Tasmania

DEPARTMENT OF MINES

GEOLOGICAL SURVEY BULLETIN

No. 31

The Zinc-Lead Sulphide Deposits of the Read-Rosebery District

Part III.—METALLURGY AND GENERAL REVIEW

BY

LOFTUS HILLS, M.Sc., Assistant Government Geologist

Issued under the authority of
The Honourable Sir NEIL ELLIOTT LEWIS, K.C.M.G.
Minister for Mines for Tasmania

Tasmania
JOHN VAIL, GOVERNMENT PRINTER, HOBART
1919

B88995

PREFACE.

THIS volume is the third and last of a series of publications intended to give a complete description from all points of view of the zinc-lead sulphide deposits of the Read-Rosebery District, situated on the West Coast of Tasmania.

For geological examination this belt was cut into two portions—a southern half and a northern half. The volumes dealing with those two portions have already been published.

This volume is designed to deal with the metallurgical treatment of the ores, and to present a general review of the zinc-lead sulphide belt as a whole. It is the natural sequel to the two previous volumes. Its publication should have immediately followed that of the later of those volumes, but this was rendered impossible owing to the development of the European war. The writer had commenced the preparation of the volume, when it became expedient to undertake the investigation of the resources of the State in regard to the munition minerals, wolfram and molybdenite. Consequently a postponement in regard to this publication was necessary, and the postponement was rendered indefinite a few months later by the enlistment of the writer for active service with the Australian Mining Corps.

The preparation, therefore, of this third publication dealing with the zinc-lead sulphide deposits of the Read-Rosebery District is now resumed immediately on the return of the writer from the front.

A total period of three years and eight months has elapsed from the time of the first postponement of the preparation of this volume until its present resumption.

The publications dealing with the zinc-lead sulphide deposits of the Read-Rosebery District are thus three in number:—

- The Zinc-lead Sulphide Deposits of the Read Rosebery District: Part I. (Mount Read Group); 30th November, 1914.
- The Zinc-lead Sulphide Deposits of the Read Rosebery District: Part II. (Rosebery Group); 30th August, 1915.
- The Zinc-lead Sulphide Deposits of the Read Rosebery District: Part III. (Metallurgy and General Review); 24th July, 1919.

Parts I. and II. have already been published; this is Part III.

LOFTUS HILLS

Launceston, 24th July, 1919.

TABLE OF CONTENTS.

The Zinc-Lead Sulphide Deposits of the Read-Rosebery District.

Part III.

(METALLURGY AND GENERAL REVIEW.)

I.—INTRODUCTION.

DURING the three and a half years that have elapsed since the completion of Part II. of this series of bulletins, some development work has been carried out on several of the mines in the district. A description of this work and the results achieved will be included in this volume. In addition great advances have been made in the metallurgy of zinc and zinc-lead sulphides in America and England, as well as in Australia. These have been carefully studied, and the results incorporated in the following pages. The information, therefore, conveyed in this volume may be regarded as representing the state of knowledge at the date of writing, namely, June, 1919.

In a publication of this type it is a very important matter to decide upon a method of presentation which is in accordance with the complexity and importance of the subjects dealt with. The two main reasons for the preparation of this volume are:—

(1) The description of the metallurgical treatment of the ore; and
(2) The consideration of the zinc-lead sulphide belt as a whole in regard to its potentialities, and the way it should be developed to the best advantage.

The best manner of approach to these questions seems to be by means of a comparison with similar zinc-lead sulphide deposits which are being worked in other parts of the world.

Accordingly, after the developments which have taken place since the preparation of Part II. have been described, and the confirmation by these of the conception of the origin and structural features of the ore-bodies fully described in Parts I. and II. has been indicated and discussed, a chapter will be devoted to a brief summary of the structural features and mineralogy of the Read-Rosebery zinc-lead sulphide deposits. Then will follow a description on the same lines of corresponding zinc-lead sulphide deposits in other parts of the world, the deposits being classified on a genetic basis for the purposes of this description. This will be followed by a chapter having as its object a comparison between those deposits and those of Read-Rosebery, particular attention being paid to their size and values and to the relation of the physical and chemical character of the ores to their metallurgical treatment.

The metallurgy of the zinc-lead sulphides will then be dealt with from the point of view of the treatment processes which have been successful on the different zinc-lead sulphide deposits of the world. This method of presentation will be used as the means of approaching the question as to the treatment of the Read-Rosebery ores, the relation of the several processes to the physical and chemical character of the ore being elucidated in each case.

With the knowledge that this method of presentation of the subject must inevitably give, a true conception can be formed as to the extent and potentialities of the Read-Rosebery zinc-lead sulphide belt. Such a conception is clearly indicated in Chapter VII.

The causes which are responsible for the delay in the development of the field are discussed in Chapter VIII., and the natural corollary thereto, and to the preceding chapters as to the future procedure which is in the best interests of the field will be easily deduced, and is indicated in Chapter IX.

The importance of these Read-Rosebery deposits as a source of zinc is so great as to warrant a discussion of the influence they are destined to exert on the spelter industry of the Commonwealth. This is presented on Chapter X.

In the preparation of this volume the writer has endeavoured to reduce the use of technical terms to a minimum in order to make it perfectly intelligible to the non-technical reader. The technical nature of the subject has rendered this a difficult task, but it is hoped that the manner of presentation will result in the average mining investor with some little knowledge of mining terms being able to read and understand without undue effort. It must be understood, however, that this volume is only one of a series of three, and that a complete knowledge and appreciation of the structural features, mode of origin, value, and potentialities of the Read-Rosebery zinc-lead sulphide belt can only be attained by a thorough study of all three. The attempt has been made, nevertheless, to present in this volume in a readable way the facts in regard to the Read-Rosebery zinc-lead sulphide deposits which must convince the mining investor that they undoubtedly justify the investment of capital. The mining engineer and geologist will not find all the information they seek in this volume, but are referred therefor to Parts I. and II.

II.—DEVELOPMENTS AT THE MT. READ AND ROSEBERY GROUPS OF MINES SINCE THE PUBLICATION OF PARTS I. AND II.

A.—Mt. Read Group.

Following upon the amalgamation of the Hercules, Tasmanian Copper, and Primrose Companies into a new organisation under the general direction of the Mt. Lyell Mining and Railway Company, and known as the Mt. Read and Rosebery Mines Limited, exploratory and development work was entered upon under the supervision of the Mt. Lyell Company's officials.

The general scheme was to search for the downward continuations of the ore bodies known at No. 4 Level, Hercules Mine, by diamond-drilling; and when this work had been completed and the ore-bodies located, to systematically open up the mine ready for ore-extraction on a considerable scale.

Altogether 19 bores were completed in the Hercules Mine, being numbered 9 to 27, in succession from No. 8, the last bore dealt with in Part I. Two of these explored country at No. 4 Level; three at 5B Level; two between 4 and 5 Levels; three at 5 Level; three between 5 and 6 Levels; and five at 6 Level. The total footage drilled in these new operations was 3433 feet.

The work at No. 4 Level was directed eastwards from the central and southern portions of the "E" ore-body, and showed 30 feet of low-grade ore at 40 feet east of the southern end of the "E" ore-body. The other bore (No. 14 Bore) showed 15 feet and 5 feet of medium grade zinc-lead sulphide at 240 and 320 feet respectively from the hanging-wall of the "E" ore-body at this level. The importance of this will be realised from a study of Plate XV. of the Mt. Read bulletin, which is a vertical section along No. 2 Bore, which is 50 feet to the north of the bore we are now discussing. The ore cut in No. 14 Bore is therefore most probably an upward extension near the crest of the next succeeding anticline to the east of the "E" ore-body, the low grade of the ore being due to the solutions having spread upwards from the main calcareous beds.

At the 5B Level, Nos. 9 and 26 Bores proved the extension of the "B," "C," "D," and "E" ore-bodies down to this level northwards of the 5B crosscut. The other bore at this level (No. 27) was put out eastwards from the southern end of the South Drive. As this was beyond the southern end of the "A" ore-body, and approximately along a Beta anticlinal axis, naturally no ore was located.

Between the 4 Level and the 5A Level, the country in the vicinity of the "F" ore-body was tested by means of two bores, Nos. 20 and 21, which were put down from the two ends of the North Drive from No. 2 Tunnel in a north-easterly direction and depressed 45°. From the explanation of the structure of the "F" ore-body, given on page 51 of the Mt. Read bulletin (Part I. of this series) (1), and a study of Plates V. and XVII. of the same publication, which show that the ore-body extends downwards from the 4 Level only at its extreme easterly portion, to again rise upwards after a descent of roughly 40 feet, it will be easily understood why these bores did not penetrate its downward extension. The successive folds on the Alpha axes take the ore further eastwards on its downward extension than the apparent dip at the 4 Level would seem to indicate.

At the 5 Level Bores Nos. 10 and 25, driven westwards from the end of 770 feet North Drive, and 35 feet therefrom respectively, proved the "E" ore-body to extend to that level with a width of approximately 40 feet at the former bore, but split up into four portions at the latter bore. No. 22 Bore, put out eastwards from 40 feet south of the old No. 4 Bore, proved the width of the new lens of ore penetrated by the latter bore to be 25 feet, where No. 8 Bore had also previously proved ore to exist to No. 5 Level. A study of Plate XVI. of the Mt. Read bulletin will show this quite clearly, and also why No. 10 Bore cut the "E" ore-body proper at the synclinal trough and showed that the "C" and "D" ore-bodies as such do not exist at No. 5 Level. It is clear, also, that No. 22 Bore should have been continued to cut the "E" ore-body proper. Plate XVII. shows why No. 25 Bore showed the ore-body to be split up, as it penetrated the portions of the "E" ore body proper and the new lens and the breaks between, which were shown by the No. 8 Bore, and indicated in the sections shown in Plates XVI. and XVII. These three bores, therefore, confirm the cross-sections shown in Plates XV., XVI., and XVII. in a very accurate manner down to No. 5 Level.

---

(1) Geological Survey, Tasmania: Bulletin No. 19.

The continuation of the ore-bodies below No. 5 Level was tested by three bores, Nos. 11, 23, and 24. The former was bored in a direction a little north of east from the starting point of No. 22 Bore in the 550 feet North Drive, and depressed at an angle of 30°. No. 23 Bore was put in westwards from the northern end of the 700 feet North Drive, and depressed 55°. No. 24 Bore was put down vertically from the same point as No. 23. No. 11 Bore proved a width along the bore of 29 feet of ore at a depth extending from 90 feet to 112 feet below No. 5 Level. The first 10 feet of this was high-grade zinc-lead sulphide, the next 10 feet lower-grade zinc-lead sulphide, while the last 9 feet was pyrite copper ore, averaging about 4½ per cent. copper. The deepest zinc-lead sulphide so far located in the Hercules mine is at 260 feet below the No. 4 Level, and has the following composition:—

Gold	0·27	oz. per ton
Silver...	13·7	,, ,,
Lead	18·4	per cent.
Zinc	43·6	,, ,,
Copper	0·8	,, ,,

No. 23 Bore showed that two bodies of ore exist at 25 feet and 35 feet below No. 5 Level with horizontal widths of 10 feet and 20 feet respectively. No. 24 Bore proved a horizontal width of 10 feet of ore at a depth of 90 feet below No. 5 Level.

In studying results in relation to Plates XV., XVI., and XVII., it must be remembered that the effects of the Beta synclinal fold with an axis at No. 8 Bore, and rising to Beta anticlinal axes both to the north and south of this point at the centre of "F" ore-body, and just north of the No. 4 Tunnel respectively, must be taken cognisance of. The position of the troughs of the Alpha synclines, therefore, rise from that shown in Plates XVI. continuously to the positions shown in both Plates XV. and XVII. In attempting to combine the results of any of these bores which are not in the same vertical plane approximately at right angles to the axial directions of the folds, hopeless confusion and misleading conceptions must inevitably result. It is thus legitimate to take a section through Bores Nos. 22 and 24, which will also include Bore No. 10 already discussed. When we remember that the position of this cross-section is approximately as far south of the Beta synclinal axis at No. 8 Bore as the section shown in Plate XVII. is to the north of it, there seems to be justification for regarding this section as representing the conditions in the portions of the ore-bearing horizon we are now discussing, with the necessary adjustment of lowering the synclinal troughs about 25 feet. Studying this section, therefore, and remembering that No. 10 Bore showed 35 ft. of ore at No. 5 Level, passing, in fact, right through the most easterly synclinal trough, it is clearly seen that No. 23 Bore passed first through 10 feet of the extreme bottom of the synclinal trough, and, after traversing the intervening argillaceous schists, entered the new tongue of ore shown in Plate XVI. as penetrated by No. 8 Bore. No. 24 Bore shows this new lens to be smaller in this southern position at 90 feet below No. 5 Level than it was further north. The result of No. 11 Bore can be plotted on to Plate XVI. as it stands, if allowance is made for a very slight rise of the synclinal troughs; and it is then perfectly obvious that it passed through the lowest portion of the synclinal trough of this new make of ore, which it proves assumes a pyritic copper facies as it turns upwards again to the next anticlinal crest. The correctness of these three cross-sections below No. 5 Level is therefore verified.

At the No. 6 Level a north drive was put in for 100 feet at a distance of 800 feet from the mouth of the adit. Five horizontal bores were put out from this drive—three from the north end in N.E., S.W., and W.N.W. directions respectively for distances of 100 feet, 50 feet and 100 feet respectively. None of these showed ore-bodies. At the other end of the North Drive at the adit itself two bores in N.E. and S.W. directions respectively were put out for a distance of 100 feet in each case. Neither showed the existence of any ore-body. At a distance of 610 feet from the mouth of the adit a bore 350 feet in length was put out in a north-easterly direction, and again showed no ore to exist. A study of Plates VII. and VIII. of the Mt. Read bulletin will clearly show why these bores did not penetrate the ore-bearing horizon. These remarks supply additional evidence of the accuracy of the cross-sections above referred to, and to the correctness of the statement made in the Mt. Read bulletin that the zinc-lead sulphide ore-bodies do not extend as deep as No. 6 Level in that portion of the field enclosed between Nos. 2 and 5 tunnels of the Hercules, and some distance east of the 700 feet North Drive.

Since the completion of these bores a start has been made to open up the mine for ore-extraction on a large scale. A new adit has been driven from near the haulage at No. 5 Level, and this is to be the main working level of the mine. It was driven in a south-easterly direction towards the "E" ore-body, which it struck at 490 feet from the mouth of the adit at the point where No. 4 Bore cut it, as shown in Plate XVII., and penetrated it for a width of 56 feet, with an average assay value of:—

Gold	0·27	oz. per ton
Silver	6·04	,, ,,
Lead	9·5	per cent.
Zinc	25·4	,, ,,
Copper	0·4	,, ,,

This crosscut showed some very high gold values, thus confirming the results of No. 8 Bore in this respect. The ore from 490 feet to 493 feet showed a gold content of 0·69 oz. per ton, and that from 493 to 498 feet 1·73 oz. of gold per ton.

The end of the adit at present shows schist, and this has been taken as the hanging-wall of the ore-body, but a study of Plate XVI., and what has been said previously in regard to the continuation of No. 22 Bore, will show that it is most probably the schist which intervenes between this new lens of ore and the continuation of the "E" ore-body proper. The adit should therefore be continued to the eastwards.

At the 550 feet point in the adit a connection was made with the northerly continuation of the old 620 feet North Drive. Ore continued from the new adit to within 75 feet of the old No. 5 adit, giving a length of 212 feet of ore, of an average assay value of:—

Gold	0·13	oz. per ton
Silver	6·41	,, ,,
Lead	6·61	per cent.
Zinc	26·6	,, ,,
Copper	0·31	,, ,,

However, a length of 74 feet occurred from 105 feet to 179 feet from the old No. 5 adit, which assayed only:—

Gold	0·02	oz. per ton
Silver	0·69	,, ,,
Lead	1·26	per cent.
Zinc	8·7	,, ,,
Copper	0·16	,, ,,

This is, in fact, "low-grade disseminated ore," and not the zinc-lead sulphide ore-body, and shows that the drive is for this distance in the break between the new lens and the " E " ore-body proper, and if it is omitted a length of 138 feet of high-grade ore exists assaying:—

Gold	0·187 oz. per ton
Silver	9·5 ,, ,,
Lead	9·5 per cent.
Zinc	36·2 ,, ,,
Copper	0·47 ,, ,,

The first 50 feet south of the new adit showed very high zinc values, the average for this length being:—

Gold	0·17 oz. per ton
Silver	13·5 ,, ,,
Lead	11·3 per cent.
Zinc	46·1 ,, ,,
Copper	0·35 ,, ,,

The old 550 feet North Drive has been continued northwards to cut the new adit, and a large trucking-chamber is being excavated therein, and the main ore-pass from the levels above will be located at this point.

An intermediate adit has been driven also from near the haulage to form a level 70 feet above No. 5 Level, and intermediate between that and No. 4 Level. It is known as No. 5A Level. It cut the " E "ore-body at 490 feet at a point 30 feet south-west of the No. 7 Bore, but only penetrated it a couple of feet. That this is the " E " ore-body proper, and not the new lens, is clearly seen by referring to Plate XVII. of the Mt. Read bulletin. From the 420 feet point a drive southwards was started, which struck zinc-lead sulphide at 98 feet from the adit. This by reference to Plate XVI. is seen to be the downward continuation of the " D " ore-body, which, as shown in Plate XIV., is a direct continuation, and in fact part of the " B " ore-body. Very high values of all the four metals were met with in this drive from the 98 feet point to the 254 feet point. From the latter point to 308 fee the ore was more pyritic in character, assaying from 1 to 1·5 per cent. of copper. At 308 feet a seam 1 foot wide of zinc-lead sulphide, high in zinc, is showing. The developments at this southern end of the " B, D " ore-body are interesting, as they are showing a pyritic tendency of the ore-body which did not occur on the No. 4 Level, and in addition are showing values to extend farther to the south than in that level. As usual, however, copper values are associated with the black schist.

The exceptionally high values of the zinc-lead sulphide in this drive are particularly interesting, the gold, silver, zinc, and lead contents all showing high figures at the various portions of the drive, as shown by the following figures:—

Distance from Adit.	Gold. (Per Ton.)	Silver. (Per Ton.)	Lead.	Zinc.	Copper.
	Ozs.	Ozs.	Per cent.	Per cent	Per cent.
190 feet to 195 feet	0·56	16·4	21·3	37·7	0·6
216 feet to 221 feet	0·43	12·6	1·7	55·6	1·2

Discussing now the effect of all these developments on the question of ore-reserves, it is obvious that a great part of the ore classed as "probable ore" in Part I. can now be regarded as definitely proved ore. The amended figures, therefore, of the Hercules Mine are as follows:—

	Above No. 4 Level.	Below No. 4 Level.	Total.
	Tons.	Tons.	Tons.
Zinc-lead Sulphide—			
Proved Ore..........................	150,000	380,000	530,000
Probable Ore........................	...	134,000	134,000
Copper Ore—			
Probable Ore	...	22,000	22,000
Grand Total	150,000	536,000	686,000

The assay value of the 530,000 tons of "proved ore" is as follows:—

Gold	0·143 oz. per ton
Silver	8·1 ,, ,,
Lead	7·3 per cent.
Zinc	30·3 ,, ,,

The total of 664,000 tons of "proved" plus "probable" zinc-lead sulphide ore exceeds the estimate made by the officials of the Mt. Lyell Company, which is admittedly a conservative one; and the writer maintains that the above estimate is justified, in that it is calculated in accordance with the conception of the structural features of the ore-bodies completely delineated in Part I., and actually confirmed by the results of the development work carried out since the preparation of that publication, but which has not been followed by the Mount Lyell Company's officials in their estimate of ore-reserves.

This completes the description of the developments carried out at the Hercules Mine. The South Hercules property was purchased by the Mount Read and Rosebery Mines Limited, and some diamond-drilling was carried out. Two bores put down at 75 feet and 150 respectively east of the shaft workings, and directed westwards at an angle of depression of 60°, showed a horizontal width of 10 feet, and 5 feet of good-grade zinc-lead sulphide at depths below the collar of the shaft of 70 and 160 feet respectively. Another bore situated 75 feet farther along the strike of the planes of schistosity, and directed correspondingly to the first two, failed to locate ore. A fourth bore, situated 80 feet east of the last, and directed correspondingly, located good zinc-lead sulphide at 160 feet below the collar of the shaft. Yet another bore situated 50 feet further along the strike of the planes of schistosity than the last-mentioned bore, and directed westwards with an angle of depression of 76°, failed to locate ore in a distance of 350 feet.

A reference to Plates VI. and VIII. of the Mt. Read bulletin will clearly explain these results. The first two bores mentioned cut the downward continuation of the ore-body seen in the bottom of the shaft. The third bore mentioned in the above description passed over the top of the ore-bearing bed, which had dipped sufficiently down towards the Beta synclinal axis situate to the south of the South Hercules eastern adit, as shown in Plate VIII., to be missed by this bore, but not so deep that the fourth bore would not cut it. By the time, however, it has reached the location of the fifth bore, it has dipped or pitched sufficiently to allow that bore to pass over it. Reference to Plate VIII. will explain this if it is remembered, as shown in Plate VI., that the ore-body in the South Hercules is the easterly descending limb from the Alpha anticlinal axis at the Mt. Read workings, which is itself dipping down towards the Beta synclinal axis in the manner shown in Plate VIII., the crest of the Mt. Read Alpha anticlinal fold being far below the surface when it reaches the locality of the bores we are now discussing.

These bores, besides demonstrating the correctness of the conception of the structural features of the ore-bodies delineated in Part I. of this series of publications (the Mt. Read bulletin), go far towards bearing out the writer's prediction contained therein that "if the ore be followed downwards below the shaft it will open out into a large body of ore." Although a considerable body of ore has now been proved to exist, yet developments have not proceeded far enough to warrant the calculation of "proved ore," but the figure of 5000 tons of "probable ore" is justified.

At the Ring P.A. Mine, Sligo's tunnel was extended to a total length of 124 feet in order to cut the downward continuation of the ore shown in the trench at the side of the Mt. Read track. This, however, proved at this depth to consist merely of pyritised schist with blebs of zinc-blende disseminated.

In Section 5671-M, in the creek near the end of Jenkin's tunnel, as shown in Plate V., some mineralisation occurs; and a tunnel is being driven southwards on it. A little galena and pyrite shows in the schist, which is of the harder quartzitic variety which lies immediately to the west of the keratophyre. The ore-bearing horizon, as will be seen by referring to Plates V. and VIII., is some distance below the surface in this locality, and this mineralisation merely represents the upward invasion of part of the ore-bearing solutions beyond the congenial replaceable calcareous beds to the harder siliceous schists which they were not able to replace.

This completes the work bearing on the zinc-lead sulphide deposits which has been done on the Mt. Read group of mines since the preparation of Part I.

B.—ROSEBERY GROUP.

The scheme followed in regard to the development of the Rosebery Mines was that of diamond-drilling from the surface to locate the downward continuation of the ore-body to the eastward of the mine workings. The bores were put down vertically, their location being determined by the intention to intersect the ore-body on the northern continuation of the various levels. In all, 25 bores were put down, with a total length of 9073 feet.

The results of these bores will now be given, all references to the "ends" of the various levels referring to those shown in Plate XVII. of Part II. of this series of publications (the Rosebery bulletin), and all widths being horizontal measurements.

At No. 3 Level, No. 14 Bore showed 32 feet of high-grade ore 370 feet beyond the end of the level. At an average depth of 42 feet below No. 3 Level, Bores Nos. 13, 15, and 16 showed 12 feet, 12 feet, and 38 feet at 0 feet, 600 feet, and 860 feet respectively beyond the end of No. 3 Level. The 38 feet was rather lower-grade ore than the average zinc-lead sulphide.

At No. 4 Level, Bore No. 13 showed 5 feet of ore 200 feet beyond the end of the level.

At No. 5 Level, Bores Nos. 18, 19, and 17 respectively showed 12 feet, 19 feet, and 13½ feet of ore at 720, 960, and 1200 feet from the end of the level. At 25 feet below No. 5 Level, Bores Nos. 5 and 6 respectively showed 6½ feet and 26 feet at 150 feet and 370 feet beyond the end of the level.

