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# GEOLOGY OF THE ATACOCHA MINE, DEPARTMENT OF PASCO, PERU[1]

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## ABSTRACT

The Atacocha lead-zinc mine, 15 km northeast of Cerro de Pasco in Central Perú, was the object of a detailed geologic investigation in 1952 by geologists of the Instituto Nacional de Investigación y Fomento Mineros and the U. S. Geological Survey. The mine is about 4,000 m above sea level, in an area of steep topography with about 900 m of relief.

Rocks exposed at Atacocha consist of limestone, chert breccia, quartz sandstone, and basalt that range from Late Triassic to Early Cretaceous

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[1] Publication authorized by the Director, U. S. Geological Survey.

in age. These rocks have been intruded by dacite of probable Tertiary age.

The most prominent structural features are the east limb of a large anticline east of the mine, and a south-plunging syncline to the west. The two folds are separated by a major fault zone. The rocks west of the fault have been dragged along it and are bent into a small cross fold, which seems to be the primary control for the localization of the ore. The main structural feature in the mine is a reverse fault on which limestone has been thrust over quartz sandstone.

The Atacocha mine contains about 30 km of underground workings on 16 levels, spaced over a vertical distance of 700 m. The workings explore portions of a reverse fault and follow veins in limestone and sandstone. Production was 600 tons of ore per day in late 1953.

Ore occurs in veins filling tension fractures in limestone and sandstone near the axis of the cross fold and in irregular replacement bodies in a narrow limestone horizon above and close to the reverse fault. Replacement bodies are also found west of the syncline in limestone close to the contact between limestone and overlying chert breccia.

The typical sulfide mineral association is galena, sphalerite, and pyrite, with minor chalcopyrite and jamesonite. Gangue minerals other than pyrite are calcite, rhodochrosite, clay minerals, and a minor amount of fluorite. Late veins of realgar and orpiment cut the ore minerals. Very little oxidation or supergene enrichment has taken place.

## INTRODUCTION

*Purpose and Scope.*—During the course of a nationwide survey of Peruvian lead and zinc resources, undertaken jointly by the Instituto Nacional de Investigación y Fomento Mineros and U. S. Geological Survey, a few districts were examined in detail. The Atacocha area was one of those selected, both because of its present important production and because it is little known geologically. This report describes some of the geologic features of the Atacocha mine, the largest in the district.

*Location and Access.*—The Atacocha mine is in the Department of Pasco in Central Perú, 15 km northeast of the great copper-lead-zinc deposit at Cerro de Pasco (Fig. 1). Atacocha is near the center of a mining district extending about 10 km from Machicán on the north to Milpo on the south. It is by far the most important mine in the district with a production of 600 tons of lead-zinc ore per day in late 1953. At that time Milpo produced about 75 tons of ore per day and Machicán about 5 tons.

Allweather roads lead from Atacocha and Chicrín (the mill site) to the railroad at Cerro de Pasco. A 3-kilometer aerial tram and a 20-kilometer road connect Atacocha and Chicrín. An underground connection has also been made by means of raises from the Chicrín adit, or 3,600 level, which passes under the principal mine workings. The nearest airport with scheduled service is at Huánuco, 80 km by road north of Chicrín.

*Topography and Relief.*—The camp at Atacocha is 4,000 m above sea level; mine workings extend from 4,300 m down to 3,600 m, the altitude of the mill at Chicrín.

The area is on the eastern edge of the high central plateau of Perú and is characterized by very rugged topography; the slope over the mine workings between 4,000 and 4,300 m, for example, is 30–35 degrees.

Quebrada Chicrín, which drains the area, is a tributary of the Huallaga River, a north-flowing stream that is part of the Amazon river system. The Huallaga River is an actively downcutting stream and relief is considerable, 400 m in the area mapped in Figure 2 and nearly 900 m between the river and the higher peaks.

*Climate and Vegetation.*—A wet and a dry season characterize the climate, with the dry season lasting from May to October. During the dry season, showers do occur, but in general the days are clear. Nights are cool throughout the year with frosts common above 3,500 m. Near the end of the dry season the scarcity of water becomes a problem at Atacocha, but Chicrín, being near the river, has ample water all year.

