal deposition is also evidenced, but few examples are free from some replacement as well; and this process is merely a preliminary to the dominant one.

The study leads also to the conception that the ore deposition took place during a distinct mineralizing epoch marked by solutions progressively changing in composition and depositing a series of sulphide minerals in sequential and transitional stages. The order of deposition, as evolved, runs from cupriferous pyrite through chalcopyrite, bornite, and chalcocite, to the tetrahedrite-enargite group (accompanied by chalcopyrite of a second generation). From this it must not be inferred that the formation of any one ore mineral was confined to any one period, or that the sequence was absolute; on the contrary there is ample evidence of transitions and overlappings, and many complications undoubtedly intervened to make the process even more involved. What is strongly manifest, however, is that the deposition of any one of the sulphide minerals, in so far as it is a prime essential in the ore as a whole, was confined to some given period in the evolution.

A further generality, so persistently applicable as to seem not without significance, is one involving a relation between three broad features of the principal ore minerals, namely, the proportion between their respective iron and copper contents, the order of deposition evidenced by them, and the extent of their individual participation in

the mineralization. The succession of deposition, as evolved, is in exact harmony with the order of increasing copper content and with that of decreasing iron content. Noting this apparent agreement as the work with the metallographic microscope progressed, a sample of pyrite free from included chalcopyrite, so far as could be detected with even the highest power objective, was tested qualitatively and found to give a copper reaction.¹ While it is by no means certain from this that the copper present in the pyrite is not due to chalcopyrite of sub-microscopic order, it is of importance in coordinating the true pyrite with the chalcopyrite; for a dissemination of chalcopyrite so fine as not to be distinguishable under the highest magnification, must have been present during solidification of the pyrite, and from this sub-microscopic chalcopyrite there is every gradation up to the megascopically prominent chalcopyrite of the pyrite ore, referred to a position consequent to pyrite in the order of crystallization. Accordingly, starting with what may reservedly be termed cupriferous pyrite, which is at once the most extensively developed and the earliest of the ore group, and passing successively through chalcopyrite, bornite, and chalcocite, the tendency is so marked as to make the different mineral species seem indicative of successive points in a steadily diminishing iron content and increasing copper content in solutions of constantly diminishing quantity.

SECONDARY ENRICHMENT.

This subject can be discussed only in a general way, because few only of the specimens available showed characteristics referable to this process. Also the writings of Sticht and Gregory, while making frequent reference to enrichments in the ore bodies, do not in every instance present criteria suitable for discriminating whether such enrichment is due to descending surface waters, or is merely a special phase of primary deposition; indeed, such criteria are difficult to obtain and a problem of this kind could be successfully attacked only through a metallographic study of specimens collected with this end in view. As the enriched portions of the ore are the ones naturally most completely worked out, such an attainment is obviously impossible.

In general, it may be said that enrichment is more prominent in the Mount Lyell body than in the North Mount Lyell deposit. The latter is marked by a uniformity of its mineral associations excepting a slight increase in proportion of chalcocite to bornite in the lower

¹ This result is the reverse of that obtained by Laney (Bull. 21, North Carolina Geol. and Econ. Survey, 1910, p. 92), Simpson (Econ. Geol., vol. 3, 1908, pp. 628-635), and Finlayson (Econ. Geol., vol. 5, 1910, p. 420), from metallographic study of "cupriferous pyrite" from Gold Hill (North Carolina), Butte (Montana), and Huelva (Spain), respectively; all of whom found that in these ores the copper content is due to definite copper minerals recognizable under the microscope, and where such are not visible the ore is copper-free.

levels. The pyrite mass, however, is not homogeneous throughout in values. Its footwall portion is richer in copper, gold, and silver than its hanging-wall portion, and several places about its periphery, but especially on the footwall side, are characterized by bonanzas formed of important admixtures of copper or silver sulphides, or both. Such areas of higher values are principally border phenomena; in the heart of the ore body only one such occurrence has been noted. This was a small, pipelike zone running from 3 to 6 per cent copper, due to chalcopyrite, and extended vertically from about the 400 to 500 foot level.