At 36 feet above No. 6 Level, Bores Nos. 20 and 21 cut 12 feet and 4 feet of ore at a distance respectively of 610 and 870 feet from the end of No. 6 Level. At the same level No. 8 Bore showed 3 feet of ore 330 feet beyond its end.

At No. 7 Level, Nos. 4 and 7 Bores proved 22 feet and 17 feet at distances of 600 and 800 feet respectively from the end of the level. At 55 feet below No. 7 Level, Bores Nos. 2 and 22 showed 21½ feet and 15 feet respectively at 310 and 760 feet from the end of the level.

Bores Nos. 3, 10, and 9 proved widths of ore of 14 feet, 18 feet, and 4½ feet respectively at a depth of 36 feet below the Main Adit Level, and 130, 350, and 570 feet respectively beyond the end of it.

Bore No. 1 proved 8½ feet of ore at a depth of 73 feet below the Main Adit, and 200 feet north of the old 500 feet Bore; while No. 11 Bore showed 7 feet or ore at the same level as, and 470 feet ahead of, that in the 500 feet Bore.

The new lens of ore disclosed in the east crosscut at the southernmost end of the Main Adit Level was proved by Bores Nos. 24, 23, and 25 to exist at 25 feet, 85 feet, and 100 feet respectively below the Adit Level, the positions of these bores being respectively 180 feet, 0 feet, and 380 feet south of the crosscut.

The result of these bores is to establish the fact that there exists, between the No. 3 Level and the level of ore proved by No. 11 and the 500-feet bores, a total of roughly 1,050,000 tons of "proved ore." This includes all the ore "blocked out" ready for mining, and is based on the boring results and the mine workings, the ore already extracted from the mine being deducted. No ore above No. 3 Level, or none of that proved by the east crosscut at south end of the Main Adit Level and Nos. 23, 24, and 25 Bores, is included in this estimate.

The assay value of this ore is as follows:—

Gold … … … … … …	0·118	oz. per ton
Silver … … … … …	10·5	,, ,,
Lead… … … … … …	7·3	per cent.
Zinc … … … … … …	25·6	,, ,,

In addition to this "proved ore" an amount of approximately 720,000 tons of "probable ore" may be accepted as existing between Nos. 1 and 2 Levels, and in the triangular block between Nos. 16 and 11 Bores and the northern boundary of the consolidated lease.

In addition, however, to the boring work carried out as described above, mining development work was started immediately the boring was completed, and consisted in continuing the drives northwards at the Main Adit, No. 6, Intermediate (a new level, 80 feet above No. 6), No. 4, and No. 3 Levels, and crosscutting at every 100 feet, and connecting by rises to the levels above. A total of 2144 feet of driving and 842 feet of rises has been completed to date. The Main Adit Level has been continued 582 feet, and the average width of the ore-body for this length is 20 feet. No. 6 Level was continued for 446 feet, with an average width of 14 feet of ore. The new No. 5 Level, 80 feet above No. 6 Level, started northwards from No. 15 Rise, and is now 474 feet long. The No. 4 Level is now 355 feet beyond the end shown in Plate XVII. of Part II., but the average width of ore has not been ascertained, but is at least 6 feet. No. 3 Level was continued northwards, and is now 287 feet further along the ore-body than shown on the abovementioned plan. The ore passed through in these drives and crosscuts was of the same general grade as that already indicated in Part II. as being the average grade of zinc-lead sulphide ore in the Rosebery mines.

The result of this driving, crosscutting, and rising is to convert more of the ore proved by boring into "blocked ore" (or ore blocked out ready for mining) than that indicated in Part II. Calculating this "blocked ore" in a similar manner as that calculated in Part II., it is found that there exists in the Rosebery mines, *i.e.*, the Tasmanian

Copper and Primrose Mines, a total of 607,000 tons of "blocked ore," of an average assay value of—

Gold	0·116	oz. per ton
Silver	10·7	,, ,,
Lead	7·7	per cent.
Zinc	27·6	,, ,,

The officials of the Mt. Lyell Company in November, 1917, estimated a conservative total of 652,351 tons of "proved ore" as the result of part of the boring work discussed above, which at that time did not include the most northerly bores. At that time, also, the mining developments had not been carried out. The figures given above of 1,050,000 tons of "proved ore," which includes 607,000 tons of ore blocked out ready for mining, are in excess of those given by the Mt. Lyell Company. They are calculated on data, some of which were not available at the time of the Mt. Lyell Company's estimate, and are presented here with the assurance that they are the result of careful calculation based on the developments by mining and boring.

No further work has been done on the North Tasmanian Copper Mine since the preparation of Part II.

On the Koonya Mine the lower tunnel penetrated the ore-body as expected, but it was rather small where cut. When driven on southwards it opened out considerably, but as driving was continued the ore-body disappeared completely, exactly as predicted in Part II. Development work on this property should be carried out on the lines clearly indicated in Part II. of this series of publications.

Some work has been done on the surface on the schist outcrop, south of the Dalmeny and east of the Koonya, but nothing beyond a mineralisation of the schist has been located.

An interesting development has occurred on the Stitt River, about 10 chains east of the bridge on the road leading from the Rosebery station to the Rosebery township. A study of Plate IX. of Part II. will show this position to be at the crest of the Alpha anticline. Here a greenish schist was found to carry splashes and small lenses of zinc and lead sulphides. The crest of the Alpha anticline is rising towards the Beta anticline to the north of this point, and, as shown in Part II. (page 92), the ore-bearing horizon is much less than 100 feet below the surface at bore sites 234A and 235A, continuing from these bores to the most southerly outcrop at the south end of the Primrose open-cuts as an outcrop, this being the reason, as explained on page 72 of Part II., that the "C," "D," and "E" bores did not cut the ore-bearing horizon, they being too far to the east. The zinc-lead sulphides shown in this occurrence on the Stitt River are the result of the ore-bearing solutions rising up from the ore-bearing horizon a short distance below into a relatively unreplaceable schist. This development certainly warrants the carrying out of diamond-drilling on the lines indicated in Part II.

A discovery of zinc-lead sulphides in what is apparently Read-Rosebery schist on the southern end of the Bobadil Plain, in the deep gully south-east of the 31-mile post (see Plate VII. of Part II.), shows than an Alpha synclinal fold has taken the Read-Rosebery schist to the level of the Pieman River in a similar way as has happened at the Stitt River bridge, but has in this case been left isolated by subsequent denudation. The occurrence of zinc-lead sulphide, although interesting, is not to be regarded as important, as the amount of Read-Rosebery schist left isolated at this point can only be very small, and therefore the ore-deposit must also be small. A few tons, however, may be ultimately obtained if development work is persisted in.

C.—General Summary.

The results of the development and exploratory work carried out since the preparation of Parts I. and II. are thus seen to be very important. They have proved by actual penetration of the ore-bodies the incorrectness, firstly, of the statement in the report of the Hercules Mine, by Mr. G. H. Blakemore, that the zinc-lead sulphides are secondary enrichments of zinc and lead bearing copper deposits, and would change below No. 4 Level into pyritic copper deposits; and, secondly, the conclusion reached by a mining engineer from the mainland, after an examination made on behalf of Melbourne investors, that the ore-body at Rosebery consisted of lenses of ore, the existence of which was determined by the meeting of certain intersecting fracture-planes, and that therefore the amount of ore was limited to a much smaller figure than that shown by the calculations made by the mine manager.

These conclusions were stated by the writer in Parts I. and II. to be incorrect, and the whole of the data and reasons for making that assertion were presented therein.

The mining developments which have taken place since that occasion have definitely and finally proved that refutation to have been perfectly justified, and in addition have supplied quite remarkable confirmation of the conception of the structural features and mode of origin of the zinc-lead sulphide deposits, which have been fully presented and described in Parts I. and II. The cross and longitudinal sections of the various mines there presented have been proved in a most definite and interesting manner to be correct representations of the actual structure of the ore-bodies.

The writer desires to draw attention to the way in which these conceptions as to the structure of the ore-bodies have been proved correct, and to emphasise the importance of the acceptance of those conceptions to the future development of the field. Particularly does he desire to indicate his insistence on the basing of all future development on the lines laid down and fully described in Parts I. and II. He is of the opinion that much futile boring will thus be saved, and misleading results prevented.

III.—SUMMARY OF THE STRUCTURAL FEATURES AND MINERALOGY OF THE READ-ROSEBERY ZINC-LEAD SULPHIDE DEPOSITS.

Having seen, therefore, in the preceding chapter that the developments at the Read-Rosebery mines since the preparation of the two bulletins descriptive of the geology and ore-deposits (Parts I. and II. of the Read-Rosebery bulletins) have confirmed the conception of the structural features, mineralogy, and genesis of the ore-bodies fully elaborated in those publications, it is deemed advisable at this stage to present a very concise resume of what that conception is. This can, however, in no sense be taken as displacing the description above referred to, as a full study of the details presented in those bulletins is essential to the proper understanding of the structural features and mode of origin.

The zinc-lead sulphide deposits of the Read-Rosebery district are metasomatic replacements of metamorphosed calcareous beds which are members of a mixed sedimentary and fragmental volcanic series converted by intense metamorphism into argillaceous, calcareous, chloritic, and quartzitic schists known as the Read-Rosebery schists. The direction of the pressure responsible for the metamorphism was directed from the westwards. This gave rise to planes of schistosity striking about N. 20° W., and dipping eastward at a steep angle, and being quite independent of the original sedimentary bedding. Concurrently with the development of this cleavage there took place a rearrangement of the mineral components of the rocks into bands of varying composition, orientated, of course, parallel to the general cleavage. At the same time, also, there was a development of a series of folds which, because of the compression and crowding of the original sedimentary beds into an area with both north-south and east-west dimensions less than before metamorphism, took place in two directions, the axes of the two series of folds being approximately at right angles to each other. The original calcareous beds represented after the metamorphism and folding by calcite schists occur, therefore, in a series of domes and basins, the original variation in composition of successive beds being preserved in the main, but with a partial rearrangement of the mineral components into bands parallel to the planes of schistosity.

The ore-bearing solutions were derived from a differentiating granitic magma situated below the field; and these ascending solutions travelled along main fracture-planes ("master fractures") until they met the old bedding-planes of the schists, whence they reached the bedding-planes of the calcareous beds, from which they passed along the schist planes, thoroughly permeating the beds themselves and metasomatically replacing them with zinc-lead sulphide ore, the composition of which was determined by the composition of the rock replaced. Thus was developed the banded texture of the ore which is so characteristic, and which is a metasome of the banding of the replaced calcite schists. In the same way was developed the variation, on a larger scale, in the composition of the ore-bodies apart from the banding, which is a metasome of the original variation in composition of the sediments on too large a scale to be obliterated by the rearrangements accompanying the metamorphism. The replacement took place at intermediate depths (4000 to 12,000 feet) at a temperature in the vicinity of 200° C.

The zinc-lead sulphide, therefore, as it replaces the calcite schists which form a series of domes and basins, occurs in domes and basins also. As these domes and basins have unequal horizontal axes, a horizontal section will be lenticular or elliptical in shape. Consequently the outline of the ore-bodies at any one level will be lenticular or elliptical.

In places where the dome or basin is of large dimensions the ore-body exposed in the mine workings may show only one limb of the anticlinal or synclinal folds (dome or basin), and consequently the ore-body will be of a general tabular character.

The exploration of the Read-Rosebery zinc-lead sulphide deposits consists, therefore, in the study and location of the folds and undulations of this horizon of calcareous schists referred to in Parts I. and II. as "the ore-bearing horizon," which persists over a length of 7 miles and a width varying from 1 to 1½ miles.

The size of the ore-bodies as disclosed by the mine workings at the present date is indicated by the following figures:—

Name of Ore-body.	Length.	Maximum Width.	Average Width.	Proved Vertical Extent.
	Feet.	Feet.	Feet.	Feet.
"E" Ore-body, Hercules..............	300	100	50	400
"B, C, D" Ore-body, Hercules	400	75	60	250
"A" Ore-body, Hercules.............	300	40	20	250
Large Lens, Mt. Read	450	100	50	110
Ore-body, Rosebery	2200	60	25	500

There is a very sharp dividing-line between ore and country-rock, solid ore persisting right up to the unmineralised country, or being separated therefrom by only a clay selvage.

The metallic minerals in the order of the proportions present are zinc blende, pyrite, galena, chalcopyrite, and tetrahedrite; and the gangue minerals are quartz, calcite, barite, and rhodochrosite, and occasionally a little fluorite. Silver and gold are present, the former in association mainly with the galena and tetrahedrite, but also to some extent with the pyrite, while the gold occurs in the free state, and also in association with the galena, blende, and pyrite. Cadmium, arsenic, and antimony are present.

The average zinc-lead sulphide ore of the Read-Rosebery district has the following mineralogical composition:—

Zinc blende...	43·3 per cent.
Pyrite	31·0 ,, ,,
Galena	10·4 ,, ,,
Quartz...	5·5 ,, ,,
Silicate of alumina	2·5 ,, ,,
Calcite	2·4 ,, ,,
Barite	1·5 ,, ,,
Chalcopyrite	1·2 ,, ,,
Rhodochrosite	1·2 ,, ,,
Tetrahedrite	0·1 ,, ,,
Silver	10 oz. per ton
Gold...	3 dwt. ,,

Although a great part of the ore-bodies carries well over 90 per cent. sulphides, yet on the average they approximately contain 85 per cent. sulphide and 15 per cent.

gangue, the chemical composition of the average zinc-lead sulphide being as follows:—

Lead...	7·1 per cent.
Zinc...	27·3 ,, ,,
Copper...	0·9 ,, ,,
Iron...	18·0 ,, ,,
Sulphur...	36·2 ,, ,,
Lime	trace
Magnesia	0·2 ,, ,,
Alumina	2·2 ,, ,,
Silica	7·2 ,, ,,
Gold...	0·150 oz. per ton
Silver	10·5 ,, ,,

The range in composition of the various grades of ore is shown by the following figures:—

Nature of Ore.	Gold. (Per Ton.	Silver. (Per Ton.)	Lead.	Zinc.	Copper.
	Ozs.	Ozs.	Per cent.	Per cent.	Per cent.
High-grade Lead Ore	0·55	6·0	22·5	34·4	0·5
ditto	0·56	16·4	21·3	37·7	0·6
High-grade Zinc Ore	0·43	12·5	1·7	55·6	1·2
ditto	0·01	11·5	8·5	46·0	0·35
Dense Pyritic Ore ...	trace	3·0	0·8	8·0	0·75

The average assay of 1,680,000 tons, which are the ore-reserves in the Read Rosebery mines at the present date, is—

Gold	0·127 oz. per ton
Silver	9·6 ,, ,,
Lead	7·3 per cent.
Zinc	27·3 ,, ,,

There is very little oxidised capping to the ore-bodies, the sulphides persisting in most cases practically to the surface. The deepest occurrence of "gossan," which consists of oxide of iron, with a little lead and zinc carbonates, but considerable silver and gold values, is 50 feet; but this is quite exceptional. There is a complete absence of masses of carbonates of lead and zinc.

The texture of the ore, as stated above, is distinctly banded, the bands being due to varying composition. The sulphide minerals exist as an extremely intimate intergrowth of a very fine grain, which is clearly indicated by the fact that it is necessary to grind the ore to pass a screen, having 200 holes to the linear inch, in order to free the constituent minerals sufficiently to enable a mechanical process of separation to be successful.

All the descriptive matter and figures so far presented in this chapter refer solely to the typical solid zinc-lead sulphide ore-bodies. There have been described in Part I., however, deposits of much lower grade, termed "low-grade disseminated deposits," which in places extend beyond the sharply-defined walls of the zinc-lead sulphide ore-bodies. They consist of disseminations of pyrite, zinc blende, galena, and chalcopyrite in chloritic or quartzitic schists deposited there by metasomatic replacement. They represent, in fact, the permeation and partial replacement of these schists by the same ore-bearing solutions which invaded the calcareous schists, and completely replaced them with solid zinc-lead sulphide. Their metallic values are as follows:—

Gold...	0·03	oz. per ton
Silver	1·5	,, ,,
Lead	0·5	per cent.
Zinc	6·5	,, ,,
Copper...	0·1	,, ,,

They are not taken into account in any calculation of ore-reserves, but, as will be shown in subsequent portions of this publication, they are destined to be an appreciable source of ore.

IV.—CONCISE DESCRIPTIONS OF CORRESPONDING ZINC-LEAD DEPOSITS IN OTHER PARTS OF THE WORLD.

A.—General Remarks.

As explained in the introductory chapter of this volume, it is deemed advisable to present in a concise and clear manner the salient characteristics of some of the similar zinc-lead sulphide deposits of the world, in order to enable a comparison to be made between them and the Tasmanian occurrences. In this way a correct perspective of the importance of the Read-Rosebery zinc-lead sulphide deposits will be attainable, for it will be possible to see at a glance in what respects they are superior, and in what respects inferior, to other zinc-lead sulphide deposits which have been and are being exploited.

In presenting the descriptions of these various deposits, the main basis of classification and grouping will be that of the mode of origin or genesis of the ore-bodies, for the reason that it is the mode of origin which determines their structural features, extent, and persistency. The important zinc-lead sulphide deposits of the world fall genetically under three main heads:—

(1) Lead and zinc deposits in sedimentary rocks, the origin of the ore-bearing solutions being independent of igneous activity.

(2) Zinc-lead sulphide deposits formed at intermediate depths by ascending thermal waters at temperatures between 150° and 300° C., and in genetic connection with intrusive igneous rocks.

(3) Zinc-lead sulphide deposits formed under high pressure, and at temperatures between 300° and 500°C. in genetic connection with intrusive igneous rocks.

Under each of these three headings deposits will be described from various parts of the world, the subdivisions under each heading being merely geographical.

B.—LEAD AND ZINC DEPOSITS IN SEDIMENTARY ROCKS, THE ORIGIN OF THE ORE-BEARING SOLUTIONS BEING INDEPENDENT OF IGNEOUS ACTIVITY AND THE SOLUTIONS SLIGHTLY, IF AT ALL, ABOVE NORMAL ATMOSPHERIC TEMPERATURE.

1. *General Description.*

The lead and zinc deposits under this heading represent a type of world-wide distribution, and, in spite of local variations, of remarkably constant characteristics. They occur in limestones, dolomites, cherts (derived from limestones by replacement of the calcium carbonate by silica), or calcareous shales. The ores lie in brecciated or fractured zones, or in crevices or joints which have been enlarged by solution. They are generally fissure or cavity fillings, showing crustification and crystallisation in cavities, but often they form metasomatic replacements in the limestone. The ore-bodies show a marked tendency to follow certain stratigraphical horizons. They are frequently found below impervious shale beds. They usually lie within a few hundred feet of the surface, and are oxidised in the vicinity of the water-level.

The ore minerals are galena and zinc blende as essential constituents, with more or less pyrite, and almost invariably, marcasite, and occasionally a little chalcopyrite. Silver is practically absent, the galena being characteristically silver-free. Gold, arsenic, antimony, and molybdenum are absent also. Nickel and cobalt are often present in small amounts. The characteristic gangue mineral is dolomite; crystalline quartz is very rare, although chert—representing a replacement of limestone by silica—is common. Barite occurs occasionally, but is not characteristic. There is practically a complete absence of other gangue minerals. The zinc blende varies in colour from a pale straw yellow through brown to black, the lighter colours predominating. It is exceptionally pure, being remarkably free from iron, which rarely exceeds 1 per cent. even in the darker varieties. The zinc blende and galena occur in separate crystalline aggregates, there being very little intergrowth. The cubes of galena measure up to several inches, or even up to 1 foot across in the crustified occurrences. In the replacement deposits, or "disseminated deposits," as they are called, the particles of galena and blende are much smaller, but even here there is very little, if any, intergrowth of these two minerals. The same applies to the marcasite and pyrite in their relation to the galena and blende.

The following are some of the localities where this type of deposit is typically developed, with details of character and extent of the ore-bodies, and the amount and composition of the output, together with the method of metallurgical treatment:—

2. *Occurrences in the United States.*

(*a*) *Joplin Region.*—These deposits are in south-western Missouri, in the Mississippi area. The ores are found as irregular deposits in the "broken ground" near the surface and as a flat "sheet ground" in the bed of limestone, which has been largely converted to chert by replacement by silica, at depths of 150 to 300 feet. Below this horizon of limestone there occur unworked deposits of "disseminated ore" in an underlying bed of limestone. In both the "broken ground" and the "sheet ground" the ore occurs as fillings of cavities, the fillings of distinct veins or crevices being subordinate. These cavities are brecciation spaces or solution cavities in the limestone.

In the "broken ground" which extends from the surface down to a depth of from 100 to 150 feet, the ores occur in a universally pockety manner in clayey chert breccias, or around the outside of "sink holes" which were caused by the sinking of the beds into a cavity dissolved in the limestone immediately below. The latter mode of occurrence gives rise to the designation of "circles," the ore having been deposited in the spaces resulting from the slipping and settling of the mass of rock which had approximately a circular cross-section. In these deposits the galena predominates, and large masses of galena are common.

A characteristic feature of this upper or "broken ground" is the occurrence of "runs," in which the developments of ore are strung out for a length of from 1 to 2 miles, following the same stratigraphical horizon at depths usually much less than 150 feet below the surface. The width of the run rarely exceeds 50 to 150 feet. Each run has usually several "openings" (brecciated ground filled with ore), each opening being rarely more than 5 or 6 feet thick.

In places the brecciation and mineralisation of the "broken ground" continues downward to the underlying

" sheet ground," but more often the latter is independent of the former deposit. The deposits in the " sheet ground " are extensive, and are from 6 to 15 feet thick, lying flat along certain horizons. The galena and zinc blende occur in brecciated chert. The sheet ground is the most important source of ore.

The ore-minerals occur as separate crystalline aggregates, to some extent mixed, but never intergrown. The upper portions of the ore-bodies are invariably oxidised to carbonate and oxide ores.

The ore-bearing solutions which invaded these pre-existing cavities were acid in character, and had a temperature not above that of ordinary surface waters. The solutions were formed by atmospheric waters descending to the underlying Cambro-Ordovician rocks, where the mineral constituents were dissolved, and the resulting ore-bearing solutions then invaded the series of limestones in which the ore-deposits are now found. Igneous activity therefore played no part in the origin of these zinc-lead deposits.

An idea of the size of these ore-bodies can be obtained from the following typical examples of deposits actually mined. One of the best defined " runs " has a length of 1400 feet, with a width varying from 12 to 30 feet and is mainly developed between the 90 feet and 150 feet levels. One of the best known " circles " measures from 300 to 400 feet in inner diameter, and 500 to 600 feet in outer diameter, giving a width of ore of about 200 feet; the ore-body extends from the surface down to 150 feet. A typical " sheet ground " deposit has been mined over an area 2000 feet long, by 400 to 800 feet wide, and 10 feet deep. It occurred at a depth of 170 feet below the surface.

The deposits are spread over an area of roughly 3100 square miles. However, over 80 per cent. of the production has been obtained from an area of about 100 square miles, all of which lies within 14 miles of Joplin. Since the discovery of the ore-deposits in 1850, the mines have yielded approximately 1,100,000 tons of lead concentrates, and approximately 4,700,000 tons of zinc concentrates. Nearly 65 per cent. of the lead was mined prior to 1893, while about 98 per cent. of the zinc has been mined since 1880. At the present time the annual output consists of approximately 35,000 tons of lead concentrates and

215,000 tons of zinc concentrates. The composition of the output is given by the following figures:—

Ore from "Broken Ground" Deposits.

		Per Cent.
Total concentrates in crude ore		4·5
Lead ,, ,, ...		0·4
Zinc ,, ,, ...		4·1
Metal content of crude ore	Lead...	0·3
	Zinc...	2·3
Average lead content of lead concentrate		79·5
Average zinc content of zinc concentrate		59·0

Ore from "Sheet Ground" Deposits.

		Per Cent.
Total concentrates in crude ore		2·6
Lead ,, ,, ...		0·5
Zinc ,, ,, ...		2·1
Metal content of crude ore	Lead...	0·3
	Zinc...	1·3
Average lead content of lead concentrate		79·0
Average zinc content of zinc concentrate		59·0

The metallurgical problem is not a difficult one. The separation of zinc-blende from galena starts in the mines where masses of either mineral occur without the presence of the other. The mixed ores go to the concentrating mills where ordinary gravity separation is the basis of treatment. This has been supplemented by the employment of the electro-magnetic separation process in the elimination of the pyrite and marcasite from the zinc concentrate. Since the advent of the flotation process, the slimes from the concentrating mills have been treated by that method, and the percentage of recovery thereby increased. The occurrence of the ore-minerals, galena, zinc blende, pyrite, and marcasite, as separate particles with very little intergrowth, and with a comparatively large average diameter, makes the ore one which is particularly adapted to treatment by mechanical processes.