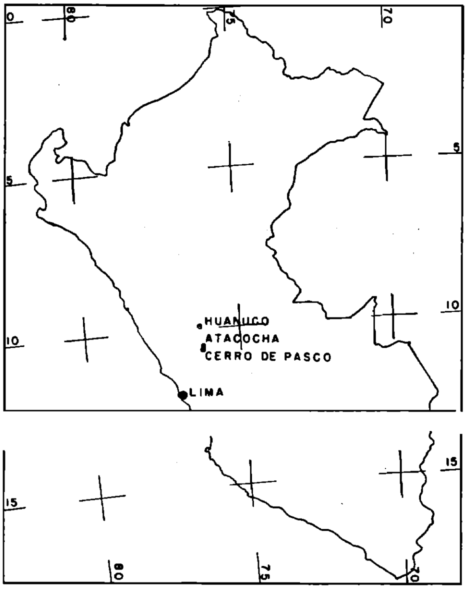

FIG. 1. Index map of Peru, showing the location of the Atacocha mine.

Most of the Atacocha area is above the tree line. Scattered trees are found in sheltered places up to an altitude of 4,000 m, but above this altitude the only ground cover is grasses and herbs. Eucalyptus has been introduced and is found as far up the Huallaga River as Chicrín, but stands suitable for mine timber are not found above 3,000 m.

*Field Work and Acknowledgments.*—Field work began in May 1952 and continued intermittently until December of that year. A plane-table map was made of the immediate mine area, using the company triangulation net for horizontal and vertical control. The underground workings were mapped geologically on a scale of 1:500 using company maps. Magnetic north is used for direction on all maps of this report.

The aid of two geologists of the Instituto Geológico del Perú is gratefully acknowledged. Alberto Manrique P. assisted the writer from May to October, and Ing° Eliodoro Bellido B. worked from October to December.

Wholehearted cooperation was received from all personnel of the Compañía Minera Atacocha. Ing° Edgardo Portaro, general manager, made the necessary preliminary arrangements for the study. Ing° Felipe Bautista C., general superintendent, provided living accommodations at Chicrín, and Ing° Carlos Valdivieso S., mine superintendent, provided accommodations and office space at Atacocha. Both gave freely of their time to discuss problems connected with the work, giving the writer the benefit of their long experience at Atacocha. Ing° Ortiz T. provided assistants and guides, as well as any information needed pertaining to company surveys. The other engineers at Atacocha, in particular Jorge Quintana S., who were in daily contact with the mining operations, assisted the writer by calling his attention to various points of geologic interest found in the course of mining. Officials of Hochschild y Cia., Ltda., kindly allowed access to an unpublished report on Atacocha by Otto Welter.

The work was greatly facilitated by the cooperation of Dr. Jorge A. Broggi, Director of the Instituto Geológico del Perú, who made available the resources of the Instituto. Mr. Frank Simons, Chief of the Geological Survey party in Perú, made valuable suggestions when visiting the party in the field, and also reviewed the manuscript for this report.

*Previous Work.*—Earlier geologic work in the Atacocha area consisted of a surface reconnaissance by J. B. Stone, of the Cerro de Pasco Corp., in 1928 and studies of the mine by Otto Welter in 1929 and by David Torres Vargas in 1948. The area was mentioned briefly in a report by Diaz (1).

The report by Welter was made before the mine was developed to any great extent. His interpretation of the surface geology differed from that of the writer in that he considered the quartz sandstone to be older than the limestone, the reverse of the present interpretation. As a consquence of his stratigraphic interpretation he considered the synclinal fold in the sandstone, shown in Figure 3, to be an inverted anticline. In addition, a fault was necessary between the sandstone and the limestone to the west and north. The writer's opposite interpretation will be discussed in subsequent sections of this report.

Geologic maps of D. Torres Vargas were made available by the company. The maps are similar to the writer's, except for a difference in the correlation of the altered rocks. Torres Vargas mapped most of the altered rocks as quartzite, whereas the writer believes that they are largely altered limestone.

## DESCRIPTIVE GEOLOGY

The general geology of the Cordillera Central in the Department of Pasco and Junin has been described by McLaughlin (3), Steinmann (5) and Harrison (2). In brief, the history of the region, from the middle Paleozoic to the Upper Cretaceous, was one of intermittent marine sedimentation, with the exception of some vulcanism and the deposition of nonmarine red beds in the Permian, and again in the Cretaceous. Orogeny began in Late Cretaceous time and continued intermittently through the Tertiary. The sedimentary rocks were folded and faulted, and intruded by igneous rocks of intermediate composition. Deposition of metallic sulfides took place after the intrusions. The region was eroded to a low undulating plain, which was subsequently elevated to its present position by a series of three uplifts. The region is being eroded so rapidly at present that except on the central plateau there is little opportunity for supergene enrichment of the mineral deposits.

Triassic to Cretaceous sedimentary rocks and Tertiary intrusives are the only rocks exposed near the Atacocha mine. The mine is located near the axis of a small fold caused by drag along a major fault. Small reverse faults probably associated with movements on the large fault are found in the mine and are important ore controls.