In the ore sections studied evidences of secondary enrichment were largely lacking. In certain specimens, however, chalcocite of probable secondary deposition was recognized as different from other and predominant chalcocite, which was in part of contemporaneous formation with the bornite and ever in sequential genetic relation with the other primary sulphides. Certain areas of tetrahedrite and chalcopyrite also showed relations suggestive of secondary origin.

GENESIS OF DEPOSITS.

To recapitulate, the ore deposits are of two kinds: (1) Great lens-shaped masses of nearly pure sulphide ores, the Mount Lyell type, and (2) mineralized bands of schist (fahlbands), the North Mount Lyell type. Microscopic study of the ores shows that this difference is one of degree and not of kind, and indicates that the same set of ore-bearing solutions gave rise to both kinds of deposition. Gregory¹ has discussed at length the ore genesis, and his conclusions may be briefly summarized as follows: Alkaline ore-bearing waters, rising along fault planes during the period of faulting, absorbed heat generated by these earth movements. With decreased pressure and lowered temperature incident upon approach to the surface, they deposited their content, forming fahlbands in the less shattered portions of the schists and producing replacement masses in the highly shattered and extremely permeable areas adjacent to fault loci. The deposition, therefore, is regarded as "due to tectonic and not to igneous action." Gregory does not explain the ultimate origin of the solutions nor of their metallic contents.

Consideration of the microscopic features of the ores has led the writers to believe that Gregory's explanation is not entirely adequate, and that the ore-bearing solutions were a deep-seated development from a differentiating mass of igneous rocks² and that these solutions rose along structurally developed channels, changing gradually in composition from the beginning to the end of the depositional epoch.

¹ Australian Inst. Min. Eng., vol. 10, 1905, pp. 145-156.

² A similar conception was developed by Spurr in 1907 (*A theory of ore deposition*, Econ. Geol., vol. 2, 1907, pp. 781-795) and later further elaborated by him (*Econ. Geol.*, vol. 7, 1912, pp. 485-492). Finlayson applies a somewhat similar explanation to the origin of the Huelva pyrite deposits.

That the ore deposition was conditioned by structural features and represented a combination of replacement and impregnation, with predominance of the former, seems conclusive and needs no further elaboration here.

ANALOGOUS DEPOSITS.

Cupriferous pyritic deposits of the Mount Lyell type play so important a part in the world's copper reserve¹ and present features of such general interest that it may be profitable to review briefly the significant geological characteristics of the leading representatives.

*Ural Mountains.*²—Numerous lenses and sheets of massive cupriferous pyrite, occurring in schists and greenstones of the Ural Mountains, contribute to the copper output of that region. The pyritic ore runs about 3 per cent in copper, due to later interstitial chalcoppyrite, which is associated with some sphalerite and galena, and in one mine, bornite. Both the wall and ore are cut by joint seams carrying enrichments of chalcoppyrite and tennantite mixed with white vein quartz and sometimes barite; these are distinctly later than the pyrite, though not necessarily attributable to the action of descending waters. The masses are replacement deposits in the schistose rocks.³

Norway.—Copper-bearing pyritic ores are extensively developed in this country, the districts of greatest import being the Sulitelma, north of the Arctic circle, and the Røros and the Meraker near Trondhjem in central Norway. These deposits, which are notably similar in character, are lenticular masses of pyrite, with admixed chalcoppyrite, averaging from $2\frac{1}{2}$ to 3 per cent copper, and occurring within crystalline schists alongside intrusive masses of gabbro, or soda granite. The bodies are comparatively small in horizontal dimensions, rarely exceeding 60 feet in width, but extend downward to great depths. According to Vogt⁴ they originated from solutions which were expelled from the intruding gabbroid and related granitic masses, and deposited their metallic content along the slipping planes of the schists during their metamorphism.

Rammelsberg.—The oft-discussed deposits of Rammelsberg, in the Hartz Mountains of central Germany, consisting of pyrite with chalcoppyrite, galena, sphalerite, arsenopyrite, barite, etc., intercalated in metamorphosed clay slates, have been cited⁵ as analogous to the Mount Lyell occurrence. According to Lindgren and Irving,⁶ how-

¹ The importance of this type of copper deposit is apt to be underestimated in the United States where copper is obtained largely from ores of an entirely different order. Abroad the dominant type of copper deposit is pyritic.