(*b*) *Wisconsin Region.*—These deposits occur in the Upper Mississippi Valley, in south-western Wisconsin, north-western Illinois, and north-eastern Iowa. The rocks of this region are limestone, sandstone, and shale. There is a complete absence of igneous rocks. The ores occur in limestone and dolomite. The mines are not deep, varying from 100 to 200 feet deep. They are distributed irregularly through the district in clusters, which are confined within the limits of flat, shallow, irregular, structural basins, which are depositional in origin.

There are four general forms of ore-bodies recognised in this region: (1) Crevices and openings; (2) honeycomb or "sprangle" runs; (3) pitches and flats; (4) disseminated ores.

The "crevices," or "gash-veins," as they are sometimes called, are developed along vertical joint-planes, which have been materially enlarged by the dissolving action of underground waters. In the north-south and quartering joints this action has been uniform, resulting in the occurrence of simple sheets of mineral, from ¼-inch to 4 inches in thickness. Along the main east-west crevices, solution has been more active, and where they cross certain stratigraphical horizons there is a distinct widening, and an open space results. These are called "openings," and are from 1 to 4 feet wide and from 4 to 6 feet high. Occasionally the rock between two crevices has been cut by solution, and broad chambers, 25 to 30 feet wide and 30 to 40 feet high, have been formed. The ore occurs lining these openings, or in loose, fallen masses buried in residual sand.

The term "run" is used in the same sense as in the Joplin deposits, and consists of a series of "openings" strung out along a certain stratigraphical horizon. Below water-level the dolomite has been rendered porous instead of being completely dissolved, the open spaces measuring from ½-inch to 2 inches in diameter, equalling half the original bulk of the rock. These spaces are either lined or partially filled with ore. When the ore is very coarse it is often spoken of as "sprangle" ore. Where the open spaces are smaller and less numerous, the term "honeycomb" is more often used.

The most interesting and unique forms of ore-bodies in the district are the "flats and pitches." In these the ores follow in part the vertical joint-planes, in part the bedding-planes, and in part the dipping joint-planes. The result is an ore-body occupying a series of horizontal sheets called "flats," connected by a series of dipping-sheets or "pitches." The following is a description of a typical ore-body, showing "flats" and "pitches," from which a clear conception can be obtained of the general character of this type of deposit. Three crevices descend from above, one near the centre and one each on the north and south margins of the upper flat, which is about 40 feet wide and 1 foot in depth. On either side this descends by slopes and steps through the lower bed of limestone until the divergent sheets are 75 feet apart. On the pitches the ore is from 2 to 8 inches thick. A narrowed seam then descends almost vertically for about 10 feet, when it reverses its pitch, and forms an extensive flat 2 feet in maximum thickness, and having a central sag of 3 feet. Below this point the tendency is towards impregnation of the rock rather than the formation of well-defined veins. The depth from the upper to the lower flat is about 50 feet. The result is that a north-south cross-section, as just described, resembles a cross-section of a domestic flat-iron. The consideration of the third, *i.e.*, the east-west, dimension makes this resemblance more complete, for the sides approach one another in exactly the same manner as those of a flat-iron, there being a pitch at the ends similar to that at the sides. It may be accepted, therefore, that in shape these ore-bodies are similar to the domestic flat-iron.

The disseminated ores are replacements of limestone by galena, zinc-blende, and marcasite, the occurrence of these minerals being sporadic, and only locally present in sufficient quantity to pay the cost of mining and treatment. The rock occupying the inside or core of a "flats and pitches" deposit is generally replaced by sufficient mineral to pay for mining and treatment.

The ore-minerals occur as separate and distinct crystalline aggregates, there being little, if any, intergrowth. In the honeycomb ore the cavities are often lined with marcasite to a depth of 0·5 to 1 millimetre thick. On it both galena and blende have been deposited, but there is a notable tendency for each mineral to be segregated, and to occupy different cavities, or different portions of the same cavity, rather than be intergrown. The fillings of crevices and openings obey the same rule, there being crustification or segregation of the component minerals into definite bands of galena, blende, and marcasite with the gangue minerals where an enlarged joint has been completely filled with ore. The ores of flats and pitches bear evidence of having been deposited in open spaces, crustification being common, and the various fracture-planes and cavities being lined or filled with sulphides.

Zinc blende is more common in these flats and pitches than galena; and marcasite is comparatively rare, as compared with its occurrence in other forms of deposits. The crystals and crystalline aggregates of both blende and galena are usually sharp-angled and idiomorphic. They vary from one-sixteenth to three-quarters of an inch in diameter. The galena is quite free from silver. The upper portion of all the ore-bodies is almost completely oxidised, the upper mine workings producing zinc and lead carbonate ores.

The metallic minerals were brought into this district by transportation incidental to deposition of sediments from Pre-Cambrians lying to the northward. They were concentrated in their present positions and condition by some phase or phases in the circulation of underground water of meteoric origin, *i.e.*, water derived from the surface by downward percolation. These ore-bearing solutions were acid in character, and were only slightly, if at all, higher in temperature than ordinary surface-waters. Igneous activity has played no part in their formation.

As regards the size of these ore-bodies, it may be mentioned that a typical "flats and pitches" deposit was 1000 feet long, 75 feet wide, and 40 or 50 feet high. A typical "crevice and opening" occurrence showed two well-marked crevices intersecting. The opening or cave at the intersection measured 500 feet in length, 25 to 35 feet in width, and 30 to 40 feet high. At the end of the cave the crevice narrows to 2 feet or less. The ore occurs on the walls of the cave, and in lumps lying in it. In all, about 7500 tons of galena and some zinc blende were taken from the cave. About ½ to ¾ mile along the crevice another cave of similar dimensions occurs. A "honey comb and sprangle" deposit was worked for a length of 300 feet, the width being 12 to 40 feet, and the height of the ore-body 8 to 50 feet.

The deposits are spread over an area of 2500 square miles. Within this territory there are broad areas, however, which are, as far as is known, entirely barren of mineral. Since the discovery of the ore-deposits in 1821, the total lead concentrates produced has been approximately 662,000 tons. The production of zinc concentrates began in 1860, and since that date approximately 900,000 tons of zinc concentrates have been sent out from the mines. The rate of production in recent years has been in the vicinity of 4500 tons of lead concentrates and 90,000 tons of zinc concentrates per annum. The following figures indicate the grade of the ore as mined, and the metal contents of the concentrates:—

	Per Cent.
Lead concentrates in crude ore (average for field)	0·4
Zinc concentrates in crude ore (average for field)	8·8
Lead content of crude ore	0·3
Zinc content of crude ore...	3·1
Average lead content in lead concentrates	77·0
Average zinc content in zinc-blende concentrates	35·0

The crude ore is crushed and sent to concentrating mills using the ordinary water concentrating methods. The separation of zinc-blende and galena is carried out to a considerable extent in mining, taking advantage of their separate occurrences in the ore-bodies. Their separation in the mills is carried out very satisfactorily by specific gravity separation, the absence of intergrowth of the two minerals making this possible. In the Wisconsin district there is generally so much marcasite associated with the zinc-blende concentrates that, owing to the nearness in specific gravity precluding the possibility of a clean separation by hydraulic methods, these have to be given a magnetising roast, and then treated in electro-magnetic separation plants for the removal of the iron. In some mills the flotation process has been lately installed to treat the fine slimes from the mills and that resulting from the fine-grinding of the disseminated ore, to free whatever finely-discarded mineral is contained therein. It is only an adjunct, however, to the main milling process, which is hydraulic.

3. *Occurrences in Europe.*

(*a*) *Aachen Region.*—Aachen is situate 44 miles west-south-west of Cologne, in Germany. The mines of the region occur in two districts, Moresnet, to the south-west of Aachen, and Stolberg, to the east of Aachen. The ores occur in limestones and dolomites of Devonian and Carboniferous age, and are confined to these rocks. Without exception they are connected with faults, which strike across the rock series carrying the limestone and dolomite beds. The deposits occur where these faults cut the limestone and dolomite beds, particularly the basal dolomite of the Carboniferous.

The deposits are in the form of fissure-fillings, as well as chamber deposits and metasomatic replacement ore-bodies, these different forms of deposit usually occurring in combination. The fissure-fillings occur where the fault-plane in the limestone has been enlarged by solution, and there is generally more or less replacement of the wall-rock. The replacement deposits, which occur along the course of the fault-fissure, particularly where it cuts the limestone and shale beds, vary greatly in form and character. One type found in the Diepenlinchen Mine has the form of a greatly enlarged vein. This form grades into thick and rounded ore-bodies, called stockworks, some of which are of very large size. One of the largest at the 200-feet level was a vein-like mass which increased in size as depth was gained, until at the 430-feet level it measured 295 feet in length and 130 feet in width. There is no sharp boundary between the ore and the enclosing limestone, the ore gradually fading into the latter. At a few points only does it end sharply against beds of solid limestone. The ore of the upper levels consists of calamine (carbonate of zinc), galena, cerussite (carbonate of lead), and some pyrite. The oxidised zinc ore passes into blende below the 294-feet level, while the cerussite continues to the 430-feet level. There are no oxidised ores at the 480-feet level. The sulphides have been proved payable to a depth of 800 feet.

The most famous of these deposits is that of Altenberg, or Vieille Montagne, in the Moresnet district. The cubic contents of this ore stock were 9,200,000 cubic feet. It yielded in 500 years 1,000,000 tons of oxidised zinc ore. The ore was an intimate mixture of calamine and hydro-silicate of zinc, with some calcite. The country-rock was dolomitic limestone, forming a synical fold.

In addition to these stock-shaped and chamber deposits, there are occurrences of ore disseminated in beds. One bed of clay slate has blende and galena disseminated through it for a distance of 1½ to 2 miles.

The ores of all these deposits, in their unoxidised state, are zinc-blende and galena, with marcasite in subordinate quantity, and a little pyrite. Silver, arsenic, and antimony are absent. The galena was deposited first, then the blende, and finally the marcasite. The zinc-blende is always more plentiful than the galena. The only gangue mineral present is calcite. The texture of the ore-deposits is generally porous and cellular. There is some intergrowth of the zinc and lead minerals, but they mostly occur as separate mineral aggregates. The average ore from the various mines of the district, when working in the unoxidised ore-bodies, contains 30 per cent. zinc-blende, 5 per cent. galena, and 20 per cent. marcasite and pyrite.

The importance of the field can be gathered from the figures given above of the size of the ore-bodies, and the output where mentioned, as well as from the fact that in 1909 the Altenberg group of mines alone produced 12,289 tons of zinc-blende, 800 tons of galena, and 938 tons of oxidised zinc ore. The Diepenlinchen Mine in 1910 produced 9611 tons of zinc-blende and 1626 tons of galena.

The metallurgical problem is not a difficult one. The oxidised ores are mined separately from the sulphides. The latter are treated in concentrating mills after the high-grade ore is picked out on moving picking-belts. Ordinary hydraulic specific gravity concentration is employed. The lead concentrates contain some zinc, however, which in the process of lead-smelting becomes concentrated in the slag. This slag has been treated by smelting with coke and air by the Schmidt and De Gras process, which is similar to the better known Oker process. The zinc is recovered in the form of zinc oxide. This will be more fully described in Chapter VI.

(*b*) *Upper Silesia.*—These deposits occur in and around Tarnowitz and Beuthen, which are situated in the south-eastern portion of Silesia, a province of Prussia. They are found in the Muschelkalk, which is a well-known limestone bed of the great German Triassic basin, and are practically confined to that portion of the limestone bed lying within the deeper portions of two synclines, known as the Tarnowitz and Beuthen synclines. The ore is actually confined to one subdivision of the Muschelkalk limestone, namely, a dolomite bed about 230 feet thick, known as the Upper Wellenkalk. The ore-bodies are quite irregularly distributed in the dolomite bed. Rich sections alternate indiscriminately with others carrying little or no ore. These rich sections are connected with the system of strike-faults and the north-south transverse-faults which are traceable to the coal measures below.

Often ore-bodies are found at two horizons, being then separated by as much as 60 feet of unmineralised dolomite, but having the same general composition. Both deposits may be purely of lead ore, as in the Tarnowitz syncline, where the ore-bed does not exceed 3 feet in thickness; or predominatingly zinc ore, as in the Beuthen syncline, where the ore-bed is as much as 40 feet in the thickness, but generally does not exceed 6 feet. The whole thickness is in no case made up wholly of ore, there being generally a mixture of ore and dolomite. Clean galena occurs at Tarnowitz in the form of narrow compact layers and partly as irregular nests and masses, the thickness of the ore-bearing layer being usually 1 foot to 1½ foot, and occasionally 6 feet. At the same locality, also, there is a soft galena layer and a solid galena layer. In the former the galena occurs as plates and masses in clay, filling the bedding and joint planes of the dolomite; in the latter it occurs solidly intergrown with the dolomite, either as a thin bed or as stringers and aggregates. The soft layers have apparentlly been derived from the hard by weathering.

In the Beuthen syncline, zinc-blende is predominant, but the ores carry considerable galena. There is here also an upper ore-bed in places, characterised by zinc-blende, and which reaches 3 feet in thickness.

The upper portions of all these deposits have been oxidised, and consist of oxide and carbonate of lead and zinc ores, calamine and cerussite predominating. The sulphide ores appear in depth as the zone of oxidation is passed through.

The sulphide minerals are zinc-blende, galena, and marcasite and pyrite; the gangue mineral being calcite or dolomite only. The galena carries about 10 oz. of silver to the ton. The sulphide minerals as a rule occur in separate aggregates, but sometimes they are intimately associated.

The average content of the ore is approximately 17 per cent. zinc and 5 per cent. lead. These deposits in 1908 produced 75 per cent. of the total zinc and 50 per cent. of the lead produced in Germany in that year. They have been producing lead since the 13th century, and zinc since the 16th century, the production for several centuries being confined to the oxidised ores which occur in such huge masses near the surface. The total production to date is unknown, but in 1908 11 mines were working, the total material mined amounting to 1,212,366 tons, from which 210,456 tons of metallic zinc and 61,733 tons of metallic lead were obtained (17·4 per cent. and 5·1 per cent. respectively).

The metallurgical treatment is exactly similar to that at Aachen, excepting that the Oker process is used in the dezincing of the zinciferous slags.

C.—ZINC-LEAD SULPHIDE DEPOSITS FORMED AT INTERMEDIATE DEPTHS BY ASCENDING THERMAL WATERS AT TEMPERATURES BETWEEN 150° C. AND 300° C., AND IN GENETIC CONNECTION WITH IGNEOUS ROCKS.

1. *General Description.*

The particular type of deposit under this head which will be considered here is confined to replacement deposits in limestone. There are some fissure-fillings, but these are only insignificant in extent, and are associated with the replacement deposits, among which are some of the great ore-deposits of the world.

At some places these zinc-lead deposits follow dykes or intrusive sheets, but such deposits were usually formed after the rock had congealed and cooled. At other places they are dependent upon impervious overlying beds of shale, &c. The ore-bodies are characteristically irregular in outline.

The gangue minerals are dolomite, dense cherty quartz, barite, calcite, rhodochrosite, and sometimes fluorite. The common primary ore-minerals are pyrite, galena, zincblende, chalcopyrite, and more rarely arsenopyrite, tetrahedrite, tennantite, enargite, bornite, bismuthinite, wolframite, molybdenite, and stibnite are of local importance. Gold is sometimes present as a primary mineral. Galena is usually rich in silver. Marcasite is absent, the iron sulphide being invariably pyrite.

The texture of the ore is usually coarse-grained, but gradations exist down to extremely fine-grained intimately intergrown aggregates of the component minerals. Some of the deposits consist of massive sulphides, while in others the gangue may prevail.

All the deposits in this group were derived from ascending ore-bearing solutions ejected from a differentiating acidic magma below.

There will now be given short descriptions of typical deposits of this type occurring in various parts of the world.

2. *Occurrences in the United States.*

(*a*) *Park City, Utah.*—These deposits are situated near the summit of the Wasatch Range, in north-central Utah. The Park City district has won high standing as a "bonanza camp," and its extensive mines rank well among the dividend-paying silver-lead-zinc mines of the world.

The ores occur as lode deposits and closely associated bedded deposits in two parallel zones extending northeastward. The lode deposits intersect the sediments and the porphyry as well, have a steep dip, and often lie in quartzite or between limestone and quartzite. The ores are in part deposited by filling of fissures in shattered ground, in part by replacement.

The bedded deposits are massive sulphides replacing limestone in two calcareous formations. They are connected with the lode deposits, representing, in fact, the paths of invasion of the ore-bearing solutions along bedding-planes at certain stratigraphical horizons, which have resulted in the replacement of a certain thickness of the limestone bed for some distance beyond the filled fissure. The bedded deposits are therefore roughly lenticular in shape, their greater axes being in the direction of the strike. The dip and the strike agree roughly with those of the enclosing limestone members. In some places entire members or beds of limestone have been replaced by ore. Many such beds end evenly above and below on bedding-planes of the overlying and underlying beds of limestone. Others extend irregularly across the bedding, some ending in tongues, and others expanding at a higher horizon to form a second ore-bed. In the same manner the ore-body is made up of layers or laminæ which correspond in all ways to the laminæ which make up the bed of limestone. These laminæ range from a small fraction of an inch to 1 or 2 inches in thickness according to the thickness of the bands forming the original limestone bed. In brief, the deposits of bedded ore occur in ore-bodies of roughly lenticular form, having a banded structure which is conformable with the bedding of the enclosing limestone, even down to minute laminations.

The ore-minerals are galena, zinc-blende, pyrite, tetrahedrite, and a little chalcopyrite. The gangue is mainly quartz and jasperoid, while fluorite, calcite, and rhodonite occur locally. The sulphide minerals occur isolated only occasionally, separate crystals of the respective mineral species being sometimes observed, but the usual manner of association of the constituent minerals is that of an intimate intergrowth of varying degrees of coarseness. The coarser type of ore, consisting of galena, zinc-blende, pyrite, and the subordinate minerals intergrown, is more characteristic of the strong fissures; and the more granular mixture of galena, zinc-blende, and pyrite, along with the tetrahedrite and a little calcite and jasperoid, is characteristic of the replacement deposits. The silver is carried in the tetrahedrite, galena, and pyrite. The ore of these ore-bodies then is a solid sulphide ore, with very little gangue, and possessing a marked banded structure. The relative proportions of sulphide to gangue, and of the various sulphides to each other, vary in the respective bands.

This zinc-lead sulphide ore has on the average the following composition:—

Gold...	0·06 oz. per ton.
Silver	20·00 ,, ,,
Lead	20·00 per cent.
Zinc	14·5 ,, ,,
Iron	13·0 ,, ,,

The approximate proportion of the sulphide minerals is:—

Pyrite	27 per cent.
Galena	23 ,, ,,
Zinc-blende...	22 ,, ,,

There is thus 75 per cent. sulphide and 25 per cent. gangue.

The ore-bearing solutions originated from a differentiating magma vertically below, which was genetically connected with the laccolitic stocks of diorite porphyry intruding the sedimentary rocks of the district. The solutions ascended fault-planes, depositing part of their mineral contents in the fissures, and in addition spread along bedding-planes and joint-planes in the limestone, replacing the latter and forming replacement ore-bodies.

The lode deposits continue to the greatest depths attained, namely, 2000 feet. They have been worked over lengths along the strike of 4000 to 5000 feet in several mines. The widths vary from 1 or 2 feet (generally in the porphyry) to as much as 100 feet. A width of 30 feet is quite usual.

The bedded deposits have been mined to a depth of 900 feet. They vary in thickness from 1 foot to 6 feet, or even 9 or 10 feet. The length along the strike varies from 500 to 800 feet, with a maximum of 200 feet along the dip.

There are two belts of ore-deposits, the northern and southern, each with a length of about 5 miles. The total length of mine workings on these belts is about 10 miles.

Since the year 1877 the field has yielded about 112,000,000 oz. of silver, 400,000 tons of lead, and 35,000 tons of zinc. The output of crude ore in a year averages about 240,000 tons. Part of this crude ore is smelted direct, being separated from the milling ore during mining operations. In 1904 one-third of the entire output was smelting ore, but this proportion has steadily decreased, until at the present time nearly the whole output is milling ore. The milling ore has the following average composition:—

Gold	0·03 oz. per ton
Silver	9·00 ,, ,,
Lead...	6 to 8 per cent.
Zinc	6 to 8 ,, ,,
Copper	0·3 ,, ,,
Iron	6 to 10 ,, ,,

The mills are modern hydraulic specific gravity concentration plants. The aim is to produce a lead concentrate as free as possible from zinc; the zinc blende and pyrite, along with whatever chalcopyrite there is in the ore, being obtained as the middling product. This latter is sometimes roasted to convert the pyrite into a magnetic product, and the zinc contents then brought up to over 50 per cent. by treatment in magnetic separators. There is, however, considerable intergrowth of the zinc-blende and galena, and fine grinding is necessary to completely free them. It has been found impossible to obtain a clean concentrate in either direction by water concentration, there being always a serious loss of zinc in the lead concentrates, as well as a considerable loss of lead in the zinc concentrates. The application of the flotation process to the treatment of the slimes has initiated a new principle of treatment, for the present tendency is towards an increased use of flotation. This, in conjunction with the electrolytic treatment of the resulting zinc concentrate, is about to revolutionise the milling methods of the district.

(*b*) *Leadville, Colorado.*—This district is situated in the Mosquito Range in the State of Colorado, at an elevation of 10,000 feet above sea-level. It is one of the most productive districts in the western United States.

The ore-deposits are found mainly in the blue Leadville limestone as replacement deposits, at or near the contact with the overlying white porphyry, which occurs as an intruded sheet. The upper surface of the ore is often remarkably regular and sharp, being formed by the porphyry contact, while the lower surface is irregular. This is the normal occurrence, but ore-bodies are also found as replacements in the limestone along fissures or fault-planes, or in fissure-veins extending below the sedimentary beds. The latter are only developed in one particular area. The main ore-bodies thus constitute sheets which sometimes make up the entire thickness of the Leadville limestone. They are unusual, in that the sulphide replacement is so complete, and that the contacts with the limestone and porphyry are so sharp. In the Iron Hill area they follow north-eastward trending zones parallel with crosscutting sheets of grey porphyry. At the famous Tryer Hill, detached masses of limestone, enclosed within the porphyry, have been completely replaced by ore.

The usual ore is a massive granular mixture of sulphides, pyrite and zinc blende being more plentiful than galena and chalcopyrite; antimony, arsenic, and bismuth are present in very small amount. Silver and gold are present in appreciable amounts. The gangue is very scanty, and consists of quartz, jasperoid, and barite. The upper portion of the ore-bodies is almost completely oxidised, and consists of the carbonates of lead and zinc with silver chloride, in a gangue of calcite, barite, limonite, &c.

There has been much discussion as to the origin of the ore-bearing solutions which gave rise to the Leadville ore-bodies. Recent observations, however, leave very little doubt but that they were ascending solutions, and were derived from the differentiating magma beneath, and that the ore-bodies resulted from the replacement of the limestone where the solutions were dammed back beneath the porphyry sheets and along fault-planes and fissures in the limestone. Wherever the stagnation of the solutions occurred, there replacement would take place, and ore-bodies have resulted.