*Triassic and Jurassic Limestone.*—The oldest rocks exposed at Atacocha are limestone and interbedded shale of Late Triassic age. They crop out over a wide area north, east, and south of the mine (Fig. 2). Gray to black limestone is the predominant rock, and black shale a minor constituent. Chert nodules and lenses are common in the limestone. Individual beds range in thickness from 10 cm to 1 m. The entire series is at least 1,300 and probably more than 2,000 m thick, as 2,100 m of conformable limestone beds are exposed in the Chicrín adit, although there may be some repetition by faulting. The base of the series is not seen at Atacocha but is found a few kilometers west of the mine where the limestones rest with slight angular unconformity on the red beds of the Mitu formation of Permian age.

Limestone and shale of Early Jurassic age rest conformably on the Triassic rocks near Chicrín. Fossils are rare and the contact could not be located precisely. No Jurassic fossils were found near Atacocha, but the presence of Jurassic strata cannot be ruled out.

In the mine area the lower part of the section consists of thick-bedded gray limestone. These beds are overlain by 100 m of thin-bedded black limestone and shale, that is overlain by 40 m of thick-bedded limestone. Conformably overlying this section are 40 to 80 m of interbedded brecciated red chert and clastic limestone that is in fault contact with quartz sandstone of the Goyllarisquisga formation. Ore has been found only in and above the thin-bedded limestone and shale; the lower thick-bedded limestone seems to be barren.

*Cretaceous Rocks.*—Resting with slight disconformity on the limestones are beds of the Goyllarisquisga formation of Early Cretaceous age. The formation was first named by McLaughlin (3) from exposures at Goyllarisquisga, northwest of Cerro de Pasco. In the mine area the formation consists of bedded chert and chert breccia at the base, overlain by dark shale and fine-grained sandstone containing charred wood fragments; these in turn are overlain by white cross-bedded quartz sandstone that makes up the bulk of the formation.

The Goyllarisquisga formation crops out in the trough of a south-plunging syncline at Atacocha and is found also above the limestone along the Huallaga River at Chicrín.

Bedded dark-gray chert can be seen lying on the limestone in the Curiajasha area. This chert and associated chert breccia contrasts strongly with