² Turner, Mining Mag., June, 1912.

³ Turner, Econ. Geol., vol. 7, 1912, p. 709. Knox, idem, pp. 295-297.

⁴ Trans. Amer. Inst. Min. Eng., vol. 31, 1901, p. 141. (See also, Weed, The copper mines of the world, 1907, pp. 103-106. Beck-Weed, The nature of ore deposits, 1905, vol. 2, pp. 462-465.)

⁵ See Gregory, Australasian Inst. Min. Eng., vol. 10, 1905, pp. 179-181

⁶ Econ. Geol., vol. 6, 1911, pp. 303-313.

ever, the ore itself has been dynamically metamorphosed, the sulphide mass (excepting the pyrite which, being too hard, has suffered shattering only) having flowed like "thick muck."

*Huelva, Spain.*¹—The greatest single copper-producing district abroad, ranking fourth among those of the world, occupies an east-west mineralized zone, lying mainly in the Province of Huelva, southern Spain, and including the well-known deposits at Tharsis and Rio Tinto. The ore is massive, homogenous pyrite, carrying chalcopyrite and subordinate associated galena and sphalerite, with local enrichments of chalcocite and minor bornite. The ore-bodies are lenticular masses, many in number and ranging up to enormous sizes (largest about 3,000 by 600 by 1,500 feet) and are mainly inclosed within those portions of Paleozoic slates and intrusive porphyries that have suffered severe dynamic metamorphism and been converted into schists (chiefly sericitic). The ore bodies are in proximity to extensive intrusions of acid and basic igneous rocks, showing advanced differentiation, and are usually located along lines of more or less fault movement. Microscopic examination of the ores by Finlayson results in the following conclusions:² (1) The copper occurs as a definite mineral in the ore and is not chemically combined with the pyrite. (2) The primary minerals have deposited in the following order: pyrite, chalcopyrite, sphalerite, galena. (3) The ore bodies have been secondarily enriched; in the lean deep ores chiefly by a change of chalcopyrite to chalcocite, and in the richer, or shallower ores, chiefly by a deposition of chalcopyrite followed by chalcocite. Bornite occurs in very subordinate amounts, and appears intermediate in formation between chalcopyrite and chalcocite. (4) The only primary copper mineral is judged to be chalcopyrite; the other copper minerals appear to have resulted from descending solutions.

The deposits are conceived by Finlayson to be due to the replacement of altered rocks by solution, rising along structural planes of maximum permeability, and originating through concentration by border segregation in deep-seated igneous rocks prior to their final intrusion and consolidation.

*Shasta County, California.*³—The deposits of this important copper district comprise numerous and extensive lenses of cupriferous pyrite inclosed within mashed alaskite-porphyry, which near the ore bodies is practically a schist, containing considerable sericite (with paragonite) and chlorite. The ore, which averages 3 to 3½ per cent copper, is pyrite with chalcopyrite and subordinate sphalerite and in less amounts still, galena, bornite, and chalcocite; the gangue is quartz, calcite, and barite. The deposition is attributed to replacement of the schistose rock by solutions, expelled from nearby igneous rocks

¹ Finlayson, The pyritic deposits of Huelva, Spain. Econ. Geol., vol. 5, 1910, pp. 356-372 and 403-437.

² Idem, p. 420.

³ Graton, Bull. 430, U. S. Geol. Survey, 1910, pp. 71-111.

upon their final consolidation, which found congenial conditions for precipitation in the more schistose phases of the alaskite-porphyry where this rock presented maximum permeability and surface of attack.

Of the ore minerals pyrite was the first to crystallize in most instances; sphalerite, on the whole, is later. Chalcopyrite is the youngest of the important minerals, forming veinlets around and in other sulphides; it prefers the company of sphalerite to pyrite and shows also an affinity for quartz and barite. Primary bornite is commonly associated with chalcocite, and the two either take the place of chalcopyrite or are intimately associated with it. Secondary bornite and chalcocite are also present, but are readily distinguished from the former.