Mining has been carried to a total depth of 1500 feet. The field has been producing since 1875. The present annual output is about 470,000 tons of crude ore, which yields 100,000 oz. gold, 2,400,000 oz. silver, 800 tons of copper, 10,000 tons of lead, and 36,000 tons of zinc. This consists of iron-manganese silver-bearing ores, and oxidised zinc and lead ores, as well as the heavy sulphide ore, which is in part smelted directly and in part concentrated. The oxidised (carbonate) zinc ore contains about 32 per cent. zinc. The zinc sulphide ore sent direct to zinc smelters assays roughly 30 per cent. zinc; that sent to lead smelters containing about 9 per cent. lead. The milling zinc-lead sulphide contains approximately:—

Gold	0·200 oz. per ton
Silver	2 to 9 ,, ,,
Lead	4 to 10 per cent.
Zinc	14 to 28 ,, ,,
Copper	0·5 to 1 ,, ,,
Iron	20 to 25 ,, ,,

The following figures will give some idea of the sizes of these Leadville ore-bodies:—

	Max. Length.	Max. Width.	Max. Thickness.
	Feet.	Feet.	Feet.
Henriette-Wolftone Shoot (oxides and sulphides)	3500	1600	200
Moyer Main Shoot (sulphides)	2340	1300	150
Greenback Shoot..................	350	500	300

The composition of the high-grade mixed sulphide ore, with considerable lead contents, as it occurs in the ore-bodies, is indicated by the following figures:—

Gold	0·2 oz. per ton
Silver	10·0 ,, ,,
Lead	10·0 per cent.
Zinc	25·0 ,, ,,
Copper	0·5 ,, ,,
Iron	22·0 ,, ,,
Sulphur	39·0 ,, ,,
Silica	4·0 ,, ,,

The zinc-lead sulphide ore was, in the early days, worked by crushing and jigging with the production of marketable lead ore and zinciferous tailings, which were dumped. There was never much profit, however, from these operations. By the improvements in gravity separation brought about by specially constructed mills, a more or less clean galena and pyrite concentrate was obtained, and a by-product with about 45 per cent. of zinc, 12 per cent. of iron, and 6 per cent. lead produced, which was saleable to zinc smelters at a low price (27s. per ton). This method was profitable for at time. By the introduction of the electro-magnetic separation process another advance in treatment was made, which enabled cleaner zinc concentrates to be obtained, assaying up to 50 per cent. zinc, 10 per cent. iron, and 1 per cent. lead. There was always, however, a considerable loss of zinc and lead in the concentrates sold owing to the intimate association of the blende and galena in the zinc-lead sulphide ore. The introduction of the flotation process to the the treatment of slimes. and the differential flotation of the various minerals has revolutionised the metallurgical treatment. These methods, in conjunction with the hydro-metallurgical and electro-metallurgical processes to be discussed in a later chapter of this bulletin, are destined to give a renewed era of activity to these important deposits.

3. *Occurrence in Europe.*

Rammelsberg, Germany.—The famous Rammelsberg deposit lies on the northern slope of the Harz mountains, in Germany, near the towns of Oker and Goslar. It has been worked since the 10th century.

The deposit is enclosed, apparently conformably, in Devonian rocks, which at Goslar appear as an overturned anticline, and dip towards the north. It lies in the Goslar slates, which are overlain by a thick series of Lower Devonian sandstone. The particular bed which is the receptacle of the ores is an impure limestone. The slates and impure limestones have suffered considerable deformation, and the ore-body apparently follows their contortions more or less closely, although in places it actually cuts across the cleavage planes. The dip of the ore-body is to the south-east at an angle of 45°. Traced along the direction of the dip the latter is seen to vary, flattening considerably, and then resuming its former angle. In certain localities it bifurcates into two legs, of which one is merely a limited off-shoot, while the other is the main ore-body continuing on the average angle of dip. On the foot-wall side of the ore-body, and from 6 to 10 feet from it, is a pronounced fault-plane, 18 inches in thickness. It follows the deposit both in strike and dip.

Traced along the strike the ore-body is found to be divided into two parts, known as the "old bed" and the "new bed" respectively, connected by a narrow seam which is contorted to a S shape. This shows beyond doubt that the two are really parts of the one deposit or ore-bed. The "new bed" does not outcrop at the surface.

The separation between the ore-body and the country-rock is generally very sharp, there being generally a selvage or clay parting.

The ore is distinctly banded, the banding everywhere following with great faithfulness the outlines of the sulphide mass, whether this is smooth or irregular. Where the ore-body cuts across the slaty cleavage, as explained above, the banding continues parallel to the walls of the ore-body, and not to the cleavage of the slates.

The principal minerals are zinc-blende, chalcopyrite, galena, pyrite, and arsenopyrite, which are abundant in approximately the order enumerated. Small amounts of antimony and bismuth are also present, as well as silver, which is generally carried by the galena; gold also occurs to a small extent. The gangue is almost entirely barite, but it rarely occurs in large quantities, and often is entirely inconspicuous. Veinlets of calcite are present in the surrounding slate, but rarely contain ore. The limits of the ore-body are sharply-defined, and the ores are composed predominantly of sulphides. The banding is due to the existence of distinct layers of different mineralogic composition. The following types of ores are recognised by the miners:—

(1) Pyritic ore: lead ore with a preponderating amount of pyrite.
(2) Mixed ore: lead ore with chalcopyrite and pyrite.
(3) Grey ore: lead ore with a preponderating amount of barite.
(4) Brown ore: lead ore with a preponderating amount of zinc-blende.
(5) Copper ore: chalcopyrite with preponderating pyrite and arsenopyrite.

The composition of these various types is indicated in the following table:—

	Gold Per Ton.	Silver Per Ton.	Lead.	Zinc.	Copper.	Iron.	Sulphur
	Oz.	Oz.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Pyritic Ore	0·05	2·0	2·10	4·5	2·24	35·94	38·72
Mixed Ore......	0·05	5·0	10·69	20·25	4·45	13·65	24·44
Grey Ore	—	0·5	15·30	2·16	0·51	4·87	16·91
Brown Ore ..	0·02	2·1	11·94	18·00	0·65	16·24	30·32
Copper Ore ...	0·05	2·1	2·31	4·50	10·10	33·35	38·39

The mineralogical composition of the average zinc-lead sulphide ore is as follows:—

Zinc-blende...	36·0 per cent.
Pyrite	24·0 ,, ,,
Barite	16·0 ,, ,,
Galena	14·0 ,, ,,
Chalcopyrite	1·5 ,, ,,
Silicate of alumina, &c. (various gangues) ...	8·5 ,, ,,

The different varieties of ore are nowhere sharply separated, but merge gradually into one another. They all consist of the same metalliferous minerals, and only exist by reason of the varied proportions in which these minerals occur.

A particular type of ore may change to another type by decrease in one mineral and accompanying increase in another, both along the strike and along the dip.

The texture of the ore varies with the locality, but it is characterised invariably by the very fine-grained intimate intergrowth of the constituent minerals. The most common texture is that of the so-called Melir-Erze, which are intimately banded, in most cases consisting of dominant zinc-blende with narrow and gently-curved streaks of chalcopyrite and galena. In places the ore contains rounded nodules, generally of pyrite, around which the fine-grained streaks of zinc-blende and chalcopyrite bend in regular curves.

The origin of this deposit has been much discussed. The ore-bearing solutions in all probability were derived from the granite batholith, 2½ miles distant. These solutions replaced the calcite of the limestone bed, forming a typical replacement deposit, but the structure of the ore has been profoundly changed by dynamo-metamorphism. While the surrounding slates are soft, they evidently behaved quite differently from the sulphide mass, which seems to have flowed almost like a mush between the slate walls.

The underground workings on this deposit extend over a horizontal distance of 6500 feet (4000 feet being in the "old bed," and 2500 feet in the "new bed"), and have attained a vertical depth of 1200 feet. The thickness of the ore-body varies considerably, being in most cases not over 6 to 10 feet, and often only 2 to 3 feet. Occasionally, however, owing to folding and local enlargement, it is as much as 100 feet in thickness.

The district has been producing for over 1000 years, and the present annual output is about 25,000 tons of mixed sulphides.

The metallurgical treatment is difficult, owing to the very intimate intergrowth of the component minerals. Advantage, however, is taken during mining operations of the occurrence of the several varieties of ore in bands, as described above, to effect some initial separation. Thus, a copper ore, which is sent to copper smelters, is obtained, and also a lead ore, which is sent straight to the lead smelters. The remaining ore is treated by roasting and lixiviation to eliminate some of the zinc as sulphate, the residue being then sent to the lead smelter. There inevitably accumulates a large percentage of zinc in the slag, and it was to recover this zinc that the well-known Oker process was invented which has been successfully applied to these slags for a number of years. It is not known whether the flotation process has been applied to these ores or whether the hydro-metallurgical and electrolytic methods have wholly replaced the smelting processes.

4. *Occurrence in Asia.*

Bawdwin, Upper Burma.—The Bawdwin mines are located in the Northern Shan States, Burma, about 80 miles south of the Chinese frontier. They were worked by the Chinese for silver and lead until their capture by the Burmese in 1868—a period estimated at, roughly, 1000 years. Their modern history starts from 1902, but development on any scale only dates from the year 1914.

The ore-bodies are confined within a well-marked zone or ore-channel, which is a brecciated fault-zone in rhyolitic tuff, near the junction of the latter and rhyolite. The ore-channel is overlain by gently-dipping sandstones and shales, which carry flat floors of ore in their lower members, but which are unimportant as sources of ore as compared with the main ore-channel. The ore-channel is probably 400 to 500 feet wide, and within this width there have been located the following occurrences:—

(1) Western lode, or Burman lode, and the Chinaman ore-body. The former is a thin regular vein of lead-silver-zinc ore, while the latter is an enormous replacement deposit of zinc-lead-silver ore.

(2) Central lode or Shan Palaung, which is parallel and similar to the Burman lode.

(3) Eastern lode, similar in character to the Shan Palaung and Burman lodes.

The inter-relations of these three ore-occurrences are as yet undetermined, but they are undoubtedly parts of the same system. The Chinaman ore-body is by far the largest and most important. It is a replacement deposit which occurs on the hanging-wall side of the ore-channel. It dips to the westward at an angle of from 70° to 80°. The hanging-wall is more or less regular, but the footwall is ill-defined, and there is a gradual passage from the solid mixed sulphide through a second-grade ore composed of dark-grey tuffs infiltrated with silica and containing nests and strings of sulphides, in which the metallic sulphides become poorer until unaltered rhyolite tuff, and in some cases true rhyolite, is found. The ore-channel itself is a nearly vertical zone of combined faulting and shearing, and although the ore-body is largely a replacement deposit, yet certain parts of it are probably the result of the filling of open-fault fissures.

The ore is a solid mixed sulphide of varying composition, but there is a perfect gradation from one type to another, just as there is at the footwall a gradual gradation to unreplaced country-rock. In places, however, the zinc-blende tends to segregate in small patches or strips or in well-defined bands, forming a typical ribbon or banded ore.

The essential constituents of the Bawdwin ores are galena and zinc-blende intimately intergrown, and of a fine to medium grain. Pyrite and chalcopyrite are sparingly distributed throughout the zinc-lead ore, the latter being for the most part exceptional in the great mass of the ore, though there is sometimes a concentration of this mineral on the hanging-wall side of the ore-body. Silver is always present where galena occurs, and is wholly carried by that mineral. Gold is practically absent. The gangue consists of the metamorphosed country-rock, in the form of kaolin and sericite and quartz, and is negligible in the high-grade ore, but becomes predominant in the lower grades of ore representing partially-replaced rhyolitic tuff.

The following types of ore have been arbitrarily determined, the classification being based wholly on assay values, there being a perfect gradation between the various types, but they are of sufficient size to be easily mined separately:—

Class of Ore.	Silver Per Ton.	Type Assay Lead.	Zinc.	Copper.
	Oz.	Per cent	Per cent.	Per cent.
Zinc-silver-lead Ore	24	26	30	trace
Lead-silver-zinc Ore.........	17	24	14	trace
Silver-lead-zinc Ore	40	30	26	trace
Copper silver Ore............	8	—	—	15

An average assay of the crude high-grade sulphide ore would be as follows:—

Silver	19·2 oz. per ton
Lead	24 per cent.
Zinc	20·7 per cent.

The upper portions of the ore-bodies are to some extent oxidised, and it was in these deposits of carbonates of lead, zinc, and copper, with silver chloride, that the Chinese carried on a large part of their mining operations.

The ore-bearing solutions were ascending solutions, probably derived from the granitic magma, which is represented by granite outcropping 5 miles away. They rose along the shattered fault zone and replaced the rhyolitic tuff, the altered felspars being first replaced, and then the groundmass. All gradations can be found, from solid sulphide ore through material composed of sulphide and residual quartz to tuff containing irregular veinlets, nests, and finely disseminated patches or crystals of galena, then to tuff, with the outlines of the felspar crystals bordered with galena, and finally to completely unaltered rock.

The ore-channel has been traced for at least 8000 feet, and is from 400 to 500 feet wide. Development work has been confined to the northern 4000 feet. The size of the Chinaman ore-body has not yet been fully exposed, but exploratory work at the Dead Chinaman tunnel level has shown a length of at least 1250 feet, with a width of high-grade ore varying from 70 to 170 feet. Exploratory work had continued, at the end of 1915, to a depth of 446 feet below the Dead Chinaman Tunnel (which was the lowest level penetrated by the old Chinese workings.

The Burman lode, ovr a length of 190 feet, showed an average width of 31 inches of high-grade ore.

The Shan lode, over a length of 150 feet, had an average width of 23 feet of high-grade ore.

In the latest report of the Burma Corporation the ore reserves are put down at 4,300,000 tons, with an average assay value of—

Silver	24 oz. per ton
Lead	26·8 per cent.
Zinc	18·7 ,,
Copper	Trace

The extremely intimate intergrowth of the component minerals makes the metallurgical problem a difficult one. The Chinese picked out rich oxidised ores, or the portions of the sulphide ore richest in galena and silver, and smelted them by their crude smelting methods, leaving huge slag dumps, which have been resmelted by the present corporation while they have been opening up the ore-deposits and investigating the metallurgical treatment of the sulphide ores. The mixture is too intimate for specific gravity concentration to be effective. Differential flotation, however, has solved the problem, and a mill with a daily capacity of 700 tons has been erected, designed to produce lead concentrates and zinc concentrates, which will be subsequently smelted. The present mill will be ultimately enlarged to a capacity of 3000 tons a day.

D.—ZINC-LEAD SULPHIDE DEPOSITS FORMED UNDER HIGH PRESSURE AND AT TEMPERATURES BETWEEN 300° C. AND 500° C. IN GENETIC CONNECTION WITH INTRUSIVE IGNEOUS ROCKS.

1. *Occurrence in Australia.*

Broken Hill, New South Wales.—The famous Broken Hill lode is situated in a low range of hills (the Barrier Ranges), near the western border of New South Wales. It has been worked since 1884—first for silver, then for silver and lead, and at present for lead, silver, and zinc.

The ore-body occurs in a greatly metamorposed series of sediments and igneous rocks of Pre-Cambrian age, now represented by gneiss, quartzitic and micaceous schists, and quartzites. They are intensely foliated, but the exact relation of this foliation to the original bedding has not been completely investigated. The gneiss contains a considerable amount of garnet and sillimanite, and is known as garnet-sillimanite gneiss. This garnet seems to be a distinct species from that occurring in the ore-body itself. Within these metamorphosed rocks occur pegmatites and amphibolites. The pegmatites are important. They occur in two distinct forms, dykes and segregations, in the gneiss. Some writers on the field have failed to realise this distinction, and have reported pegmatite dykes or parts of dykes adjoining the ore-body. What they have really seen, however, are the segregations of pegmatite in the gneiss, which have been formed during the process of metamorphism.

The ore-deposit consists of a tabular lode, with enormous, more or less saddle-like ore-bodies springing from it, chiefly into the hanging-wall. However in the central portion of the ore-body (Blocks 12, 13, and 14) it may be rather described as a saddle-like deposit with a prolongation of a tabular ore-body extending upwards from its apex.

The tabular ore-body is continuous, but is sometimes poor and sometimes narrowed, and is almost invariably on the footwall side of the ore zone. It becomes appreciably thicker in the South Blocks Mine, where it is worked as the ore-body of that mine.

The large ore-bodies of Broken Hill are, however, as stated above, enormous bulges springing from this persistent tabular body.

They are, approximately, saddle-shaped in section, with anticlinals of crystalline rocks above and below, but are characterised by great irregularity and departures from this general shape. The main locus of deposition in these bulges takes an arch-shape in the direction of the strike of the ore zone, the crown of the arch being situated on the Proprietary Mine. Both to the north and south of this mine the point on the tabular body from which the saddle-like bulging ore-body springs becomes deeper and deeper as distance from the Proprietary increases. The main ore-bodies at Broken Hill therefore have a north-easterly pitch to the northward, and a south-westerly pitch to the southward, of the Proprietary Mine. Recent investigations seem to show that the northerly pitch changes further northward to a southerly pitch, but this requires further research. The latest developments show that there are more than one saddle-like bulge, the new ones being discovered below the one already known. In one place at least a distinctly synclinal bulge or reversed saddle also occurs.

The main outlines of these saddle-shaped ore-bodies as a general rule follow conformably the folded features of the enclosing rocks. In places, however, the wall of the ore-body is at various angles up to a right angle to the foliation.

Where the wall is finely foliated, the ore butts abruptly on to the schist, the boundary between ore and schist being extremely sharp, lying along a foliated plane. Where, however, the wall-rock is quartzite or rudely foliated quartz schist, the sulphide merges gradually into unmineralised rock by a gradual diminution of the amount of sulphide present.

There are many faults in and in the vicinity of the ore-body, but the most important is that known as the "lode fault," which is practically everywhere parallel to both strike and dip of the foliation and of the tabular ore-body. It is on the footwall side of the ore-body in the upper levels, being separated from the ore by a few inches to a few feet of barren material—either secondary quartz or much-cleaved schist—while in the deeper levels, owing to the effect of a transverse fault, it lies in many places on the hanging-wall side of the ore-body. The fracture itself is filled with pug or flucan, and is devoid of sulphide minerals.

The ore-bodies show no signs of banding, the sulphides forming a massive granular deposit of a fairly uniform quality, with the gangue locally and sporadically assuming the ascendancy and constituting large masses, with some disseminated sulphides. A notable feature is the occurrence of flat "heads" or joint-planes within the ore-bodies. These are nearly horizontal, and are markedly persistent, being used in mining as the roof of the "flat-backed stopes." Their origin has not been investigated.

The mineralogical composition is of two distinct types, the distinction being based on the character of the gangue minerals, and not on that of the metalliferous components, which are identical in both, viz., galena, zinc-blende, pyrrhotite, with occasional patches of arsenopyrite and chalcopyrite and pyrite. With these minerals as the metalliferous components, the ore-bodies are classed as (1) silicate-gangue ore-bodies; or (2) carbonate-gangue ore-bodies—according as the gangue minerals consist predominantly of silicates, such as garnet, rhodonite, &c., or carbonates, such as calcite. The silicate-gangue ore-bodies constitute by far the greater part of the ore-deposits, while the carbonate-gangue ore-bodies occur at the two extremities of the ore zone as at present visible, namely, in the North Mine and the South and South Blocks Mines. The ore-bodies in the North and South mines are, however, not confined to the carbonate-gangue type, as the silicate gangue type is also present. The exact relationship between the two has not yet been fully investigated, either structurally or genetically.

Galena occurs in coarsely crystalline masses and segregations, especially in the carbonate-gangue type, but the typical development is that of a granitic intergrowth with the zinc-blende.

Zinc-blende always contains much iron and manganese as impurities. It is black, and practically opaque, sometimes occurring in large crystal aggregates, but more commonly in close association with galena.

Quartz is practically always of an opalescent bluish-grey colour, and transparent. It occurs as blebs scattered through the massive ore.

Garnet occurs as individual crystals scattered through the ore, and as a massive aggregate of small garnet crystals occurring in a loosely coherent condition within the ore-bodies, and known as "garnet sandstone." The garnets occurring in the country-rock and those constituting the "garnet sandstone" are of the iron-alumina type, while those occurring in the ore-body as large crystals are manganese-alumina garnets.

Rhodonite, a manganese silicate, occurs as crystalline aggregates, either red or flesh-pink in colour, and occasionally as large reddish-brown crystals, which are often much corroded by sulphides.

Fluorite occurs as rounded or irregular blebs up to 3 or 4 inches in diameter, and also as irregular stringers.

Calcite and mixed carbonates of manganese, copper, and iron occur occasionally in the silicate gangue ore-bodies.

Pyrrhotite occurs as blebs and larger masses in the ore-bodies, and is sometimes intergrown with the other sulphides. Chalcopyrite and arsenopyrite also occur as blebs quite sporadically distributed throughout the ore-mass.

Silver occurs associated with the galena and with the zinc-blende. Gold is present, but in a quite inappreciable amount, and no estimate of the gold contents of the concentrates is usually made.

Arsenic and antimony are present, as well as cadmium, cobalt, and nickel.

A great range in the ratio of sulphide to gangue exists in various portions of the ore-body. Generally, it may be stated that the silicate-gangue ore-bodies are richer in zinc and silver than the carbonate-gangue ore-bodies, which, however, are richer in lead than the former type. The general character of the composition of the zinc-lead sulphide ore of Broken Hill is indicated by the following figures, which do not, however, represent the average composition of the Broken Hill ore-bodies:—

Character of Ore.	Silver Per Ton.	Lead.	Zinc.	Copper.	Iron.	Sulphur.	Silica.	Manganese Oxide.	Lime.	Alumina.
	Oz.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Silicate-gangue Ore, Central Mine..........	13·2	18·2	19·6	trace	4·2	15·3	33·4	3·0	4·7	1·7
Carbonate-gangue Ore, South Mine	3·8	19·5	11·0	trace	3·5	10·0	31·0	2·7	12·4	2·6

The average grade of the zinc-lead sulphide is indicated by the following figures, which represent the average value of 500,000 tons of zinc-lead sulphide, as mined in the second half of 1908, from the principal mines along the Broken Hill lode:—

Mine.	Tons.	Type of Ore.	Silver Per Ton	Lead.	Zinc.
			Oz.	Per cent.	Per cent.
South Blocks (1 year) ...	89,000	Carbonate gangue	2·7	16·6	10·0
South	112,288	Silicate gangue and carbonate gangue	5·6	16·2	12·1
Central.................... ..	92,945	Silicate gangue	13·3	16·6	18·3
Block 10	76,085	Silicate gangue	13·9	14·3	18·5
Junction North	62,126	Silicate gangue	9·8	14·4	9·0
North	67,530	Silicate gangue and carbonate gangue	7·0	16·3	13·8

These figures give an average of :—

Silver	8·3 oz. per ton
Lead	15·5 per cent.
Zinc	13·4 ,,

The average zinc-lead sulphide of Broken Hill may be stated to consist of approximately 45 per cent. of sulphides and 55 per cent. of gangue.

The texture of the ore is even-granular, the grain size being, approximately, one-tenth of an inch in diameter on the average. Within the ore-bodies all gradations exist from solid sulphides with a small amount of gangue minerals, to huge masses of gangue consisting of garnet, sandstone, quartz, and rhodonite, or calcite and quartz, with disseminated sulphides, which always, however, carry a minimum of from 2 to 3 per cent. of lead and zinc. The masses, consisting of fine-grained rhodonite, quartz, and sulphides in granitic intergrowth, present to the millman a very tough ore for crushing, but there is always a complete freeing of the coustitutent minerals from each other after moderately fine crushing. There is apparently no definite law regulating the distribution of the various grades of ore. which occur sporadically throughout the ore-bodies.

The origin of the Broken Hill lode has been much discussed, but the absence of a systematic survey and study of the geology and ore-deposits of the district has made any final solution of the problem impossible. However, such a systematic investigation is now being undertaken, and therefore the problem may be fully expected to be shortly solved.

It is certain, however, that the ore-bearing solutions were ascending, and of magmatic origin. The deposition of the minerals from such solutions took place at considerable depth, and at a temperature much higher than that at which the zinc-lead sulphide deposits of the type last described were formed. This is proved by the occurrence of the iron sulphide as pyrrhotite, which is purely a high-temperature mineral, and garnet and rhodonite, which also are never found in the lower temperature deposits. The temperature of formation, therefore, was somewhere between 300° and 500° C. It seems highly improbable that the ore-bodies were deposited in cavities. It seems very probable that the lode-fault was the main path for the upward passage of the ore-bearing solutions, from which they spread into the surrounding country-rock, and by metasomatic replacement thereof formed the present ore-bodies. The factors determining the location and mineralogical type of the ore-bodies are as yet unknown. It has been suggested that calcareous beds existed where the ore-bodies are now, and that these were metasomatically displaced by the ore-bearing solutions; but there is no definite evidence as yet indicated of the existence of these calcareous beds, and it must be remembered that at the high temperature of formation (300° C. to 500° C.) rocks could be replaced by zinc-lead sulphides, which would be unaffected at the temperature of formation of the type of zinc-lead sulphide, which, as described previously in this bulletin, have been formed at from 150° C. to 300° C., and most probably at about 200° C.