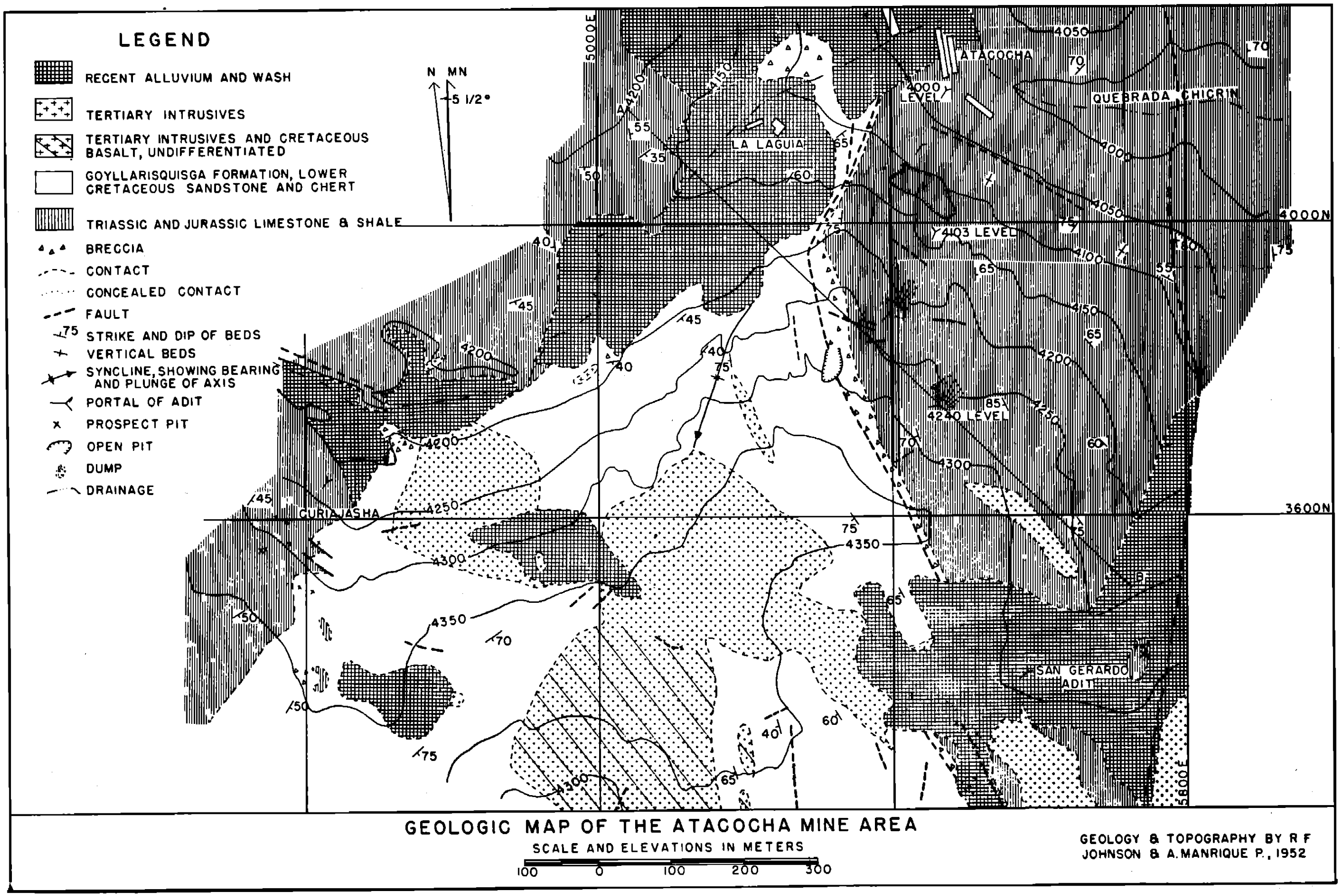

FIG. 2. Geologic map of the Atacocha area.

the brecciated red chert mentioned previously, but both may be in the same stratigraphic position.

Basalt flows are interbedded with and overlie the upper quartz sandstone beds. The flows are metamorphosed by a dacite intrusion near the mine and are indistinguishable in the field from fine-grained borders of the intrusive; exposures were not good enough to map the two rocks separately. Unmetamorphosed flows near Chicrín are found to be olivine basalt with diabasic texture. Violet-colored titanaugite phenocrysts up to 4 mm in diameter are a striking feature of some flows.

*Intrusive Rocks.*—The sedimentary rocks and lava flows have been intruded by dacite (or tonalite porphyry). The largest intrusive is an irregular stock that crops out from the San Gerardo adit northwesterly to Curiajasha. Dikes and sills of similar composition are found on all sides of this stock over an area of several square kilometers.

The rock is greenish gray to dark gray on fresh surfaces, and weathers to a reddish brown. Phenocrysts of plagioclase and quartz up to 3 mm. in diameter, with smaller crystals of hornblende and biotite, are enclosed in a fine-grained groundmass. In thin section the composition of the plagioclase proves to be on the andesine-labradorite boundary, $An_{50\pm5}$. Phenocrysts make up 50 percent of the rock with plagioclase forming about half of the phenocrysts. The percentages of quartz, hornblende, and biotite are about equal. Biotite is commonly altered to an aggregate of carbonate, chlorite, and epidote. Quartz and plagioclase phenocrysts generally have rounded corners or are embayed showing the effects of resorption. The groundmass is crystalline and is largely plagioclase and quartz; orthoclase is probably present but could not be positively identified.

*Contact Metamorphism.*—Contact effects of the intrusive rock vary both in the intrusive bodies themselves and in the intruded rocks. Along some contacts the dacite has a chilled border very similar in color and texture to the metamorphosed basalt, but on other contacts no chilled border is evident. Quartz sandstone shows little change; along some contacts the sandstone has been converted to quartzite. Contact alteration of the limestone, with the development of wollastonite and garnet, was found in two areas, one on the 4,103 level near coordinate 3,600 N, and the other on the mine road about 2 km from the mine. Limestone seems to be unchanged along some porphyry contacts, particularly near the smaller dikes.

*Alluvium.*—No rocks younger than the dacite are found at Atacocha. Unconsolidated alluvium covers the bottoms of valleys, and slope wash and talus mantle from hillsides. This unconsolidated material is not thick, but it effectively obscures the bedrock over extensive areas.

## STRUCTURE

The mine area can be divided into three distinct structural groups. East of the mine the sediments form the flank of a large anticline and have a regular east dip. South and west of the mine the rocks are folded into a south-plunging syncline that has been intruded by the igneous rocks. North and west of the mine the beds of limestone seem to be thrown into minor folds that are difficult to relate to either of the other structures, but the major structure seems to conform to the synclinal structure found farther south. Faulting is extensive in the western blocks, and strike faults are found in the mine where the 3,600-level adit crosses the eastern block, although these are not apparent on the surface. The ore bodies and veins seem to be confined to the southwestern block.