*Ducktown, Tennessee.*¹—These important deposits, which are notable for successful working of low-grade ore, form lenticular to tabular masses, inclosed within deeply dipping schists of sedimentary origin, and represent limestone intercalations which have suffered replacement by ore-bearing solutions from probable magmatic sources. The primary ores consist of pyrrhotite and pyrite with chalcopyrite and subordinate sphalerite; these are associated with specularite, magnetite, actinolite, calcite, tremolite, quartz, pyroxene, garnet, zoisite, chlorite, mica, graphite, titanite, and feldspar. Secondary enrichment has proved of importance only near the surface, where chalcocitization has taken place in a narrow zone rarely over a few feet in thickness, between the gossan and primary sulphide zone. The Ducktown occurrence is not a strict analogue of the Mount Lyell deposit, though presenting many features in common.²

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¹ Emmons and Laney, Preliminary report on the mineral deposits of Ducktown, Tennessee. *Bull.* 470, U. S. Geol. Survey, 1910, pp. 151-172.

² From the foregoing review it is seen that the great cupriferous pyrite deposits of the world are strikingly alike in their geologic relations, mineralogic content, and origin. It may therefore be generalized that any region of schistose rocks (especially sericite and chlorite schists) that is intruded by a differentiated series of igneous rocks, is one favorable to the occurrence of such deposits, and where in such regions gossans are found, which in their outcrops show values in gold and silver and the presence of barite, lenses of cupriferous pyrite at depth may be anticipated with considerable confidence.

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Text-figure: Sketch map of the Mount Lyell District. (Modified from Gregory.)

EXPLANATION OF PLATES.

PLATE 48.

- Fig. 1. Polished section of typical cupriferous pyrite ore from Mount Lyell Mine, showing schistose pattern resulting from replacement. Natural size. Cat. No. 77549.
2. Polished section of pyrite (light) with seams and veins of enargite (dark). Mount Lyell Mine. Natural size. Cat. No. 77552.

PLATE 49.

- Fig. 1. Incipient stage of replacement. Chalcopyrite (white) subordinate to gangue (gray). $\times 30$. North Mount Lyell Mine. Cat. No. 77571.
2. Advanced stage of replacement. Chalcopyrite (light) predominating over gangue (dark). $\times 30$. North Mount Lyell Mine. Cat. No. 77571.
3. Chalcopyrite (dark) cementing granulated and shattered pyrite (light). $\times 30$. Mount Lyell Mine. Cat. No. 77549. Shows that the chalcopyrite was developed later than the pyrite.
4. Area of primary chalcocite, showing characteristic cleavage developed by etching with dilute nitric acid. $\times 30$. North Mount Lyell Mine. Cat. No. 77593.

PLATE 50.

- Fig. 1. Enargite field (light) including minute ramifications of chalcopyrite (dark). Pyrite grain to left of section. $\times 30$. Mount Lyell Mine. Cat. No. 77552.
2. Portion of enargite field of figure 1, enlarged to 180 diameters, showing the included chalcopyrite (dark). The latter, though appearing so in the photograph, is probably not a fracture filling in the enargite, but of contemporaneous development.
3. Bornite (dark) and chalcocite (light), showing crystallographic intergrowth between the two, indicative of simultaneous development. $\times 30$. North Mount Lyell Mine. Cat. No. 77593.
4. Crystallographic intergrowth of bornite (dark) and chalcocite (light). Portion of figure 3 with magnification $\times 120$. North Mount Lyell Mine. Cat. No. 77593.

PLATE 51.

Fig. 1. Quartz crystal partly replaced by enargite (light) and pyrite (dark). The black areas are irregularities in the section. $\times 40$. Mount Lyell Mine. Cat. No. 77552.

2. Intergrowth of bornite (dark) and chalcopyrite (light), indicative of simultaneous development. North Mount Lyell Mine. $\times 40$. Cat. No. 77601.

3. Grain of bornite (*b*) in gangue (*g*), surrounded by border of tetrahedrite and chalcopyrite (white). The tetrahedrite and chalcopyrite can not be differentiated in the photograph, but their relations to bornite are similar; they were probably developed simultaneously and are later than the bornite. $\times 200$. North Mount Lyell Mine. Cat. No. 77597.



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