The Broken Hill lode is worked at present for a length of 3 miles, there being 10 mines distributed along this total length. The depths of the shafts vary from over 800 feet to 1800 feet. The length of the ore-bodies varies from 500 feet to 6000 feet, and the width from 1 foot to 425 feet. The largest ore-body, as shown at any one level, is that at the South, Central, and Proprietary Mines, at the 600-feet level, which is 6000 feet in length by an average of 90 feet in width. The average width if the ore-body was continuous over the whole length of 3 miles down to the average depth mined (1000 feet) would be, approximately, 20 feet. The size of the lode at various points is indicated by the following figures:—

Name of Ore-body.	Length.	Maximum Width.	Average Width.	Proved Vertical Extent.
	Feet.	Feet.	Feet.	Feet.
South Blocks	1000	150	10	1450
South	2400	400	90	1400
Central	1100	425	100	1400
Block 10	1000	300	90	1800
Proprietary	2500	250	50	1500
North	2000	150	100	1400

The Broken Hill lode has been worked since 1884. Since that date up to the end of 1916 a total of 31,000,000 tons of ore have been raised, which have realised the sum of £91,000,000, of which, roughly, £19,000,000 have been paid in dividends. This output has included about

450,000 tons of oxidised ores, and, approximately, 4,000,000 tons of zinc concentrates. The annual output of crude ore averages about 1,500,000 tons, the maximum yield having been 1,744,000 tons in the year 1913.

The ore reserves at the end of 1916 were estimated to be considerably more than 12,000,000 tons of ore actually blocked out.

The history of the metallurgical treatment of the Broken Hill ores is a very interesting one, and one which reflects the greatest credit on Australian metallurgists. In the very early days of mining operations the oxidised lead and silver ores were smelted directly at Broken Hill, and also treated by amalgamation as well as by lixiviation with hyposulphite solutions. With the extension of mining operations into the sulphides, the treatment became more difficult, and concentrating mills were erected using hydraulic specific gravity concentration as the basic principle of treatment. The smelters were moved away from Broken Hill to Port Pirie and Cockle Creek to smelt the concentrates sent from the mines. It was found that with moderate grinding a clean galena concentrate could be produced from the partially-oxidised sulphide ores, which were friable, and relatively high in lead and silver and low in zinc. As the unaltered zinc-lead sulphide was penetrated by the workings, concentration became more difficult, but it was still found possible by grinding to separate the constituent mineral particles. The production of lead concentrates was accompanied by the unavoidable production of middlings or tailings high in zinc because of the closeness in the specific gravities of zinc-blende, garnet, and rhodonite. At the same time as these tailings in the form of sand were produced, owing to the relative softness of galena and the hardness of rhodonite and garnet, a preponderatingly large amount of slime was separated and dumped.

The general practice of milling, producing tailings and slimes as untreatable residues, was persisted in for some years. An attempt was made to sinter the slimes by heap roasting, and subsequently smelting the sintered product for lead at the lead smelters. This was partially successful, but the losses were very high, and the process was abandoned.

Then came the application of electro-magnetic separation to the treatment of the tailings, whereby the zinc blende was separated from the garnet and rhodonite, and combined with subsequent water-concentration, partially solved the tailings and middlings treatment problem.

The attempt to apply a chemical process to the treatment of the Broken Hill zinc-lead sulphide was made on a large scale at Cockle Creek, where the Ashcroft process of roasting succeeded by leaching with ferric chloride solutions, and the subsequent electrolytic precipitation of the zinc, was fully tried out. This will be more fully described in a subsequent chapter of this publication.(2)

The development of the flotation process, however, finally solved the problem of treatment of the tailings and middlings, and the further development of this process in the direction of differential flotation has finally solved the problem of the treatment of the slimes.

It is seen, therefore, that the physical character of the ore permits of the successful separation of the several mineral constitutents by purely mechanical processes.

The following figures will illustrate the grade and composition of the various concentrates from all milling and treatment operations:—

Product.	Silver Per Ton.	Lead.	Zinc.
	Oz.	Per cent.	Per cent.
Mill Concentrates	23·6	64·7	7·3
"Middlings"	8·6	6·0	21·4
Tailings	2·6	2·7	7·8
Slimes	17·2	17·9	20·9
Flotation Zinc Concentrate from Middlings and Tailings	16·0	8·7	46·3
Flotation Lead Concentrate from Slimes	84·0	63·0	8·0
Flotation Zinc Concentrate fron. Slimes	13·0	4·0	50·0

---

(2) See below, p. 81.

V.—COMPARISON BETWEEN THE READ-ROSEBERY DEPOSITS AND SIMILAR DEPOSITS IN OTHER PARTS OF THE WORLD.

Using the data presented in the two preceding chapters, it is now possible to compare and contrast the Read-Rosebery zinc-lead sulphide deposits with other important sources of zinc and lead, in order to see in what respects they are similar and in what dissimilar, and to ascertain how far the experience gained in development and treatment of these other deposits can be applied to the Tasmanian occurrences. Particularly the texture of the ore and the manner of aggregation and interrelations of the component minerals, as influencing the metallurgical treatment, can be discussed, and conclusions deduced as to the complexity or otherwise of the problem of the successful extraction of the metal values from the Read-Rosebery ores. At the same time also there will be developed a true perspective of the relative importance of the Read-Rosebery zinc-lead sulphide belt as compared with these other similar occurrences throughout the world.

In the first place, it is seen that the type of ore-deposit is distinct, on the one hand, from the very low-temperature deposits of Missouri and Wisconsin, in the United States, and Aachen and Upper Silesia, in Europe, and, on the other hand, from the high-temperature deposit of Broken Hill. The absence of marcasite and the presence of gold and silver differentiate the Read-Rosebery deposits from the former, and the absence of garnet and rhodonite and pyrrhotite from the latter, these being the minerals which are indicative of the temperature of formation. Actually, therefore, the temperature of deposition of the Read-Rosebery ore-bodies, with the iron sulphides wholly in the form of pyrite, was in the vicinity of 200° C., which is intermediate between that of, approximately, atmospheric temperatures of the Missouri and Wisconsin and Aachen and Upper Silesian deposits, and a temperature between 300° C. and 500° C., which characterised the formation of the Broken Hill lode.

Genetically, therefore, the Read-Rosebery zinc-lead sulphide deposits are most closely related to those of Park City, Utah; Leadville, Colorado; Rammelsberg, Germany; and Baldwin, Upper Burma; and more especially to the two former, in that they are identical in being metasomatic replacements of calcareous beds which have taken place at about 200 C°.

In regard to the structural features and general shape of the ore-bodies, their occurrence in lenticular or elliptical masses is shared by the ore-bodies at Broken Hill and at Park City, Utah, and to some extent by those of Leadville, Colorado; but the latter are, on the whole, much more irregular in outline than the Read-Rosebery lenses, a statement which is to some extent true also of the Park City occurrences. The big saddle-like offshoots of the Broke Hill lode resemble in general form some of the Read-Rosebery occurrences, and give elliptical-shaped outlines on the mine levels in a similar way to the "E" ore-body in the Hercules Mine. The northerly and southerly pitch of this saddle-like offshoot from the tabular ore-body at Broken Hill repeats to a limited extent the occurrence of domes in the Read-Rosebery District. It will be interesting to see whether future developments at Broken Hill will prove the extension of this dome into a series of undulations to the northwards and southwards similar to those at Read-Rosebery. The occurrences in the Read-Rosebery District where the ore-body as at present visible is purely tabular, resemble to some extent the tabular ore-bodies at Broken Hill, Rammelsberg, and Bawdwin, but lack the saddle-like offshoots of the two former deposits. The narrowing and bulging of the tabular ore-body at Rammelsberg is repeated in the tabular ore-body of the Rosebery Mine, as are also the sudden variations in strike from the normal figure for comparatively short distances. This latter variation is due to folding in both cases.

These remarks apply only to the horizontal dimensions, and when the vertical dimensions are considered, some of the similarities described above become less pronounced. The lenticular ore-bodies at Park City, for example, have a vertical measurement of only from 1 to 10 feet, and those of Leadville a maximum of 300 feet. The lenticular ore-bodies of Read-Rosebery have already been proved to have a vertical extent of 350 feet, so that their character in this respect more nearly resembles the Leadville occurrences, having, however, a somewhat greater vertical measurement. The saddle-like offshoots at Broken Hill have in general similar vertical dimensions to the Leadville deposits. It must be remembered, however, in comparing these lenticular or saddle-like offshoots from the more persistent tabular ore-body with the Read-Rosebery lenses.

that the latter are actually parts of and continuations of the same main ore-body in its folds and undulations, rather than offshoots. The portions of the Read-Rosebery ore-bodies which are tabular in form differ essentially from the tabular masses of Park City, Rammelsberg, Bawdwin, and Broken Hill, in that they have a limited downward extension, because of their tendency to turn up again eastwards towards the next anticlinal fold. Their greatest proved vertical extent is 500 feet at the Rosebery Mine (which may, however, subsequently be proved to be exceeded), whereas they reach 2000 feet at Park City, 1200 feet at Rammelsberg, 700 feet at Bawdwin, and 1800 feet at Broken Hill. The proved length of the tabular ore-body at the Rosebery mines is at least 2000 feet, and more probably 3200 feet, which is a dimension of, roughly, the same order as the 4000 feet at Park City, 2500 feet and 4000 feet at Rammelsberg, and 1250 feet at Bawdwin, but is somewhat lower than the 4500 feet and 6000 feet at Broken Hill.

The occurrence of the ore-deposits in "runs," "openings," and "circles," and as "sheet-ground" deposits in the Joplin District, Missouri, and as "flats and pitches" in the Wisconsin area, is so completely different from the mode of occurrence of the Read-Rosebery deposits that it is quite objectless to compare them, for although the horizontal dimensions are of the same general order, yet the vertical extent is very limited, being at a maximum of 150 feet, but more frequently from 1 to 50 feet, which approximates the vertical dimensions of the Upper Silesian deposits, which sometimes reach 40 feet, but are more usually in the vicinity of 6 feet.

The thick and rounded stockworks of the Aachen deposits are not reproduced in any of the other zinc-lead sulphide deposits, their approximately equal horizontal dimensions (290 and 130 feet for example) with their vertical extent (800 feet as a maximum) being wholly characteristic.

In mineralogical composition the Read-Rosebery ores most nearly approach those of Leadville, Park City, and Rammelsberg. The zinc-lead sulphide of Leadville contains the same minerals in, approximately, the same proportions as the Read-Rosebery zinc-lead sulphide, the only difference being that barite is slightly more plentiful in the latter. They are both characterised by the small percentage of gangue, the sulphides constituting over 90 per cent. of the main mass of the ore, and averaging in the vicinity of 85 per cent. for the whole ore mined. They have both been formed by the metasomatic replacement of limestone with sulphides, which has been practically complete in both cases. The Rammelsberg ore carries distinctly more barite than the Read-Rosebery, the respective average percentages being 16 per cent. and 1·5 per cent.

There is relatively more zinc-blende and pyrite and less galena in the latter than in the former ores, but the percentage of copper is the same. The proportion of sulphide to gangue in the Rammelsberg ore is lower than at Read-Rosebery or Leadville, the sulphides constituting 75 per cent. of the ore, which corresponds to the proportion in the Park City ores, which further differ from the Read-Rosebery ores in containing in portions of the ore-bodies a small amount of rhodonite. There is, roughly, twice as much zinc-blende, and only half as much galena, but the same proportion of pyrite, in the Read-Rosebery as in the Park City ores. There is thus a general similarity between the mineralogical compositions of the zinc-lead sulphides of Read-Rosebery, Leadville, Park City, and Rammelsberg, the two former being practically identical.

As regards the proportions of the sulphide minerals, the Bawdwin ores most nearly approach those of Broken Hill, rather than the Read-Rosebery, and are further differentiated from the latter by the absence of barite and rhodochrosite. They are, however, quite distinct from the Broken Hill ores in total mineral composition, owing to the complete absence of Broken Hill's characteristic minerals, garnet and rhodonite. The Bawdwin deposits also differ genetically from those of Read-Rosebery in not being replacements of limestone, but of rhyolitic tuff. The Broken Hill zinc-lead sulphide carries far more gangue than that of the Read-Rosebery, the proportions of sulphide to gangue being respectively 45 per cent. : 55 per cent; and 85 per cent. : 15 per cent.

The group of zinc-lead sulphide deposits, with marcasite as the characteristic iron sulphide, in Missouri, Wisconsin, Aachen, and Upper Silesia invariably carry much higher percentages of zinc-blende than of galena. The American occurrences carry over 90 per cent. of gangue, but the European deposits only about 50 per cent., the percentages of zinc-blende and galena being 4·5 and 0·5 per cent. respectively in the former and 30 per cent. and 5 per cent. respectively in the latter. These figures, together with the absence of silver and gold, and the limitation of the gangue minerals to calcite and jasperoid quartz, mark them as distinct in mineralogical composition from the other type of zinc-lead sulphide deposits.

The Read-Rosebery deposits are unique in that they possess merely a shallow deposit of oxidised and carbonate ores, the sulphides persisting almost to the surface. In the other deposits there are extensive occurrences of oxide and carbonate of zinc and lead ores with high silver values.

Passing now to a consideration of the actual assay value or contents of saleable or extractable metals, it is found as would be expected from the similarity in mineralogical composition as shown above, that there is a greater resemblance between the Read-Rosebery and Leadville ores than any others, the respective metal values being practically the same in these two ores, except that the zinc is somewhat lower in the Leadville ores. The Park City ores only carry about one-half the gold and zinc, but about twice the silver and lead, contained in the Read-Rosebery ores. The Rammelsberg ores carry somewhat less zinc and slightly more lead and copper, but only one-third the gold and silver; the Bawdwin ores contain twice the silver and three times the lead, but only two-thirds of the zinc; while the Broken Hill ores carry twice the lead, but slightly less silver, and less than one-half the zinc, and a very small fraction of the gold, as compared with the Read-Rosebery ores. These figures are made plainer by the following table, which gives the metal contents of the average ore from the several occurrences, the content of the total sulphide minerals in the ore being added for the purpose of comparison:—

Name of Occurrence.	Total Sulphide Min erals in Ore.	Gold Per Ton.	Silver Per Ton.	Lead.	Zinc.	Copper
	Per cent.	Oz.	Oz.	Per cent.	Per cent	Per cent.
Read-Rosebery	85	0·127	9·6	7·3	27·3	0·5
Leadville, Colorado......	85	0·200	8·0	7·0	22·0	0·6
Park City, Utah	75	0·060	20·0	20·0	14·5	0·5
Rammelsberg, Germany	75	0·040	3·0	12·0	24·0	0·5
Bawdwin, Burma	65	trace	19·2	24·0	20·7	trace
Broken Hill, N.S.W. ...	45	trace	8·3	15·5	13·4	trace
Joplin, Missouri	4	—	—	0·5	2·1	—
Wisconsin	10	—	—	0·3	3·1	—
Aachen, Germany	55	—	—	4·3	20·1	—
Upper Silesia, Germany	50	—	0·5	5·0	17·0	—

The distinctive character of the last four occurrences is clearly seen in this table, and especially the very low grade of the average ore from Missouri and Wisconsin. By reference to the concluding portion of Chapter III., the metal contents of the ores of Missouri and Wisconsin will be seen to be lower than those of the large "low-grade disseminated deposits" of Read-Rosebery, which are not taken account of in the present estimation of ore reserves but which must eventually constitute important sources of ore, containing, as they do, the same amount of lead, and from two to three times the amount of zinc, as the Missouri and Wisconsin ores do, and, in addition, carrying 1½ oz. of silver and some gold per ton. These deposits are not included in the above table, as present attention is wholly confined to the typical and more important solid zinc-lead sulphide ore-bodies.

One feature, however, which these figures do not indicate is the very high zinc and gold contents of big masses of the Read-Rosebery ore-bodies: figures ranging from 46 to 55 per cent. zinc and 0·4 to 1·6 oz. of gold are obtained for considerable lengths of the ore-bodies. Such high zinc and gold values over appreciable portions of the ore-bodies seem to be peculiar to and characteristic of the Read-Rosebery zinc-lead sulphide belt.

The very important question of texture next comes up for comparative review. Texture on the larger scale includes banding. The banded structure of the Read-Rosebery ores is not unique, the deposits at Park City, Leadville, and Rammelsberg all possessing banding. In the two former, however, the banding is nearly horizontal, and is directly due to the replacement of the original sedimentary bedding in the limestones, being distinct from the highly-inclined banding, which represents the replacement of successive bands of varying composition developed in calcareous beds during metamorphism, and which is, in fact, parallel to the planes of schistosity of the enclosing schists. The banding at Rammelsberg is similar to that of the Read-Rosebery ores, being highly-inclined and parallel to the general schistosity of the country-rock, but differs from it in having been mainly developed in the ore subsequent to the formation of the ore-body. The massive texture of the ore-bodies at Bawdwin and Broken Hill is in marked contrast to distinct banding in these three occurrences.

The manner of association of the mineral constituents of the ore-bodies, and more especially the inter-relations and amount of intergrowth and fineness of grain of the sulphide minerals, are important from the metallurgical point of view, and serve as a most valuable and instructive basis of comparison of the various ore-deposits we are now discussing. The zinc-lead sulphide ores of Wisconsin and Missouri and of Aachen and Upper Silesia may again be regarded as a separate class to themselves, the sulphide minerals occurring in separate mineral aggregates, although intergrowth occurs to a limited extent. In the fissure-fillings of Park City also there is not much intergrowth of the sulphide minerals, but in all the replacement deposits of Read-Rosebery, Park City, Leadville, Rammelsberg, Bawdwin, and Broken Hill there is an intergrowth of varying intimacy of the sulphide minerals with each other and with the gangue. The degree of intimacy of this intergrowth varies considerably amongst the several deposits and within each deposit itself, but there is a general type or extent of intergrowth which is characteristic of each. At Broken Hill the minerals are intergrown, but the average grain size is in the vicinity of one-tenth inch diameter, and if the ore is crushed to pass a 60-mesh screen, there is practically a complete liberation of the mineral particles from each other.

The zinc-lead sulphide of Bawdwin is more intimately intergrown, the zinc-blende having a grain size of from $\frac{1}{2000}$ to $\frac{1}{200}$ inch in diameter, and the galena occurring as thin filaments through and around these grains. It is therefore necessary to crush this ore to pass a 100-mesh screen to obtain complete freeing of the constituent mineral particles, and in practice the grinding is carried to pass 150-mesh. A still greater intimacy of intergrowth is shown by the Read-Rosebery zinc-lead sulphide, which has a minimum grain size of $\frac{1}{2500}$ inch diameter. It is found in the case of these ores that crushing has to be carried to pass a 200-mesh screen, to make quite certain that there is a complete absence of particles consisting of two or more minerals. The Rammelsberg ore approaches more nearly to the Read-Rosebery than to the others in its degree of intimacy of intergrowth. In the general character of the intergrowth of the constituent minerals, the ores of Park City and Leadville most closely resemble those of Broken Hill, with the exception, however, that in certain portions of the ore-bodies there exists a more intimate admixture approaching in character that of the Bawdwin ores.

The Read-Rosebery ores, therefore, possess a finer texture and a more intimate intergrowth of the constituent minerals than any of the other zinc-lead sulphide deposits.

As regards the actual size of the ore-bodies in the various deposits, and the extent of the ore-belt or ore-bearing zone, the following table, which is taken from the information on these points contained in Chapers III. and IV., will enable comparisons to be easily made:—

Name of Deposit or Ore-body.	Length.	Width.	Depth.	Length or Area of Ore-belt.
	Feet.	Feet.	Feet.	
Read-Rosebery, Hercules	400	60	250	7 miles
Read-Rosebery, Hercules	300	50	400	
Read-Rosebery, Mt. Read	400	50	110	
Read-Rosebery, Rosebery	2000	25	500	
Park City, Lode Deposits	4000	10	2000	Two belts, each 5 miles long
Park City, Replacement Deposit	600	100	5	
Leadville, Moyer Main Shoot	2340	600	80	10 square miles
Leadville, Greenback Shoot	350	250	110	
Rammelsberg, Old Bed	4000	10	1200	6500 feet
Rammelsberg, New Bed	2500	10	1200	
Bawdwin, Chinaman Ore-body	1250	100	725	8000 feet
Broken Hill, North Mine	2000	80	1400	3 miles
Broken Hill, South Mine	2400	90	1400	
Broken Hill, Central Mine	1100	100	1400	
Broken Hill, Block 10	1000	90	1800	
Broken Hill, South Blocks	1000	10	1450	
Missouri, "Run"	1400	20	60	3100 square miles
Missouri, "Circle"	550 outer diam. of circle	200	150	
Missouri, "Sheet Ground"	2000	600	10	
Wisconsin, "Flats and Pitches"	1000	75	40	2500 square miles
Wisconsin, "Honeycomb"	300	25	30	

If these figures are considered in conjunction with those in the following table a more correct conception can be acquired of the relative extent and importance of the Read-Rosebery deposits. The table which follows gives the number of years the respective deposits have been worked, their total and annual outputs, and their ore reserves, where the figures are available:—

	No. of Years since First Worked.	Crude Ore.		Ore Reserves where Available.
		Total Output.	Annual Output.	
		Tons (approx.).	Tons (approx.).	Tons (approx.).
Read-Rosebery	28	296,000	·	1,680,000
Park City	42	2,000,000	240,000	—
Leadville	44	—	331,000	—
Rammelsberg	1000	-	25,000	—
Bawdwin	1000	—	245,000	4,300,000
Broken Hill...........	35	31,000,000	1,500,000	12,000,000
South-West Missouri .	69	220.000.000	8,275,000	—
Wisconsin	98	132,000,000	1.100,000	—
Altenberg (Aachen) ...	500	1,000,000	14.000	—
Upper Silesia	700	—	1,200,000	—

No annual output can be given for the Read-Rosebery mines, as they are not at present producing. The enormous tonnages in Missouri and Wisconsin are remarkable, but should be taken in conjunction with the figures previously given of the extremely low grade of the ore. The figures for the whole of the Aachen region are not available, those given referring only to the Altenberg group of mines. The total output from Leadville is probably about the same as that from Park City. The total outputs from Rammelsberg and Bawdwin are not available, but would probably be in the vicinity of 5,000,000 tons in each case. In the case of Rammelsberg, however, the deposits have been almost depleted of ore, and there are not many productive years in sight, but the Bawdwin deposits have entered on a new lease of life, and may only now be regarded as being properly developed and exploited.

The Broken Hill deposits have obviously been very actively developed and exploited, being in fact, an outstanding example in this respect. The position is much further improved by the existence of huge tonnages of probable ore, in addition to the actual ore reserves actually blocked out.

In view of the number of years that have elapsed since their first discovery, the Read-Rosebery deposits have had a very small production. Taking into consideration the size of the ore-bodies and the extent of the zinc-lead sulphide belt, the amount of ore reserves is surprisingly small. From the figures presented in the foregoing pages it would be a justifiable expectation that the output and ore reserves would approach the figures for Broken Hill. That this is not so is due to the following causes:—

(1) Absence of large quantities of oxidised ores;
(2) Metallurgical difficulties owing to the extremely intimate intergrowth of the constituent minerals; and
(3) The policy adopted by those responsible for the development of the field.

These will be more fully discussed in Chapter VIII.

VI.—THE METALLURGY OF THE ZINC-LEAD SULPHIDES.

A.—GENERAL REMARKS.

This chapter is not meant to be anything approaching a complete treatise on the treatment of the zinc-lead sulphide ores, but is designed to present to the mining and investing public a concise description of the general character of those processes which have been or are being used in the extraction of the metal values from zinc-lead sulphide deposits throughout the world, and to indicate to what extent they are applicable to the Read-Rosebery ores. These ores have been proved during the investigations brought to a close by the publication of this volume, to consist of an extremely intimate and very fine-grained mechanical admixture of zinc-blende, galena, pyrite, and some accessory sulphides, with small percentages of quartz, barite, and calcite as gangue minerals, and therefore it is possible for a treatment process to be based solely on the physical properties of these constituent minerals and need not be restricted to chemical processes.