*Folds.*—The most prominent fold in the area is a faulted anticline that can be traced for several kilometers. The east flank of this anticline is well exposed between Atacocha and Chicrín; the anticline is faulted, probably near its axis, and the west flank is not clearly defined. The sandstones and immediately underlying limestones west of Quebrada Chicrín and south of La Laguia have a steep west dip, and probably represent a portion of the west flank. The structure in the limestone is not well known north of La Laguia where small irregular folds complicate the picture.

FIG. 3. View southward showing the Atacocha mine. The syncline in sandstone is visible at upper right and cross fold on the left. The dashed line represents the approximate trace of the No. 1 fault.

An asymmetric syncline is well exposed in the sandstone cliffs near La Laguia (Fig. 3). The steeper east flank dips 75° W and the west flank dips 40–60° E. The axis of the syncline strikes N 20 E and plunges 40° SW. To the south the syncline is interrupted by intrusive rocks. The limestone beds to the north seem to reflect the synclinal structure, but the relations are not clear.

A small cross fold formed by drag along a large fault was mapped in the sedimentary rock directly over the mine workings. This fold seems to be one of the principal controls in the localization of the Atacocha ore bodies. Ore is found near the axis of the fold, in veins and in replacement bodies.

*Faults.*—A large fault zone extends along the east side of the mapped area and for several kilometers north and south. Its position is well marked topographically along part of its length, particularly on the east side of Quebrada Chicrín, but in many places it cuts across the present topography, and its position is marked by changes in strike of the limestone beds and by a breccia zone. A 60-meter breccia zone was found where the 3,900-level adit crosses the fault zone.

Total displacement and direction of movement are not known. The east side may have moved up and to the north relative to the west side. North of Atacocha the beds west of the fault are bent sharply and dragged to the north showing that the movement had a horizontal component.

The fault appears to be premineral because the structures that control ore deposition are due to movements along it. In the 3,900-level adit the fault breccia is recemented, except along the western contact where a gouge zone may represent a later period of movement.

The No. 1 fault is the chief fault exposed by the mine workings. Its trace on the surface is not well exposed, but it must crop out at the base of the brecciated red chert zone; black gouge marks the outcrop of the fault just south of La Laguia. The No. 1 fault dips 45 to 60 degrees east below the 4,103 level and is the contact between Triassic or Jurassic limestone in the hanging wall, and sandstone of Cretaceous age in the footwall; this relationship indicates that the fault is a reverse fault. The fault closely follows the strike of the bedding, even to the turn made in the cross fold. On and above the 4,103 level the No. 1 fault steepens and joins a steep west-dipping fault (Fig. 4). This latter fault is on the contact of the red breccia and sandstone and closely follows the dip of the beds as well as the strike.

No direct evidence was found for the premineral or postmineral age of the No. 1 fault. Veins terminate against it, but no evidence was found that indicated offsetting of the veins. The abundant gouge formed along the fault may have inhibited the formation of potential ore-bearing structures. Mr. Bautista reported that on one level mineralization seemed to be continuous across the fault zone between the Veta Prima (Main Vein) and the No. 1 ore body, which also suggests a premineral age for the fault. Smaller faults branching from the No. 1 fault in the sandstone do offset veins a few meters, so possibly there was both premineral and postmineral movement.

Numerous smaller faults were observed in the course of surface mapping. The most common strike directions are within a few degrees of north and N 60–80° W. Many other faults are undoubtedly present but escaped notice. A probable fault exists in the San Gerardo area where the quartz sandstone south of the porphyry mass in the quebrada is offset to the west relative to the sandstone north of the porphyry. The porphyry may have been intruded along a zone of weakness caused by faulting.

Hydrothermal alteration and offsetting of the contact between the chert and limestone in the Curiajasha area indicate faulting, and small northwest-striking faults have been found, but no large fault was found that could be the one mapped by Welter (8). He mapped a large fault on the contact, extending from near Curiajasha east to La Laguia and on to the north, and indeed such a fault was essential to his stratigraphic interpretation that the sandstone is older than the limestone. There is evidence of local faulting on the contact, but in other places the chert can be seen lying conformably on the limestone.

## GEOLOGIC HISTORY

Limestone of Triassic age is the oldest rock exposed in the mine area, either on the surface or in the mine workings. The limestone is largely recrystallized, but its association with limy shales indicates that it is biochemical in origin rather than clastic (4, p. 293). The presence of black limy shale also suggests that stagnant conditions existed at times during the deposition of the limestone.

The area was probably uplifted and eroded in the interval between the deposition of the limestone and the Goyllarisquisga formation, even though the two formations are largely conformable. A conglomerate containing limestone and chert cobbles is present on the contact at Chicrín. The contact is marked by chert and chert breccia in the mine area, indicating a possible marine basin that did not extend as far east as Chicrín. The isolated limestone outcrops in the Curiajasha area, near the contact, may represent an uneven surface on which the chert was deposited.

The sea receded during the period in which Goyllarisquisga sediments were deposited. The marine chert was followed by carbonaceous shale and fine-grained sandstone representing deltaic conditions, and these in turn were followed by crossbedded quartz sandstones that probably represent flood-plain deposits. Volcanic activity began near the end of the period of sandstone deposition and brought that period to a close. A new marine invasion followed as shown by marine limestone beds above the basalt flows. This limestone has been eroded from the mine area, but is present at Chicrín.

After a period of unknown duration the sediments were folded and faulted and subsequently were intruded by dacite. The dacite intrusions in Central Perú are generally considered to be Tertiary in age.

Sometime after the intrusion, the rocks were altered by hydrothermal solutions, and the metallic sulfides were deposited. Galena-rich veins were formed in the quartz sandstone, and galena-sphalerite-pyrite veins and replacement bodies in the limestone.

A large region in central Perú was reduced to an area of low relief by Pliocene time, according to McLaughlin (3) and Harrison (2), and subsequently elevated to its present height in three stages.

Glaciers were present in the Atacocha area during the Pleistocene but their extent is not known. Excavations in Quebrada Chicrín above the mine exposed unsorted gravels, probably of glacial origin. Closed basins and U-shaped valleys found above 4,000 are also evidence of glacial activity.

At present erosion is proceeding so rapidly that there is little opportunity for soil development, or for the development of zones of oxidation or supergene enrichment of ore bodies. Sulfide minerals are found at the surface, notably in the San Gerardo area.

## HISTORY AND PRODUCTION OF THE ATACOCHA MINE

The presence of mineralization at Atacocha was known in colonial times, but no work was done due to the low silver content of the ore.

Modern exploration of the deposit began about 1910. J. H. Fleming abandoned the property after doing a small amount of work near the present 4,240 level. Another group also abandoned the property without doing much work.

About 1920 a claim on the property was filed by Sr. J. F. Gallo of Cerro de Pasco. He carried on intermittent operations until 1929 when conditions caused by the world economic crisis forced a shut down. In 1936 he resumed operations on the 4,000 level, and subsequently found the No. 1 ore body. On the basis of this discovery the Compañía Minera Atacocha was formed. The company developed the mine rapidly, and expanded it to its present important position.

TABLE 1

METAL PRODUCED FROM THE ATACOCHA MINE, 1940–1952 (METRIC TONS)

| Year | Ore milled | Lead | Zinc | Silver (kilos) |
|---|---|---|---|---|
| 1940 | 49,019 | 3,337 | | 9,335 |
| 1941 | 47,470 | 4,054 | 2,734 | 10,208 |
| 1942 | 50,868 | 5,615 | 6,215 | 12,628 |
| 1943 | 51,146 | 5,769 | 5,267 | 14,718 |
| 1944 | 57,329 | 7,710 | 9,195 | 16,636 |
| 1945 | 58,519 | 7,240 | 9,657 | 17,894 |
| 1946 | 52,257 | 5,768 | 7,373 | 16,967 |
| 1947 | 54,902 | 5,628 | 4,529 | 13,640 |
| 1948 | 56,613 | 4,409 | 2,242 | 10,980 |
| 1949 | 59,263 | 6,105 | 1,852 | 14,583 |
| 1950 | 111,162 | 9,306 | 4,419 | 26,100 |
| 1951 | 155,106 | 11,357 | 5,135 | 28,931 |
| 1952 | 192,692 | 14,950 | 6,698 | 35,216 |

Data from "Anuario de la Industria Minera en el Perú" and from company records.

Production figures for the early operations are not known. Table 1, showing the production since 1940, gives some idea of the steady growth of the operation.

## GENERAL FEATURES OF THE ATACOCHA MINE

The mine is developed by about 30 km of workings on 16 levels, covering a vertical distance of 700 m. Vertical spacing between levels ranges from 25 to 55 m, with one gap of 175 m betweeen the Chicrín tunnel, or 3,600 level, and the principal mine workings above. The altitudes used for numbering levels are based on an arbitrary datum that is about 25 m too low, but the distances between levels are correct. All the levels are connected by internal shafts or raises. The workings follow veins in limestone and quartz sandstone, and in the upper levels also explore a strong fault zone extending south toward the San Gerardo area.

Several unmineralized faults containing abundant gouge are found in the mine. The relation between four numbered faults of this type is best shown by Figures 4 and 5. Number 1 fault is the main fault along which the limestone has been thrust over the quartz sandstone; it has been traced from the 3,805 level up to the 4,103 level. At the 4,103 level the fault steepens and joins a steeply dipping fault separating the brecciated red chert and reddish quartz sandstone. The downward extension of this latter fault is not known; it does not cut the "D" vein on the 4,048 level. Faults numbered 3 and 4 seem to be splits from the footwall of No. 1 fault as shown on the section (Fig. 4).