The processes which utilise the purely physical properties of the component minerals will be first described under the heading of "mechanical processes." Then will follow the processes which make use of the chemical properties of the ore, those necessitating the application of high temperatures for smelting and fluxing being described under the heading of "direct smelting," while those utilising chemical solutions at ordinary temperatures, and which in many cases include electrolytic deposition of the metals, are dealt with under "hydro-metallurgical and electrolytic processes." Following this description of the general principles of the different types of processes, there will be presented a brief *résumé* of their application to the various zinc-lead sulphide deposits of the world dealt with in this volume.

This method of presentation will serve as the best manner of approach to the question as to the present position in regard to the treatment of the Read-Rosebery zinc-lead sulphides.

There will not be presented in this chapter a statement of the details of metallurgical experiments, as these are apt to be very misleading to the layman. The general results of such experiments and tests will be indicated, and the conclusions resulting therefrom clearly expressed.

B.—MECHANICAL PROCESSES.

1. *Specific Gravity Concentration.*

The form of concentration using the property of specific gravity as the basis which is used in treating zinc-lead sulphide ores is that known as "wet or water concentration," or "hydraulic concentration," in which a moving current of water is used. In these advantage is taken of the difference in the specific gravities of the metalliferous minerals and the gangue, sulphide minerals having specific gravities which are higher than those of most gangue minerals. The pulverised ore is allowed to fall with or through a moving current of water, which carries away the lighter gangue minerals, while the heavier sulphides, being less affected by the transporting or moving power of water, remain behind, and are collected by suitable means.

A great number of machines and appliances have been devised to make use of these principles, among which may be mentioned jigs, vanners, buddles, concentrating-tables (such as Wilfley and Card tables), blankets, riffles, cement tables, trommels, screens of various types, classifiers, pulp-thickeners, &c. With the evolution of the process great improvements were effected, and by the systematic and scientific adaptation of the details of treatment to the character of the ore, together with the advance made in sizing of the crushed material, and the separation of slimes, the application of the process was considerably extended. It thus became possible to separate minerals the specific gravities of which made a nearer approach to each other than was formerly considered permissible.

Such has been the general development of the process of wet concentration of lead and zinc ores. In the very early days of the application of the process to these ores, attention was almost wholly confined to those deposits or those portions of the ore-bodies which consisted predominantly of galena to the exclusion of zinc-blende, or zinc-blende to the exclusion of galena. In the former case the problem consisted in the separation of galena with a specific gravity of 7·5 from gangue minerals such as quartz or calcite with specific gravity 2·6, or chalybite with specific gravity 3·6, which was a straightforward proposition. In the latter case the problem was the separation of zinc-blende with specific gravity 4·0 from a gangue of quartz and calcite, which was relatively simple. In these operations, whatever zinc-blende occurred in the galena ore was either obtained in the lead concentrate or washed away with the gangue, and in a similar way the galena associated with the zinc ore was carried into the zinc concentrate. With the exhaustion of the supplies of unmixed ores, and the necessary incursion into the mixed galena and zinc-blende deposits, it became increasingly necessary to improve the methods whereby a separation could be obtained of the galena with specific gravity ranging from 7·2 to 7·7 from the blende with specific gravity of from 3·9 to 4·2.

The attempts to so improve the methods met with varying success in different fields. It was found that the texture of the ore was a most important factor. Where the mixed zinc-lead sulphide ore was coarsely granular, and relatively coarse crushing freed the component minerals, the improved methods could produce lead concentrates with a low zinc content and zinc concentrates with a low lead content, both of which were saleable and profitable products. At the same time there was produced a certain amount of "middlings" product, which carried lead and zinc values in approximately equal proportions (the actual proportion depending on the lead and zinc contents of the original ore), and which were stacked for future treatment, which ultimately was effected by means of the electromagnetic or flotation processes to be described in a subsequent part of this chapter. It was found also that it was impossible to obtain satisfactory separation in the slimes, which were dumped as waste, and the whole scheme of crushing and reduction in the concentrating mills was designed to minimise the production of slimes. The process accordingly became decreasingly successful as the grain-size of the minerals became less, and the finer grinding necessary for the freeing of the minerals produced a larger percentage of slimes. Obviously, therefore, the process was impossible of application where it was necessary to reduce the whole of the zinc-lead sulphide to slime to free the constituent minerals, as has been shown to be the case in the Bawdwin and Read-Rosebery ores.

With the application of the improved process to various ores, new difficulties were encountered, some of which were overcome, but others remained insuperable. The occurrence of pyrite, marcasite, and chalcopyrite, with specific gravities ranging from 4·1 to 5·2, made it impossible to secure a clean zinc concentrate, although the lead concentrate could be obtained practically free from the iron sulphides. It became necessary to submit the zinc concentrate carrying pyrites to a subsequent roasting and electro-magnetic separation (to be described subsequently in this chapter). Such are the conditions obtaining in the Joplin and Wisconsin Districts of the United States. The same treatment is necessary in the case of the occurrence of the mineral siderite as a component of the gangue, for its specific gravity of 3·4 to 3·9 drives it to a considerable extent into the zinc concentrate. The occurrence of the minerals garnet and rhodonite greatly complicates matters. These minerals occur at Broken Hill with specific gravities of 3·9 and 3·5 respectively, and make it impossible to produce a zinc concentrate. A lead concentrate is produced, together with a quartz tailing low in zinc values, and a "middlings" product, which contains most of the zinc and garnet and rhodonite. This is subsequently treated by flotation methods (to be subsequently described), with the production of a zinc concentrate.

On the whole this process has a wide application in the treatment of zinc-lead sulphide ores, constituting, as it does, an essential portion of the treatment at Wisconsin, Missouri, Broken Hill, Leadville, Park City, Aachen, and Upper Silesia.

2. *Electro-Magnetic Separation.*

With the failure of specific gravity concentration to effect a satisfactory separation of minerals having closely approximating specific gravities, attempts were made to utilise other physical properties as a basis for separation. Thus the magnetic properties of minerals were studied, and it was found that minerals could be classed in two groups, as—(1) magnetic, and (2) non-magnetic; and, further, that the magnetic minerals varied in their magnetic power or permeability, which could in many cases be increased by heating or roasting. Appliances and machines were then developed, making possible the application of magnetic fields of high intensity, resulting from the use of electro-magnets, to the separation of minerals of low magnetic permeability from non-magnetic minerals, and also the separation from each other of magnetic minerals with magnetic permeabilities closely approximating each other.

In the application of these principles to zinc-lead sulphide ores, it is found that galena is non-magnetic, as are also the gangue minerals quartz, calcite, and barite. Zinc-blende is generally non-magnetic; but occasionally, as at Broken Hill and certain parts of Colorado, it is feebly magnetic, and can be separated from non-magnetic material.

Pyrite and marcasite are either non-magnetic or feebly magnetic, but can be converted by a partial roast at a low temperature into highly magnetic material. The same applies to siderite. Garnet and rhodonite possess a magnetic permeability higher than that of the zinc-blende at Broken Hill.

It is possible, therefore, by electro-magnetic separation to separate zinc-blende from galena, pyrite, and quartz, as is done in Colorado; marcasite, pyrite, and siderite from the " zinc middlings " product from the wet concentration mills of Wisconsin and Missouri, leaving a high-grade zinc concentrate; and from the "middlings" product of Broken Hill mills two separate magnetic products—garnet and rhodonite constituting the first (or more highly magnetic) product, and zinc-blende the second (or slightly magnetic) product, leaving a non-magnetic residue containing galena and some blende, with quartz and calcite, which was quite amenable to wet concentration. The two former operations are still being carried out, but the application at Broken Hill has been abandoned for many years in favour of flotation.

It was found in this process (as in the case of wet concentration) that the process became less efficient with increased fineness of the ore, and totally impossible with slimes. The process, therefore, is impossible of application where the ore has to be reduced to slime in order to free the constituent minerals, as is necessary with the Read-Rosebery ores.

3. *Flotation.*

(*a*) *General Principles.*—The physical properties on which the process of flotation depend are not as clearly understood as those controlling the two types of processes already described. The process was discovered more or less by accident, and not by utilisation of a known physical property, and its earlier development was brought about by more or less blind trials and experiments. Gradually, however, there has been acquired a more complete understanding of the basic principles of the process, and research is now carried out on more scientific and systematic lines, although certain underlying principles and controlling factors still require further study and elucidation.

The basic principles of the process cannot be stated in terms of one single physical property, as in the case of water concentration and electro-magnetic separation. They involve principles of surface tension, adhesion, electrostatics, and colloid chemistry, the respective parts played by these being as yet not definitely determined.

In essence, the modern process consists of the production of a froth in a freely moving fluid, carrying finely-divided ore, whereby the sulphide minerals rise to the surface with the froth, and can be collected by suitable means, while the gangue minerals sink through the fluid and are carried away as tailings. The net result, therefore, is the opposite of that attained in wet concentration, where the heavier mineral sinks, and the lighter is carried away by the current of water.

The mechanical means adopted of obtaining this froth are various, but all consist of the aeration, by agitation or the direct blowing in of compressed air, of water, to which, in the greater number of processes, has been added a small quantity of eucalyptus or pine oil, or any other oil of the class to be described below as "foamers." The depth of this froth varies from 6 inches to 36 inches, but is generally from 6 to 15 inches.

In approaching the question as to why certain minerals rise up with the froth while other minerals do not, it is first necessary to examine this froth to see what it really is. The froth is, in fact, a collection of bubbles, which may be of any size, but in the actual working of the process vary from about 3 inches in diameter to $\frac{1}{8}$-inch in diameter, or less. Each bubble consists of air wholly or partially surrounded by a thin, tenuous surface of liquid. Where the bubble is not wholly enclosed by its own liquid envelope, it still retains its existence by the enclosing effect of the surfaces of neighbouring bubbles. Froth, therefore, consists of a very large water surface in contact with air. In fact, a normal water surface in contact with air, if replaced by a froth 6 inches deep, the constituent bubbles of which average $\frac{1}{4}$-inch in diameter, is thereby increased in area 750 per cent.

The next step is the consideration of the properties of a water surface in contact with air. This introduces the property of surface-tension into the discussion. The subject cannot be discussed in full in this publication, and it will suffice in this place to state that the surface-tension of water in contact with air is a force which, acting parallel to the mutual surface, and resulting from molecular activity within the water, tends to resist rupture of the surface. It is illustrated by the experiment of placing a clean, dry needle carefully on a surface of water. If the manipulation is skilful enough the needle will float, but if the smallest drop of water is placed upon the needle it will sink; in fact, any condition which will cause the needle to be "wetted" will destroy its floating properties. In the same way, also, the presence of a film of rust or tarnish on the needle will render the experiment unsuccesful. It is apparent, therefore, that the condition of the surface of the needle is a determining factor in its flotation on a water surface. The existence of the force of surface-tension makes it possible for a substance with a certain maximum weight to float on water, but whether it will actually do so depends on the mutual surface action of that substance and water. If the substance is "wetted" by the water, it will sink; but if not wetted, it will float, provided, as stated above, it does not exceed a certain maximum weight. This "wetting" is indicated by the "contact angle," which is the angle formed by the water surface and the surface of the solid in question. If the water surface is depressed in contact with the solid below the general surface making an acute angle with the solid, the latter is not wetted, and the angle is known as a "non-wet contact angle," while if it is raised with reference to the general surface, wetting of the solid results, and the obtuse angle so formed is known as a "wet contact angle." Solids giving "non-wet contact angles" with a water-air surface will therefore float.

Without at present going further into the question as to what are the factors controlling the contact angle, it is now possible to see why a solid particle possessing a non-wet contact angle will move upwards with the froth. If a thin pulp, consisting of water and finely-divided ore (to which about 1 lb. of eucalyptus or other "frothing" oil per ton of ore has been added), is being agitated and aerated, there will exist innumerable upward moving bubbles of air within the pulp. Confining our attention to one such bubble, it may be accepted that it comes into contact during the agitation with particles of ore, amongst which will be one or more particles having a non-wet contact angle. There are thus present all the conditions of our previous experiment of the air-water surface and the solid with a non-wet contact angle. The particle of ore, provided it is not of too great a weight, will therefore float on the inside surface of the bubble, and being thus permanently attached will travel upwards with it, to be included within the froth and removed therewith. It is seen, therefore, that the amount of such a floatable mineral which is carried upwards in the froth will depend on the number of bubbles formed within the pulp, and the degree of fineness of the mineral particles.

Coming now to the question as to why the surfaces of solids are " wet " or " non-wet," the limitations of our understanding of the basic principles of the subject are fully realised. It is known that " oil and water will not mix," or, in other words, particles of certain classes of oils will not be " wetted " by water. It is also easily demonstrated by experiment that globules of such oils suspended in water will attach themselves to certain solids introduced therein, and not to others. For example, if a perfectly clean, bright copper wire be used for stirring, it will be found that it is impossible to form any attachment between it and the bubble; if the wire is filmed with a sulphide coating, attachment takes place readily, and removal is difficult, and, when accomplished, leaves a film of oil on the wire; if, however, the wire has a thin film of oxide, attachment between oil and wire is still impossible. This preference of attachment between certain oils and sulphides is a well-established fact, but it is uncertain what physical forces are responsible for it—it may be adhesion, whatever that property may be, or it may be due to the presence of electrostatic charges of opposite kinds residing on the oil and sulphide respectively. It is sufficient for present purposes to know that the preference exists, and it is now clear that sulphide minerals so coated with an oil film will have a non-wet contact angle, and therefore float in the froth bubbles.

Thus, we see why it is that there are used in flotation oils which do not assist in forming a froth. In fact, oils may be divided into two groups—" oilers " and " foamers." In the first group, or " oilers," are contained those whose duty it is to provide a non-wet film to sulphide particles, such as coal-tar, creosite, cresol, kerosene sludge, &c.; while the second class, or " foamers," are for the purpose of increasing the production of froth, and are exemplified by eucalyptus oil, pine oil, &c. In actual practice, therefore, a mixture of the two classes of oils is used, the relative proportions being 80 to 95 per cent. " oiler " to 20 to 5 per cent " foamer," the rate per ton of ore being 2 to 4 lb. of " oiler " and ½ to 1 lb. of " foamer."

In practically all modern flotation processes sulphuric acid or an alkaline salt of that acid is used. The exact role played by this acid, which is used in quantities ranging from 5 to 25 lb. per ton of ore, is uncertain; but the quantity used is so small that it seems certain that it can have no chemical action on the ore. Its chief function seems to be in preventing emulsification of the oil during agitation, for oil in an emulsified condition will not form films on sulphides. Whatever its function, however, it is an essential element in a great number of flotation processes.

(*b*) *Collective Flotation or Flotation Concentration.*—In the actual application of the basic principles of the flotation process so far described, the ore is broken in rock-breakers of the reciprocating jaw type, whence it passes through a series of rolls, screens, and pulp thickeners, ultimately reaching tube or similar mills, at the feed end of which the mixture of oils is added, although in some cases the "oiler" is added separately from the "foamer," in which case the "oiler" is added previous to the tube-milling, and the "foamer" at the entry of or within the flotation-boxes. Sometimes a mixer intervenes between the tube-mill and the flotation-box, where the acid and "foaming" oil is added. The pulp then passes to the flotation apparatus proper, which possesses an almost infinite variety of forms, description of which will not be attempted here. Suffice it to say that they are simply mechanical contrivances designed to bring about the agitation and aeration of the pulp, and the collection and removal of the resulting froth in such a way that it does not lose its load of sulphide particles before separation from the pulp. The process is completed with the breaking-down of the froth after separation from the pulp by skimming or otherwise, and the filtration of the resulting mixture of sulphides and water by continuous or intermittent mechanical filters.

Thus is effected the separation from the gangue of the sulphide minerals of an ore in the form of a concentrate. The process is, in fact, that of "flotation concentration." It is applicable to a wide range of ores, the adjustments necessary for each type of ore being brought about by the variation of the relative proportions of ore, water, oil, acid, and air, and in the particular kinds of oils used, as well as the temperature of operation. The recovery of the metallic values varies from 80 to 95 per cent., and is usually in the vicinity of 90 per cent. The costs of flotation concentration range from 3s. to 5s. per ton of ore treated. Its application to the treatment of zinc-lead sulphide ores consists in the treatment of zinciferous middlings and tailings from the wet concentration processes at Broken Hill and Park City with the production of zinc concentrate, which can be freed from the galena contents if they are too high by subsequent treatment by specific gravity concentration; and the treatment of the slimes product from wet concentration mills in Wisconsin, Missouri, and Park City, where the ratio of gangue to total sulphides is high, with the production of a mixed sulphide concentrate consisting of galena and zinc-blende with pyrite and marcasite, which is more or less completely separated into lead and zinc concentrates by treatment on slime-tables by water concentration. Its application to the zinc-lead sulphide ores with a small percentage of gangue, such as the Read-Rosebery ore, is obviously not advantageous, since that ore is already a high-grade sulphide concentrate. Its application in the future, however, to the low-grade ores of this district, which have been described in Parts I. and II. of this series of publications as "low-grade disseminated deposits," will make available a very large amount of ore which is at present not included in the ore reserves.

The flotation process has, however, been developed further than the evolution of flotation concentration. Referring back to the description given as to the means adopted of rendering the surface of sulphide particles non-wet, the further question may be asked as to whether the surfaces of sulphides under all circumstances have the attraction for oil there indicated and whether they themselves possess wet or non-wet contact angles without the adhering film of oil. As a matter of fact it was the investigation of this very question which has been responsible for the developments in the flotation process which have rendered possible an infinitely wider application than that of flotation concentration.

(c) *Preferential or Differential Flotation.*—It has been found that, according to the conditions of acidity or alkalinity of the water, amount and variety of oil, amount of agitation or aeration, and temperature, different sulphide minerals develop non-wet surfaces. By discovering such essential conditions for a certain mineral, and gaining control of the system, it was found possible to obtain a preferential flotation of that mineral. The Lyster Process was one of the earliest developments in this direction. Lyster discovered that in the presence of a neutral or alkaline solution of the sulphates, chlorides, and nitrates of calcium, magnesium, sodium, or potassium, and a frothing oil such as eucalyptus oil, the mineral galena developed a non-wet surface, and could therefore be removed by agitation or aeration, while the zinc-blende was wetted, and remained with the gangue. By subsequently adding acid and more oil to this residue, the zinc-blende developed a non-wet surface, and could be floated. Thus was evolved the process of preferential or differential flotation, as distinct from flotation concentration or collective flotation.

It was further discovered that the presence of certain chemical reagents in the solution had the effect of altering the surface of certain minerals in such a way that they are wetted by water while others are not so affected. In this way the minerals whose surface is so affected remain with the gangue, while the other minerals are floated off in the usual manner. Thus, if a small quantity of potassium or sodium permanganate is added to the solution, the zinc-blende is wetted, but not the galena, which is floated with the use of oil and agitation. A dilute solution of potassium or sodium bichromate converts the surface of the galena into a wetted one, and the zinc may be floated therefrom. Sulphurous acid, or SO_2 in dilute solution has the effect of wetting the zinc-blende, but not the galena and pyrite, which can thus be separated by agitation with air and oil.

The same effects of rendering wet the surfaces of certain minerals may be obtained by the process of roasting at a low temperature. This is the basis of the Horwood process of differential flotation, which converts the surfaces of galena, pyrite, and chalcopyrite, into oxides and sulphates, by roasting, but does not so affect the zinc-blende. In this way the latter mineral can be floated off from the remainder, which then possess wetted surfaces.

It has been found that the success of these methods of differential flotation is very largely dependent on the degree of fineness of the material treated, and that the process in general is specially suitable to the treatment of slimes. It is therefore particularly suited to the treatment of those zinc-lead sulphide ores, which must be reduced to slime to free the constituent minerals. Differential flotation was evolved at Broken Hill, and was the result of the endeavour to adapt the flotation process to the treatment of the accumulated slime products resulting from the other methods of treatment, none of which, as we have seen above, was successful in treating slimes. The presence of galena and zinc-blende in these slimes compelled the investigation of the possibility of floating one mineral to the exclusion of another. And so at Broken Hill there was developed a number of processes of differential flotation based on the principles indicated above, which more or less completely solved the problem of the treatment of slimes. The most successful of these is the Bradford process, which has as its basis the utilisation of sulphur dioxide gas (SO_2), which is passed into the pulp as the means of wetting the zinc-blende. The agitation and aeration of the pulp so treated in the presence of oil and acid, or merely of sodium and potassium sulphates or other similar salts enumerated above without oil, at a temperature of from 85° to 90° F., will result in a froth which carries over the galena contents of the ore. By dewatering the residue, and thus eliminating the SO_2, and subsequently treating it to a process of flotation involving the use of water, oil, acid, and air at a temperature of 140° F., the zinc-blende is obtained as a flotation concentrate. This process has been very successful at Broken Hill, and the problem of the treatment of slimes on that field may be regarded as solved.

The application of these various processes of differential flotation to the treatment of the Read-Rosebery ores is attended with difficulties which are not presented at Broken Hill, although their applicability to slime material makes them peculiarly suitable to the Read-Rosebery ores, which, as has been repeatedly pointed out, must be reduced to slime—*i.e.*, to pass a 200-mesh screen to free the constituent minerals. As pointed out in Chapter V., the Read-Rosebery ores vary from the Broken Hill ores in many particulars, amongst which is the large amount of pyrite present in the former as contrasted with its almost total absence in the latter.

In the application of the process of differential flotation, therefore, to the Read-Rosebery ores, three minerals are to be considered instead of two. It has been found that in the application of the processes successful in Broken Hill the pyrite and galena behave similarly towards the reagents used, and these minerals are therefore obtained as a flotation product, while the zinc-blende is obtained by itself as a very pure concentrate. Such has been the result of the application of the Bradford process, which has given results superior to those obtained by any other differential process. The problem, however, of the differential flotation of the galena from the pyrite is still unsolved, and the investigation of this question is now in progress. The present position is that two products are obtainable from Read-Rosebery ores by differential flotation—a high-grade zinc concentrate and a lead-iron product—the most profitable method for subsequent treatment of which is still under investigation.

C.—DIRECT SMELTING.

In this type of process the valuable constituents of an ore are concentrated into a relatively small mass of metal or matte, while the valueless or unrecoverable portions are converted into an easily fusible slag by adding suitable fluxing materials. The metal or matte separates from the slag by virtue of its higher specific gravity. The fusing of the mixture of ore and fluxing materials is easily attained by the addition of coke to the charge, and the combustion of this by air blown into the charge under pressure, or by the burning of coal in a separate hearth from that in which the charge is smelted. The first method is known as the blast furnace smelting, and the second as reverberatory furnace smelting. The basic principle of both is the same, namely, the chemical properties of the constituents of the ore and fluxes at a high temperature.

In the smelting of lead ores the process consists of first roasting the ore to convert the lead sulphide to lead oxide, and until the total sulphur content is reduced to as low a figure as possible. The roasted ore is then mixed with the requisite proportion of silica, limestone, and iron oxide, to convert the metallic oxides of the ore to a suitable slag, and coke in sufficient proportion to reduce the lead oxide to metallic lead, and by oxidation to supply sufficient heat for the melting of the charge; and the whole mixture is then charged into a blast furnace. Metallic lead and slag are tapped from the bottom of the furnace at separate discharging openings.

If zinc-blende exists associated with the galena in the lead ore the roasting must be carried to as complete a point as possible. In the subsequent smelting the zinc oxide goes mostly into the slag but a certain amount is lost as fume. Any zinc which is present in the roasted ore as sulphate or unaltered sulphide will in the smelting pass both into the slag and into the metal or matte. Its affect on the slag is to render it highly viscous and less fusible, and to increase its specific gravity, so that the separation of metal and slag becomes difficult, and ultimately impossible. It has been found possible, however, to roast the ore so completely that slags containing up to 25 per cent. zinc oxide have been produced. Interpreted, this statement indicates that zinc-lead sulphide ores containing from 20 to 30 per cent. zinc can be roasted and smelted with the production of lead bullion, carrying most of the silver and gold values, and slag containing from 20 to 25 per cent. oxide of zinc; provided there is available at the same time for smelting with it a quantity of high-grade clean galena ores sufficient to supply sufficient lead for the necessary amount of bullion-fall.