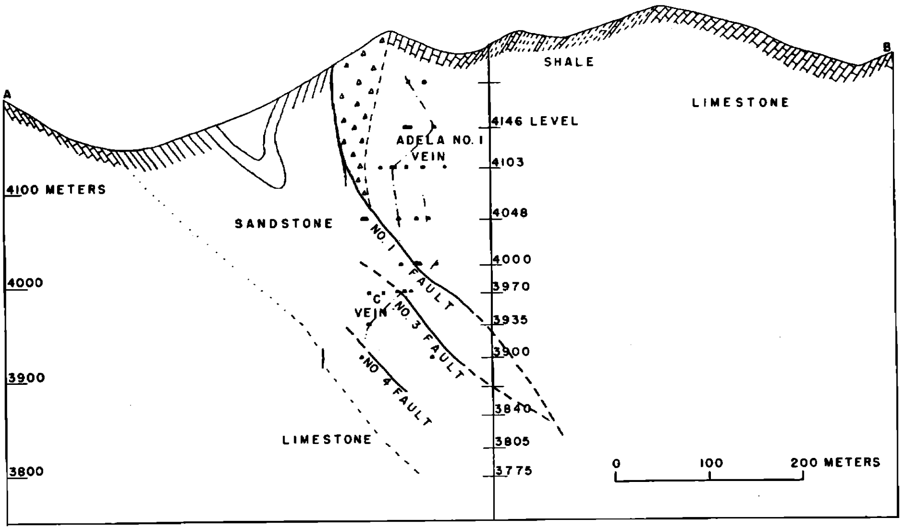

FIG. 4. Cross section through the Atacocha mine.

The importance of the No. 1 fault and its extension above the 4,103 level is its relation to the replacement ore bodies. The largest ore bodies found to date have been in the limestone hanging wall within a few meters of the fault. The abundant gouge may have acted as a barrier to the ascending solutions from which the ore minerals were deposited, concentrating them below the fault. In areas where the fault surface was broken by cross structures, such as Veta Prima (Main Vein) and possibly the Tres Mosqueteros dike, the solutions had easy access to the limestone and the replacement of favorable beds by ore minerals was possible.

The No. 2 fault is a steep fault below No. 4 fault that seems to follow a shale band between the quartz sandstone and the underlying chert breccia. The intersection of the two faults plunges southeast. Neither the shale nor