Such was the general process applied to the Read-Rosebery ores by the Tasmanian Smelting Company at Zeehan up to the year 1913. It was the failure of supplies of clean galena ores that brought about the difficulties which finally resulted in the closing down of that smelting plant. The loss, however, of all the zinc values of the ore was a serious drawback to this method of treatment, and the failure to successfully solve the problem of the recovery of the zinc from the slag was one of the contributing causes of the cessation of smelting operations. Technically, the problem of the recovery of zinc from the slag in the form of zinc oxide has been completely solved, and the Oker and the Schmidt and De Graz processes have been in successful operation in Germany for some years, as a method of extracting the zinc from the slags produced in the direct smelting of zinc-lead sulphide ores at Rammelsberg, Aachen and Upper Silesia. These processes consist of crushing and briquetting the slag with the addition of powdered coke and smelting with blast. The zinc oxide is volatilised, and is collected in suitable condensing chambers or bag houses. The higher rate for labour, and the very much higher price of coke on the West Coast of Tasmania as compared with Germany, made this process impossible of profitable application to the Read-Rosebery ores.

D.—HYDRO-METALLURGICAL AND ELECTROLYTIC PROCESSES.

1. *General Principles.*

The whole of the processes included under this heading are based on chemical reactions which take place at or near atmospheric temperatures. These reactions are brought about by the use of the aqueous solutions of certain reagents. The ore is invariably roasted, either for oxidation or chloridisation, and the roasted product is then treated with the aqueous solution of the reagent or solvent. After filtration to separate the solid residue from the solution containing the soluble metals, the latter is freed from its impurities by suitable reagents, and the purified solution is then treated for the precipitation of the valuable metal. This is carried out either by chemical means or by deposition by means of an electric current. This latter method is that of electrolysis, and it has the great advantage over chemical methods of precipitation of the production of metal of very great purity.

These wet chemical processes of extraction of metals from their ores are not new in principle, as certain wet processes, such as the chlorination and cyanide processes for gold and silver extraction, and the leaching of oxidised copper ores with dilute sulphuric acid, have been in use for many years. It is an undeniable fact, however, that the greater number of chemical processes, which worked to perfection in the laboratory, failed lamentably when attempted on a commercial scale. It is only during the last decade, asd particularly during the last four years, that these hydro-metallurgical processes have made such strides as to be now well-established commercial processes, destined, in fact, to rival and actually displace many smelting and other processes which have been in operation for years. This has been brought about by the gradual mastering of the mechanical difficulties of handling the solutions and a proper understanding of the effects of small quantities of impurities. Much of the advancement is due to the war, in that the high prices of metals resulting therefrom enabled experiments to be made which otherwise could not possibly have been afforded.

In treating ores which contain more than the one valuable metal which it is desired to separate a solvent must be used which will dissolve one metal to the exclusion of the others. In practically all the proposed processes the selective solution is directed towards the zinc contents to the exclusion of the lead, iron, silver, and gold contents, which all remain together as an insoluble residue, free, or nearly free, from zinc. This is the object aimed at in the processes described below, and it is the degree of completeness of this selective action that determines the efficiency of the process as applied to the treatment of zinc-lead sulphide ores. That efficiency has already been shown to be high, and there is no doubt whatever that these hydrometallurgical and electrolytic processes are destined to play a most important, and, in fact, an essential part in the successful treatment of the Read-Rosebery zinc-lead sulphides. The physical character and texture of the ore has very little to do with the success of the processes, the important factor being the chemical composition, so that the unique character of the Read-Rosebery ore, which has prevented its participation in the success attained by so many processes on other zinc-lead sulphide ores, will not debar the application of such hydro-metallurgical processes which are successful in treating zinc-lead sulphide ores in other parts of the world.

2. *Ashcroft Process.*

This process was a complete success when tried on a small scale in the laboratory, but its working on a commercial scale at Cockle Creek, New South Wales, was found to be impossible, and was ultimately abandoned. It is mentioned here to indicate that a serious attempt was made as long ago as 1896 to apply hydro-metallurgical treatment to zinc-lead sulphides in Australia. That it did not succeed is due, not so much to any fault in the chemical basis of the process, but to the drawbacks affecting the hydro-metallurgical processes as a whole—drawbacks which, as stated above, have now been overcome.

The first stage in the process was that of roasting the ore to eliminate all sulphur, and for the conversion of the zinc sulphide to zinc oxide. This roasted product was then treated with a solution of ferric chloride ($FeCl_3$), which dissolved the zinc oxide with the formation of zinc chloride and granular ferric hydroxide according to the equation:

$$2FeCl_3 + 3ZnO = 3ZnCl_2 + 2Fe(HO)_3.$$

The zinc chloride solution was separated by filtration from the insoluble ferric hydroxide and the insoluble portion of the ore carrying the lead, silver, and gold values, which was smelted in the ordinary way. The solution thus obtained contained zinc chloride, with varying amounts of chlorides and sulphates of lead, antimony, arsenic, silver, and iron. Sodium sulphate was added to eliminate the lead, and zinc oxide to precipitate the iron, while zinc dust was used to precipitate the silver, antimony, and arsenic. These precipitates were got rid of by filter-pressing. The purified zinc chloride solution was then subjected to electrolysis, using both iron and carbon anodes and zinc cathodes, zinc being deposited at the cathode and ferric chloride being generated at the iron anodes, which were converted into ferric chloride in those cells where the carbon anode was used. Thus was regenerated the original solution.

In actual practice the ferric chloride solutions were found difficult to work with, as they corroded pipes, valves, &c.; the ferric hydroxide was formed as an almost impermeable flocculant precipitate, and not in the granular form; silica went into solution and choked all filters. &c., with gelatinous silica; and manganese could not be got rid of, and gradually fouled all solutions. In addition, it was found impossible to obtain a solid zinc sheet in the electrolysis. as spongy zinc invariably formed. Add to all these troubles those experienced in roasting the ore, which we now know is an extremely delicate operation even in modern furnaces, and which was therefore hopeless in the crude hand-rabbled furnaces used at Cockle Creek, with the resulting poor extractions through incomplete roasting. It is not surprising that, burdened with all these troubles, the process succumbed. Even the replacement of the ferric chloride by dilute sulphuric acid as the solvent did not succeed in overcoming the difficulties, and the plant was ultimately dismantled.

3. *Bisulphite Process.*

This is the process which has been used by the Tasmanian Metals Extraction Company at Swansea in Wales and at Rosebery, although at the latter place it has not as yet been proved a commercial success. It was first introduced into Tasmania in 1909, when a start was made to erect a plant at Rosebery. Actual operations were started in 1912, and continued at intervals until January, 1915, since when no work has been done at Rosebery.

The ore is first roasted and the oxidised product then leached with a solution of the sulphur dioxide gas from the roasting furnaces, obtained by allowing water sprays to fall through the upward rising furnace gases. The zinc goes into solution as zinc bisulphite, and the other constituents remain in the insoluble residue. The filtrated solution of zinc bisulphite is then heated by passing over a revolving drum internally heated. This drives off one molecule of sulphur dioxide, and insoluble zinc monosulphite is precipitated on the drum, whence it is scraped off and sent to a reverberatory furnace. Here the remaining molecule of sulphur dioxide is driven off, and a granular zinc oxide remains, which can be used as zinc oxide for paint, or smelted with coke and coal, with the production of metallic zinc or spelter.

In the operation of the process at Rosebery, many difficulties were encountered, the first of which was in roasting, where the mistake was originally made of putting in non-water-cooled rabbles. After this defect had been remedied, trouble was experienced with the heating of the bisulphite solutions and the collection of the monosulphite. These were partially overcome by the installation of the revolving drum described above but one of the final difficulties encountered was in the roasting and controlling of the sulphur dioxide. The plant did not run long enough to afford an opportunity of properly gaining control of this part of the process. Complete control, however, is regularly maintained at Swansea.

Since the last attempt made at Rosebery in 1914-15, the process has been in operation at Swansea, and has been remodelled to permit of the application of electrolysis. In this remodelled process, the solution of zinc bisulphite is obtained as described above. This solution is then purified to put it in a proper condition for electrolysis. The impurities to be removed are arsenic, antimony, bismuth, iron, copper, and cadmium, the first four of which are removed by adding limestone or zinc oxide, and the two latter by adding zinc dust in a generally similar manner to the methods adopted in those processes, described below, which use sulphuric acid as the solvent. Very satisfactory zinc sheets are obtained in the electrolysis, aluminium cathodes being used. This process has been thoroughly tried out in Swansea, and operations are shortly to be started at Rosebery to adapt the plant to the altered process. Most of the new plant has already arrived, and the results of the operations are awaited with interest.

4. *Processes Using Sulphuric Acid.*

(*a*) *Purely Chemical.*—There are a great number of processes which have been in use for years, and are still in operation, which separate copper and zinc by using a dilute solution of sulphuric acid, and precipitate the metals from the resulting solutions by purely chemical means. There is no need to deal with those used on copper ores, and attention will be here devoted to a hydro-metallurgical zinc extraction process of long standing, which is still in use at Rammelsberg, in Germany. The ores treated are the "grey ore" and "brown ore," described in Chapter IV., and known together as "lead ore." The average content is 10 per cent. lead and 18 per cent. zinc. The works are known as the Herzog Julius and Frau Sophienhütte. Here the "lead ore" is given a sulphatising roast, and is subsequently leached with dilute sulphuric acid solution. The resulting solutions are removed by decantation to settling vats, whence clear solutions are drawn off to lead pans, where they are heated for the precipitation of basic ferric sulphate. The clarified solution is then evaporated in lead pans, and subsequently removed to V-shaped lead-lined wooden vats, where zinc sulphate crystallises. The "mother-liquor" is returned to the leaching plant, to be made up into new solution. Copper gradually accumulates in the solution, and is removed periodically. The residue from the leaching-plant is then completely roasted and smelted.

(*b*) *Electrolytic.*—All the plants in successful operation in America and Tasmania which are treating zinc ores by hydro-metallurgical and electrolytic methods use dilute solutions of sulphuric acid as the active solvent, and precipitate the zinc by electrolytic methods. Their details of operation may vary, but they are all similar in that they without exception start off with an oxidising roast, following by leaching with dilute sulphuric acid, and ending with the precipitation of zinc by electrolysis. The process is really quite an old one, and was, in fact, tried during the final stages in the history of the Ashcroft process, but its successful operation has only been accomplished during the last four years, and it is now a definitely established process.

The outline of the process remains the same, whether it is being applied to zinc concentrates containing 50 per cent. zinc and 5 per cent. lead, or to crude zinc-lead sulphide with any relative proportion of zinc and lead contents.

The ore is first crushed to pass a 60-mesh screen, and it is then roasted. The latter operation is a vital one to the process, and it is not a straightforward or simple proposition by any means. The object aimed at in the ideal is the conversion of the lead, iron, and zinc sulphides to oxides, but as the elimination of all the sulphur is not found possible in actual practice, all efforts are made to ensure that the sulphur which does remain is in the form of sulphate. Zinc-blende possesses a higher ignition temperature than either pyrite or galena, asd consequently the temperature of roasting must be higher than that of an ordinary sulphatising roast. The temprrature must not, however, be allowed to exceed 600° C., as above that temperature zinc ferrate or ferrite is formed which is insoluble in sulphuric acid, and is therefore not extracted in the leaching process. The actual temperature employed varies between 575° C. and 600° C., which gives the maximum development of sulphates and gives the minimum production of ferrates or ferrites. On the success of the roasting operation largely depends the percentage of extraction of the zinc contents in the subsequent leaching operations.

The roasted ore is then agitated by any of the well-known appliances used in the cyanide and similar processes with a dilute solution of sulphuric acid and the resulting solution decanted and the residue freed from zinc sulphate solution by washing and filter-pressing. The resulting solution should be slightly acid and consists of a dilute solution of zinc sulphate, together with sulphates of the following metals:—iron, manganese, arsenic, silver, antimony, tin, bismuth, nickel, copper, cadmium, and cobalt, if the original ore contained any of these metals. It is necessary to eliminate all of these metals except manganese, as they all seriously interfere with the electrolytic operations. The solution is then passed on to the purifying tanks. In the first of these, powdered limestone is added to precipitate arsenic, antimony, bismuth, tin, and iron, which fall as a basic precipitate from a neutral solution. If cobalt is present, zinc oxide is added at this stage, and the temperature raised, as under these conditions, in the presence of arsenic, cobalt is precipitated. In place of adding powdered limestone at this stage the same metals are precipitated by bringing about the neutral condition of the solution by the leaching of the roasted ore in stages, so that the nearly neutral solution comes in contact with fresh ore, thus being completely neutralised. In this way the basic precipitate forms under the neutral conditions existing in the last leaching vat, and zinc oxide can be added at this stage also if necessary.

In either case the partially-purified solutions are freed from the precipitate by filter-pressing, and passed on to the next purifying tanks. Here zinc dust is added, which precipitates silver, copper, cadmium, and nickel. These are also removed by filter-pressing, and the resulting purified solutions passed on to the electrolytic cells.

It is only during the last four or five years that the problem of the precipitation of solid zinc plates by electrolysis has been successfully solved. In previous attempts, spongy zinc was invariably produced, which is too bulky to allow of continuous operation of the cells, and, in addition, is very largely oxidised during the subsequent smelting into zinc ingots. There were many other technical difficulties, such as the growth of zinc "flowers" on the zinc sheet in the electrolytic cell, which, if not prevented, caused cross-circuiting between the cathode and anode. All these difficulties have now been overcome by the puri fication of the solutions and the using of certain current densities, &c., and large plants are now in continuous operation, producing solid zinc sheets averaging one-tenth of an inch in thickness. The process is a continuous one, the solutions flowing through the electrolytic department from one cell to the next. It is essential that the solutions should consist of a solution of zinc sulphate with a little manganese as the sole impurity. Aluminium cathodes and lead anodes are used. Zinc is deposited on the aluminium sheets, and sulphuric acid is regenerated. The rate of the passage of the solutions through the electrolytic department is so regulated that 50 per cent. of the zinc is deposited, the other 50 per cent. remaining in the solutions which are returned to the leaching plant. The circuit is therefore a closed one. The zinc sheets are stripped about once a week from the aluminium cathodes and melted into ingots in an ordinary melting furnace. The resulting zinc or spelter is very pure, containing over 99·95 per cent. metallic zinc.

The residues remaining from the leaching process will vary in character according to the original composition of the ore which is being treated. In the case of a zinc concentrate, it will contain equal quantities of lead and zinc, and is, therefore, unsuited for lead smelters. It can, however, be treated in special furnaces, in order to volatilise the lead and zinc as oxides, which can be collected in condensing chambers or bag houses, and used as paint material. If the ore being treated is crude zinc-lead sulphide, the residue will contain all of the lead, silver, and gold, and most of the iron, and its disposal will depend on the lead-content, and also on the proximity of a lead smelter.

These processes are at the present time successfully treating zinc-lead sulphide ores from Park City and Leadville and also at Anaconda Montana. On such ores it is a definitely-established and very successful process. It is in successful operation at Risdon, Tasmania, on zinc concentrates from Broken Hill, and the present capacity of 100 tons of electrolytic zinc per week is to be increased to ten times that figure. They have certainly solved the question of the treatment of zinc-lead sulphides, and threaten to displace to a very large extent the recovery of zinc from zinc concentrates by roasting and retorting. Their existence, however, is wholly dependent upon the availability of cheap electrical power. Their application to the Read-Rosebery ores has been thoroughly tested by laboratory trials, and a large-scale working test of a 100-ton parcel at Anaconda, Montana, and found to be very successful. From 80 to 85 per cent. of the zinc can be recovered as pure electrolytic zinc, and a lead-iron product obtained carrying all of the lead, silver, and gold, together with most of the iron, the metals being in the form of sulphates and oxides. The disposal of this residue is discussed in a subsequent portion of this chapter. The tests are being continued on a considerable scale in the trial plant erected at the research laboratory of the Mt. Lyell Company, at Queenstown.

E.—OUTLINE OF THE COMPLETE TREATMENT METHODS IN USE AT THE VARIOUS ZINC-LEAD SULPHIDE DEPOSITS.

1. *Missouri and Wisconsin.*

The separation of the lead and zinc ores is commenced in the mines, where a certain amount of the ore consists of galena or zinc-blende exclusively. The mixed ores are sent to wet concentration mills, which produce clean galena concentrates, assaying 77 to 79 per cent. lead, and a zinc-iron concentrate assaying from 35 to 59 per cent., according to the amount of marcasite and pyrite present. The Wisconsin zinc concentrates have the latter figure, and the Missouri the former. Where the pyrite and marcasite is in excess, the zinc concentrate is sent to electro-magnetic separator plants, where it is given a magnetising roast, and the iron removed as a magnetic product. The zinc concentrate is thus enriched. The slimes are now being treated by differential flotation, with the production of lead concentrates and zinc concentrates.

The lead concentrates are sent to lead smelters and the zinc concentrates to zinc smelters, where metallic lead and zinc are respectively produced by roasting and smelting in the ordinary way.

2. *Aachen and Upper Silesia.*

The oxidised ores are mined separately from the sulphides and smelted direct. The mixed sulphides are hand-picked on sorting belts, and clean galena or zinc-blende picked out. The remaining mixed sulphides are sent to wet concentration mills, where lead concentrates with a little zinc, and zinc concentrates with a little lead, are obtained. The former are roasted and smelted in blast furnaces, with the production of lead bullion and a zinciferous slag, which is dezinced by the Schmidt and De Graz or the Oker processes. The zinc concentrates are roasted, and the zinc distilled in retorts in the ordinary way, and the residue is sent to the lead furnaces for recovery of its lead content.

3. *Park City and Leadville.*

The ores from the oxidised portion of the ore-bodies are mined separately as lead or zinc ore. The sulphides are sent to wet concentrating mills, where lead concentrates are produced, which are sent to lead smelters, together with a zinc concentrate, which, however, is only derived from the coarser end of the milling. At the same time, there is produced from the finer portions of the milling operations a zinc middlings product, which is subjected to flotation when a zinc concentrate is obtained. The slimes up to quite recently have been dumped, but are now being treated by differential flotation, producing lead concentrates (which are sintered by the Dwight-Lloyd process and sent to the smelters) and a zinc concentrate.

The zinc concentrate from all these operations go partly to zinc smelters, where they are roasted and retorted in the ordinary way, and partly to the electrolytic zinc works, which have sprung up during the last four years, and which are producing electrolytic zinc and a relatively small quantity of zinc oxide for paint.

During the last four years also have appeared the plants which are treating the more intimately intergrown zinc-lead sulphides, less answerable to wet concentration than the coarser-grained ores by hydro-metallurgical and electrolytic processes.

These plants produce electrolytic zinc and a lead-bearing residue, which is sent to lead smelters, and are, in fact, exactly the same in design and working as those treating zinc concentrates only.

4. *Rammelsberg.*

The ore is separated during mining, and subsequent hand-picking on moving belts, into the five classes of ore described in Chapter IV. (p. 41). The "copper ore," "mixed ore," and "pyritic ore," with an average content of 5 per cent. copper, are sent to smelters, where they are roasted to such a degree as to leave enough sulphur to form a copper matte. They are then smelted in a blast or reverbatory furnace, and lead bullion and copper matte produced, together with a slag carrying considerable zinc values. The lead bullion and copper matte are separated within the furnace by intermittent and selective tapping, or in forehearths. The lead bullion is refined for pure lead and silver, while the copper matte is converted to blister copper, which is subsequently refined to pure copper, and the silver and gold content recovered. The zinciferous slags are treated by the Oker process, and the zinc recovered as zinc oxide.

The " grey ore " and " brown ore," collectively known as " lead ore," which contains, approximately, 10 per cent. of lead and 18 per cent. zinc, is sent to a separate treatment works. Here the zinc is extracted by a hydro-metallurgical method, using dilute sulphuric acid as a solvent, and the zinc is obtained as crystallised zinc sulphate. The insoluble residue is completely roasted and smelted, the products being lead bullion (which is purified) and a zinciferous slag, which is dezinced by the Oker process.

5. *Bawdwin.*

The ore as mined is crushed by breaker, rolls, and tube mills to pass a 100-mesh screen. The slimes thus produced are treated by differential flotation, with the production of a zinc concentrate, which is sold to zinc smelters, and a lead-iron concentrate, which is roasted and sintered, and smeltered in blast furnaces, with the production of lead bullion, which is sold as such.

6. *Broken Hill.*

The ore is sent, as mined, to wet cncentration mills. These produce—(1) lead concentrates, which go to the lead smelters at Port Pirie and Cockle Creek, or are sold as such; (2) zinc middlings or tailings, which go to flotation concentration plants, which produce zinc concentrates, which may or may not be subsequently re-treated by wet concentration for the elimination of most of the galena contents; (3) slimes which are treated in special differential flotation plants, with the production of lead concentrates and zinc concentrates. The metal contents of these various products are shown in Chapter IV. (p. 55).

At Port Pirie the lead bullion produced is refined to pure lead and pure silver. Cockle Creek produces lead bullion. The zinc concentrates go partly to Port Pirie and Cockle Creek, where spelter is produced by roasting and retorting, partly to Risdon, Tasmania, where electrolytic zinc is produced by hydro-metallurgical and electrolytic processes, and partly to America, Japan, &c., as zinc concentrates.

F.—STATEMENT OF THE PRESENT POSITION IN REGARD TO THE TREATMENT OF THE READ-ROSEBERY ORES.

In the preceding pages there have been studied the physical and chemical charactristics of the zinc-lead sulphides of the Read-Rosebery District in their relationship with the other zinc-lead sulphide ores of the world. There have also been presented the metallurgical processes which have been, or are being, used in treating zinc-lead sulphides throughout the world, and the relation between these processes and the physical and chemical characters of the ore are discussed. Their applicability or otherwise to the Read-Rosebery ores has been clearly indicated. It is therefore possible now to present a summary of the treatment problem of the Read-Rosebery ores as it exists at present, using the above information as to the bearing of the physical and chemical character on the success of the processes actually in use in the various cases, as an indication of the type of process that is to solve the problem.

Specific gravity concentration is impossible, and so is electro-magnetic separation.

The application of flotation concentration is restricted to the treatment of the "low-grade disseminated deposits" for the production of a high-grade zinc-lead sulphide concentrate.

Differential flotation has been successful on the zinc-lead sulphide ore, especially that process known as the Bradford process. From 80 to 85 per cent. of the zinc is recovered in the form of a zinc concentrate assaying 55 per cent. zinc and 2 per cent. lead, with a little silver. The remainder of the sulphides are contained in the lead-iron concentrate, which assays, approximately, 18 oz. silver per ton, 15 per cent. lead, and 6 per cent. zinc.

Direct smelting, with dezincing of the zinciferous slags by the Oker process, has been a technical success; but under the conditions existing on the West Coast of Tasmania, is economically a failure, and therefore impossible of application.

The electrolytic type of the hydro-metallurigcal processes has been proved by large-scale trials to be applicable to the Read-Rosebery ores. An extraction of from 80 to 85 per cent. of the zinc, in the form of electrolytic zinc, is assured. The remaining components of the ore remain in the lead-iron residues.

The choice of a process, therefore, lies between two types, namely, differential flotation and electrolytic hydro-metallurgy, both of which have already been proved to give results which are commercially profitable when considered in conjunction with the existence of large resources of cheap hydro-electric power in the vicinity of the field. Before a final choice be made, however, it is desirable to ascertain which process will give the greater profit, and which shows most chance of being improved. These are the considerations which are now being gone into. In the first place, the hydro-metallurgical processes have the advantage over differential flotation in that the amount of grinding necessary is to pass 60-mesh in the former case, and 200-mesh in the latter process—figures which make a considerable difference in power costs. In differential flotation, the zinc concentrate obtained would have to be roasted and leached, and electrolytic zinc deposited from the resulting solutions, but the lead-iron residue is more difficult of utilisation. If a lead smelter were operating in the vicinity, it could be roasted and smelted, but that would necessitate the addition of clean galena ores, as there is not enough lead in it alone for a lead furnace charge. Experiments are now being conducted, however, with the object of effecting a differential flotation of the galena from the pyrite, and already have met with some measure of success.

The electrolytic type of hydro-metallurgical process gives the same extraction of 80 to 85 per cent. of zinc, but, whereas differential flotation produces a zinc concentrate, this process produces chemically pure zinc, so that to compete on this point the subsequent treatment of the flotation zinc concentrate would have to give an extraction of 100 per cent., a result which is manifestly impossible. The leaching process also has the advantage over flotation, in that the lead-iron residue is already in the roasted form, and it is doubtful whether the roasting of the two products of differential flotation separately, as described above, could be as economically effected as by roasting the original ore. In view of the wonderful advances made in hydrometallurgy during the last five years it seems very probable that this roasted lead-iron residue will be treated by some such method as the dissolving of the lead by a sodium chloride solution and the silver by cyanide or hypo solutions, and subsequent precipitation, rather than by smelting. If this eventually happens, the electrolytic process is the one to adopt for the original ore, as it provides an already completely roasted product.

The hydro-metallurgical process also has the advantage over differential flotation, in that there is not the loss of lead and silver with the zinc, although these go into solution to a small extent, yet they are precipitated and returned to the insoluble residue. Against this is the fact that if the treatment of the zinc concentrates is being carried out by the producers of it the lead content is ultimately recovered as lead oxide or sulphate for paint purposes.

It will be seen, therefore, that the present position is one of rivalry between the two successful processes, and the deliberations are taking the form of minute calculations and estimates of working costs and possibilities of improvements, which are all being investigated by trials in specially-constructed research apparatus and in plants to be operated on a commercial scale by skilled and experienced metallurgists. The final decision will be awaited with interest, but in the meantime there is not the shadow of a doubt that the successful treatment of the Read-Rosebery zinc-lead sulphides has been accomplished at last.

VII.—THE EXTENT AND POTENTIALITIES OF THE READ-ROSEBERY ZINC-LEAD SULPHIDE BELT.

To obtain a correct conception of the potentialities and extent of the zinc-lead sulphide deposits of the Read-Rosebery District, it is necessary to refer to Plate V. of Part I. and Plate IX. of Part II. of this series of publications. These are on the same scale, and if they are joined together, using the Rosebery-Williamsford-road and the northern boundary of the Jupiter consolidated lease as registering points, the whole Read-Rosebery zinc-lead sulphide belt will be seen in plan on a scale of, approximately, 530 feet to an inch. With this plan, should be studied Plate VIII. of Part I., and Plate XII. of Part II., which are vertical sections in a general north-south direction. Plate VII. of Part I. and Plate X. of Part II., should be next referred to, as giving vertical sections in a west-east direction.

The zinc-lead sulphide deposits are thus seen in the plan to occur at intervals along a belt 7 miles in length in a general north-south direction, the mines in which zinc-lead sulphide ore-bodies have already been located being from south to north—Dunne's Blocks, Mt. Read Mine, South Hercules, Hercules, Ring P.A., Jupiter, Koonya, Dalmeny, Primrose, Tasmanian Copper, and North Tasmanian Copper—a total of 11 mines.

The longitudinal vertical sections in the north-south direction show the ore-bearing horizon to be undulating continuously along the whole length of the 7-mile belt.

The vertical cross sections similarly show the ore-bearing horizon to be undulating from west to east, being in places denuded and completely missing, but existing as undulations below the surface for definitely proved widths, varying from 7000 feet as a maximum, down to 800 feet as a minimum, and extending to an unknown distance eastward of this.

The portions of the ore-bearing horizon over this area of occurrence which actually carry zinc-lead sulphide deposits have only been located in the instances cited above, where the mine workings have penetrated them, but as fully discussed asd explained in Part II., there is every réason to believe that the greater part of it will carry zinc-lead sulphide ore-bodies. The chances which the boring operations, carried out on the lines of the diamond-drilling scheme indicated in Parts I. and II., will actually have of locating ore are in direct ratio to their nearness to a zinc-lead sulphide ore-body alrealy located.

The production of zinc-lead ore from the mines operating on the belt has been, approximately, 296,000 tons. made up as shown in the following table, which also indicates the actual receipts for the ore as sold:—

Mine.	Output.				Value.
	Zinc-lead Sulphide.	Gossan.	Copper Ore.	Total.	
	Tons.	Tons.	Tons.	Tons.	£
Hercules	165,704	15,376	346	181,426	264,316
Tasmanian Copper ...	50,826	—	—	50,826	47,500
Primrose	45,864	—	—	45,864	50,000
Mount Read	8059		—	8059	8000
Jupiter	7000	—	22	7022	7500
Ring P.A.	—	—	2340	2340	6000
North Tasmanian Copper..............	200	—	—	200	100
			Totals	295,737	£383,416

In indicating the amount of ore reserves, it is necessary to include "proved ore," or that which has been definitely established by mining or boring as actually existing, being exposed on three or four sides; and "probable ore," which is definitely located on one or two sides. In addition, it is necessary to give some information as to the "prospective ore," or that which, while not actually located, yet, from the geological evidence and its proximity to ore already penetrated, seems reasonably possible.

The amount of "proved ore" in the Read-Rosebery zinc-lead sulphide belt has been indicated in previous pages of this publication, and are summarised in the following table:—

Mine.	Proved Ore.				
	Amount. (Tons.)	Gold. (Ozs. per ton.)	Assay Silver. (Ozs. per ton.)	Lead %	Zinc. %
Tasmanian Copper Primrose Rosebery Mine	1,050,000	0·118	10·5	7·5	25·6
Hercules	530,000	0·143	8·2	7·3	30·3
Mount Read	100,000	0·110	9·0	7·0	22·0
Total	1,680,000	0·127	9·6	7·4	27·3

The amount of "probable ore" is more difficult to satisfactorily express in figures. In the following table, however, the approximate amounts of "probable ore" in the various mines are indicated:—

Mine.	Probable Ore (Amount in Tons).
Tasmanian Copper Primrose Rosebery Mine	720,000
Hercules	156,000
Mount Read	24,000
North Tasmanian Copper	10,000
South Hercules	5,000
Total	915,000 tons

The amount of "prospective ore" cannot of course be expressed in figures, but at the following specific localities of the zinc-lead sulphide belt, there is every justification on the geological evidence for the expectation that appreciable bodies of ore may be located by exploratory work carried out on the lines indicated in this series of publications.

(1) To the east of and below the present workings of the Mt. Read Mine.

(2) To the east, both north and south of the South Hercules shaft and below the South Hercules eastern adit.

(3) The southern end of the "C" ore-body at No. 4 level, Hercules.

(4) The ground between the main crosscut and No. 4 tunnel at No. 4 level, Hercules, which contains the southern continuation of the "E" ore-body with its Beta fold (see Plate VIII., Part I.).

(5) The corresponding ground south of the No. 3 tunnel, Hercules.

(6) The ground to the south of the 3A crosscut at the "E" ore-body, Hercules.

(7) To the east of Nos. 8, 11, 23, and 24 bores, Hercules.

(8) To the east of and below Sligo's tunnel, in the Ring P.A.

(9) To the east of and below the No. 3 level, Jupiter.

(10) To the north and south of and below the No. 2 level, Koonya.

(11) To the east, both to north and south of the Dalmeny shaft.

(12) Between the Primrose open-cuts and the new discovery on the Stitt River, above the road bridge.

(13) To the east and north of the bores on the Rosebery Mines, including the North Tasmania Copper.

In addition, there is every justification of the expectation that zinc-lead sulphide ore-bodies will be discovered by the diamond-drilling scheme outlined in Parts I. and II. at any part of the zinc-lead sulphide belt in the undulations of the ore-bearing horizon over a meridional direction of 7 miles, and a width known to vary from 800 to 7000 feet, and to an indefinite distance eastwards of this.

In addition to the ore referred to up to this point, which includes only those ore-bodies which consist of the typical solid zinc-lead sulphide, there exist throughout the field large quantities of lower grade ore, which have been described in Parts I. and II., but which have not been included in any estimate of ore reserves. They have been referred to in these publications as "low-grade disseminated deposits," and consist of pyrites, zinc-blende, galena, and chalcopyrite disseminated in schist, the metallic values being approximately:—

Gold	0·03 oz. per ton
Silver	1·5 ,,
Lead	0·5 per cent.
Zinc	6·5 ,,
Copper	0·1 ,,

As pointed out in the chapter dealing with the metallurgy of the zinc-lead sulphides, these deposits are ultimately destined to supply considerable quantities of zinc-lead sulphide concentrates as the result of their treatment by flotation concentration. When the metal contents of these disseminated deposits are compared with those of the Wisconsin and Missouri deposits, which possess lower metallic contents, but which are amongst the most important zinc and lead producers in the United States their potential value will at once be apparent.

Taking the figures given in this chapter in conjunction with those in Chapter V., it is seen that, taking cognisance of the size of the ore-bodies, metal contents, extent of the ore-bearing zone, and the amount of ore reserves considered in relation to the relatively small amount of systematic mining carried out in spite of the 28 years' opportunity, the Read-Rosebery zinc-lead sulphide deposits can be placed high in the list of the potential sources of the zinc and lead supplies of the world.

VIII.—THE CAUSES RESPONSIBLE FOR THE DELAY IN THE DEVELOPMENT OF THE FIELD.

On studying the last table given in Chapter V., which presents the output and ore reserves, and the number of years since the discovery and first working of the various zinc-lead sulphide deposits of the world, it becomes apparent that the Read-Rosebery field is markedly backward in its development as compared with other fields which have been known for, approximately, the same number of years; and, in addition, it has had no annual output since 1913. It is the object of this chapter to inquire into the reasons for this, and to state them in a clear and concise manner.

The best method of approach to this question seems to be that of an inquiry as to whether the causes of this delay lie—(*a*) in the location and position of the field as a whole; (*b*) within the ore-deposits themselves; or (*c*) in the policies adopted by the groups of individuals in control of operations in the field.

An examination of the first factor certainly demonstrates that the difficulties of access in the very early days of the discovery of the field were a hindrance to its development; but this drawback was removed, and therefore ceased to operate at the end of the year 1899—six years after the first discovery of zinc-lead sulphide ore—by the completion of direct railway communication with the ports of Burnie and Strahan. With the advent of railway communication, the geographical situation actually became an advantage, as the field was thus placed in easy communication with the lead smelters, which the occurrence of clean galena ores at Zeehan had brought into existence. Zinc-lead sulphide as high in lead and silver as could be selectively mined was sold to these smelters, but the zinc was not paid for or recovered, but went, for the most part, into the slag. It was when an investigation was made as to the applicability of the Oker process in recovering the zinc from these slags that the geographical position was realised to be a serious hindrance to development, in that the Read-Rosebery zinc-lead sulphide belt, in common with the whole West Coast of Tasmania, is so far removed from a source of cheap metallurgical coke and coal as to make any process involving their use financially impossible. It was this factor that finally caused the smelters to close in

1913, and this was undoubtedly a great setback to the field. Recent developments, however, are demonstrating that this geographical position, which was stated and believed by many to be an insuperable obstacle to progress, is the very factor that will make possible the development of the field and the utilisation of the ores, situated, as they are, in close proximity to the sources of the great hydro-electric power of the Central Plateau and the West Coast mountain range. The availability of this cheap power is one of the great economic advantages of the Read-Rosebery field, and there is no doubt that if the development and harnessing of this power had already taken place, the field would have been further ahead to-day than it is.

The investigation of the question as to how far the reason for the delay lies within the ore-deposits themselves leads us to a comparison between the Read-Rosebery deposits and similar deposits in other parts of the world. This is fully presented in Chapter V., where the similarities and divergencies of the various deposits are discussed. As regards the general character of the deposits, it is noticed that the Read-Rosebery occurrences differ from all of the other zinc-lead sulphide deposits described in Chapter IV. in possessing only a relatively negligible quantity of oxidised ore. It was the existence of these rich carbonate and oxide ores, carrying high silver values, which was responsible for the early, and, in most cases, rapid development of the well known zinc-lead sulphide deposits of the world.

The oxidised ores were rich and easily treated, and so the development of the various fields was rapid and profitable until the unoxidised ores were encountered. By this time there had been accumulated sufficient reserve funds, or there still remained sufficiently large quantities of the oxidised ores to permit of the experimentation and research as to the best method of treatment of the primary zinc-lead sulphide ore. These conditions did not obtain in the Read-Rosebery field, and after the excavation of the only few tons of " gossan " available, the question of the treatment of the zinc-lead sulphide forced itself under notice as the one outstanding problem, the satisfactory solution of which was absolutely essential to the development of the field.

In regard to the character of the zinc-lead sulphide itself, it is clearly shown in Chapter V. that again the Read-Rosebery ore differs from all the others described in Chapter IV., in that the grain size of the constituent sulphide minerals is very much smaller, and the degree of intergrowth much greater. The result of this is that the ore must be ground to pass a 200-mesh screen before any mechanical process of separation would have a chance of success. It was impossible, therefore, to apply the process of water-concentration, which had proved at least partially successful on the other zinc-lead fields, where the maximum grinding needed was to pass a 60-mesh screen. Especially was this so because of the practically negligible proportion of gangue present, the object to be attained being a separation of the sulphides from one another, rather than that of the separation of the sulphides from gangue, which was the problem more or less successfully solved in most of the other fields. This question of metallurgical treatment is fully discussed in Chapter VI., and there is no need to further dilate upon the matter here. Suffice it to say that the Read-Rosebery zinc-lead sulphide presented most exceptional difficulties to treatment, and did not possess the characteristics which in the other zinc-lead sulphide deposits of the world enabled a partial success to be attained which was sufficient to keep the mines operating at a profit.

In discussing the proportion of the responsibility for the delay attributable to the effect of the policies pursued by those directing operations on the field we are on more debatable ground, but there are certain facts in this connection which were so obviously contributing factors to the lack of progress that it is deemed advisable to indicate them. In the first place, this field, in common with many other mining fields the world over, has suffered from those whose operations are solely directed towards the making of money by dealings in scrip, and to whom it is a matter of very little moment whether the mining industry benefits or suffers. The total amount expended on the mining ventures on the Read-Rosebery zinc-lead sulphide belt is, approximately, £650,000. What proportion of this has been spent in the actual development of the properties is uncertain, but there is no doubt that the amount spent outside the field on expenses other than those of metallurgical research has been disproportionately great. The Mt. Read Company seems to have been the greatest offender in this respect, for up to the end of 1913 the total expenditure of the company had been £20,874. Of this amount, the sum of £12,278 had been spent in Tasmania, and £8596 in London. The latter figure did not include one penny for metallurgical research. Obviously the property did not get fair treatment by such a policy. Even the sum expended in Tasmania was not spent to the best advantage, as is pointed out in Part I. The following figures, taken from the balance-sheet for the two years up to 30th June, 1905, show the apportionment of the expenditure:—

Expenditure in Tasmania.	£	s.	d.	Expenditure in London.	£	s.	d.
Rents and fees	169	19	6	General expenses	128	11	6
Cables	5	11	0	Directors' fees	1350	0	0
General expenses	87	8	1	Stationery and printing	27	0	4
Freight	178	14	8	Audit fee	52	10	0
Wages and stores......	2670	16	9	Office rent, secretary's salary, and clerical assistance	600	0	0
Salaries	648	0	0				
	3760	10	0		2158	1	10
Less sundry receipts...	9	18	0	Less sundry receipts...	94	0	7
	£3750	12	0		£2064	1	3

There is no need to further comment on these figures.

In not one instance do the annual reports of the various companies up to the year 1913 show an expenditure in regard to metallurgical research. This, in view of the early realisation of the metallurgical difficulties, clearly shows that the development of the field was not in the hands of the type of individual best qualified to bring it about. The solution of a metallurgical problem is not furthered by the policy of waiting and hoping for successful processes to turn up. There was nothing done even in the matter of the investigation of the question as to whether the zinc-lead sulphide was a chemical compound or a mechanical mixture, which was the first step in deciding what general process was necessary. The action, however, of that group of directors responsible for the initiation of the Tasmanian Metals Extraction Company's process at Rosebery is to be commended, and they are certainly not to blame that the process has not as yet proved a success on the field.

The policy adopted in regard to the field has, in fact, been characterised by the attitude of regarding the mining industry as a means of getting rich quickly with the outlay of little capital, and not as a legitimate enterprise demanding systematic and scientific handling, and an investment of the nature of a sound business. The transition of the risks of the average mining venture into the essential elements of a sound business enterprise calls for the application of modern scientific knowledge and methods which cannot be obtained except for adequate remuneration. It is the failure of those directing so many mining operations in Tasmania to fully realise this fact, and their unwillingness to pay the salaries necessary to secure the services of men best qualified to solve the particular problems, which has been largely responsible for the failure or the unduly delayed development of so many Tasmanian mining fields, the Read-Rosebery being, perhaps, the most notorious.

These, then, are the main causes of the delay in the development of the Read-Rosebery zinc-lead sulphide belt:—The absence of large quantities of oxidised ores; the extremely intimate intergrowth of the constituent minerals of the zinc-lead sulphide ore; the failure of those directing operations on the field to undertake at an early stage a systematic investigation of the metallurgical treatment of the ore; and the dilatoriness of the State of Tasmania in developing its resources of hydro-electric power.

IX.—THE PROCEDURE ESSENTIAL TO THE SUCCESSFUL DEVELOPMENT OF THE FIELD.

Since the advent of the Mt. Lyell Company into the field, under the title of the Mt. Read and Rosebery Mines Limited, and the taking by them of an active part in its development, the whole complexion of matters has altered, for they have introduced the very elements which were so sadly lacking before.

They have carried out exploratory work by drilling, and have initiated the systematic opening up of several of the mining properties which they control (Hercules, South Hercules, Tasmanian Copper, and Primrose mines), with the result, as indicated in Chapter II., that tonnages of ore have been proved and made available for immediate extraction, sufficient to justify operations being undertaken on a considerable scale.

In addition, they have undertaken the systematic investigation of the metallurgical treatment of the ore, based on modern scientific methods and principles. The general manager of the company was sent to the United States to there investigate the developments in the treatment of zinc-lead sulphide ores, and a parcel of 110 tons of Read-Rosebery ore sent there for trial treatment by the processes which were being successfully used on similar ores. Two metallurgists were appointed, each of whom was eminent in the branches of metallurgy respectively of hydrometallurgy and electrolysis of zinc and differential flotation, and provided with metallurgical research laboratories. The result of these researches is indicated in Chapter VI.

The amalgamation of interests, in so far as this has been accomplished by the absorption of three of the principal mines (Hercules, Tasmanian Copper, and Primrose), together with 17 other properties along the belt, under the one organisation known as the Mt. Read and Rosebery Mines Limited; the initiation of a complete scheme of development and exploratory work; and the appointment of metallurgists of ability and experience to investigate the treatment of the ores in a scientific and practical manner—all these are in accordance with the procedure laid down in the preliminary report by the writer on the Mt. Read District (Geological Survey Report No. 3: Preliminary Report on the Zinc-Lead Sulphide Deposits of Mt. Read) as essential to the successful development of the field.

As this procedure has been adopted, and success seems assured, there no longer exists the necessity to indicate and discuss it, except to state that any additional organisation should proceed on the same general lines. At the same time, however, there are certain points in connection with the present situation that are deserving of special mention.

As fully described in Chapter VI., The Tasmanian Metals Extraction Company has adapted its bisulphite process to electrolytic precipitation of zinc, and after successfully running at Swansea, Wales, is to be tried out on a large scale at Rosebery. Concurrently, litigation is threatening between this company and the Tasmanian Copper Company in regard to contracts for the delivery of zinc-lead sulphide, the former company being now faced with the possibility of being short of ore if their process proves successful in operation at Rosebery. At the same time, the stage reached in the researches by the metallurgists mentioned above is that in which economic considerations constitute the main factor governing the decision as to which of two successful types of processes shall be adopted. In view of the probable success of a third process, it seems very desirable to await the demonstration of its degree of success and economic factors (provided it is not too long delayed) before finally deciding on the process to be adopted. If it so eventuates that the Tasmanian Metals Extraction Company's process proves to be the most desirable one, then a further amalgamation of interests should take place. In this way litigation can be avoided, and the money which would go to the lawyers could be much more efficiently employed in developing the Read-Rosebery field.

The decision to erect a 200-ton flotation plant at Rosebery is certainly sound, as even in the event of differential flotation not being the type of process ultimately selected for the treatment of the zinc-lead sulphide, flotation concentration will still be needed for eliminating the gangue from the lower-grade and the low-grade disseminated deposits. In addition, invaluable data will be obtained during its operation as to the results of the process of differential flotation and the amount of control attainable under large-scale working conditions.

It is essential that the work of providing cheap hydro-electric power for the field be immediately proceeded with. The Lake Margaret scheme can supply power for preliminary operations, but large scale working will necessitate much greater amounts of power, and as this can be supplied from the proposed King River scheme, which is designed to develop [redacted] horsepower, and which would necessitate the construction of only about 25 miles of transmission line, it is obvious that it should be carried to completion with all possible dispatch. If this is not done immediately, the development of the field will be still further delayed.

50,000

Finally, it remains to lay special stress on the point previously explained in this publication that all exploratory work should be carried out on the lines clearly indicated in this publication and Parts I. and II., and in accordance with the conception of the structural features and mode of origin of the ore-deposits evolved in the preparation of Parts I. and II., and clearly expressed therein, and confirmed by the exploratory work since carried out. It must be realised by the mining industry of the State (and the sooner it is fully realised the better) that exploratory work in mining should be directed by an economic geologist. This has been already realised in other parts of the world, with the result that most mining companies employ a staff of trained economic geologists, which is in charge of exploratory and developmental work. Just as the evolution took place in mining from a " manager " (who carried out all the technical work of the mine) to a " general manager " (who co-ordinated the work of the mine manager, metallurgist, mill superintendent, mechanical and electrical engineers), so the evolution has gone still further, and now the work previously performed by the mine manager has been divided between the economic gologist (who is in complete charge of all exploratory work) and the mining engineer (who is responsible for all mining operations and the actual extraction of ore). The application of this practice to the Read-Rosebery field and the other important mining fields of Tasmania is essential in the best interests of the mining industry.

X.—THE RELATION OF THE READ-ROSEBERY ZINC-LEAD SULPHIDE DEPOSITS TO THE SPELTER INDUSTRY OF THE COMMONWEALTH OF AUSTRALIA.

The world's output of spelter (the commercial term for zinc) is, approximately, 900,000 tons per annum. The annual production of the Commonwealth is, approximately, 500,000 tons of concentrates, which contain on an average 47 per cent. of zinc, giving an annual output of spelter of 235,000 tons, or 26 per cent. of the world's output.

When the Read-Rosebery field resumes production, it will supply a considerable amount of spelter, inasmuch as the ore has a high zinc content of 27·3 per cent., and the output of the Commonwealth will be considerably increased. It is impossible at present to say to what extent this will take place, as this is inherently bound up with the cost of equipment, metallurgical plant, &c., which are purely matters for the mining engineer; but it is certainly justifiable to assume that in view of the existence of 1,680,000 tons of "proved ore," and the general facilities for working, that an annual output of 150,000 tons of zinc-lead sulphide is assured. This would mean an annual output of 35,000 tons of spelter, bringing the Commonwealth production up to 270,000 tons, or 30 per cent. of the world's output. As previously discussed in this volume, there is every justification for the belief that future development will disclose larger quantities of ore, and, therefore, that the possible annual production will become greater. The Commonwealth's contribution to the world's output of spelter will thus be made to exceed 30 per cent., and thus Australia is destined to be one of the great controlling factors in the Zinc industry.

An important point that should not be lost sight of in this connection is the fact that the output from the Read-Rosebery field will be in the form of metallic zinc of exceptional purity (electrolytic zinc), or spelter, and is therefore immediately available to the metal market. Taking this, in conjunction with the inevitable development of the Electrolytic Zinc Works at Risdon, near Hobart, which are converting the Broken Hill concentrates to spelter, the Commonwealth of Australia will before very long be actually producing in the metallic form over 30 per cent. of the world's output of zinc.

XI.—CONCLUSION.

There has thus been presented a full and complete description of the Zinc-lead Sulphide Deposits of the Read-Rosebery District in all their various aspects. They undoubtedly constitute a most important asset to the State of Tasmania, and to Australia as a nation. Their size and importance are too great to permit of their concise description in this chapter, and therefore it will not be attempted. To gain a true conception of their size and importance a study of this volume is essential, which itself is not possible without a study of Parts I. and II. Parts I., II., and III., of the Read-Rosebery Bulletins are parts of a complete description of the Read-Rosebery zinc-lead sulphide deposits, and no one part is complete without the others, and, as such, the public are referred to them for the information they require.

The investigation has been an arduous one, but as the results are destined to be of considerable service to the field, the labour will not have been in vain.

LOFTUS HILLS, M.Sc.,
Assistant Government Geologist.

Launceston, 24th July, 1919.