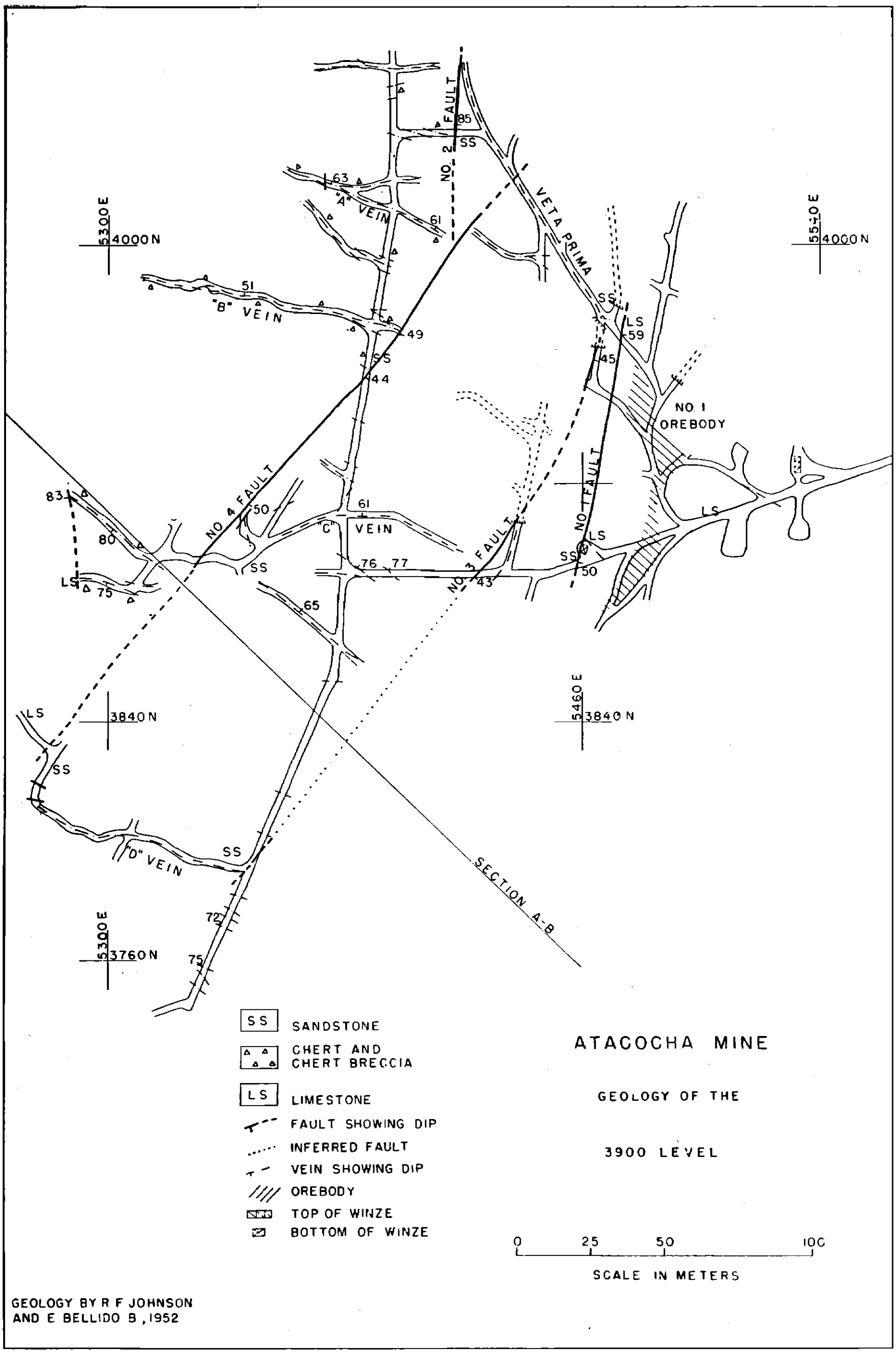

FIG. 5. Geology of the 3,900 level, Atacocha mine.

a fault was found above the No. 4 fault. On the 3,900 level the No. 2 fault contains abundant gouge, but on lower levels it is marked only by shearing in the indurated shales. The Veta Prima terminates on the west against No. 2 fault or its enclosing shale. This vein may be faulted, but, as it narrows and becomes pyritic on entering the shale, a more probable explanation is that the vein fissure dies out in passing from the brittle sandstones into the incompetent shale. Not enough work has been done west of the shale to see if the fissure develops again in the brittle chert breccia.

Innumerable small fractures are found in the mine. Some are unmineralized, others contain only pyrite, and others contain sphalerite and galena as well as pyrite.

## ORE DEPOSITS

Ore is found as irregular replacements in limestone and as veins in either limestone, quartz sandstone, or chert breccia.

*Replacement Bodies.*—Several replacement ore bodies have been found during the development of the mine. The majority have been found in the limestone above or east of the No. 1 fault or its upper extension; the No. 5 ore body is partly in red chert breccia east of the fault (Fig. 6). Ore bodies have also been found below the 3,900 level in the limestone west of the syncline in quartz sandstone. The contact of the chert breccia and limestone is faulted on the 3,900 level, but seems to be a normal depositional contact below.

Veins have been followed westward through the quartz sandstone and gray chert breccia, and on entering the limestone some of them have opened up into irregular replacements. Not enough work has been done as yet to determine the size of these bodies. A large ore body in limestone was found on the 3,600 level west of the chert breccia.

The replacement deposits are the major source of ore. They consist of incomplete replacements of limestone by pyrite, sphalerite, and galena, with varying amounts of gangue, largely clay minerals. They vary widely in both size and grade. The No. 1 ore body, now largely worked out, had a pitch length of about 250 m, a breadth of 40 to 70 m, and a thickness of from 4 to 10 m. The No. 4 ore body has a stope length of 35 m and a thickness of as much as 25 m but may not have the vertical extent of the No. 1 ore body. The grade of the ore ranges from 8 to 20 per cent combined lead and zinc in approximately equal proportions.

A spatial relationship exists between some ore bodies and the stronger veins. Ore body No. 1 and the Veta Prima are found together on opposite sides of the No. 1 fault. Fault No. 3 splits from the No. 1 fault near the Veta Prima (Fig. 7) and may also have some relationship with the localization of the No. 1 ore body. Ore bodies 3 and 4 are located at the change in strike of the No. 1 fault, near the axis of the cross fold mentioned earlier, and on the opposite side of the No. 1 fault from the "D" vein. Orebody No. 5 is adjacent to the Tres Mosqueteros dike that may cross the No. 1 fault. These relationships suggest that the ore bodies formed where strong fractures crossed the No. 1 fault and intersected the favorable limestone horizons above.

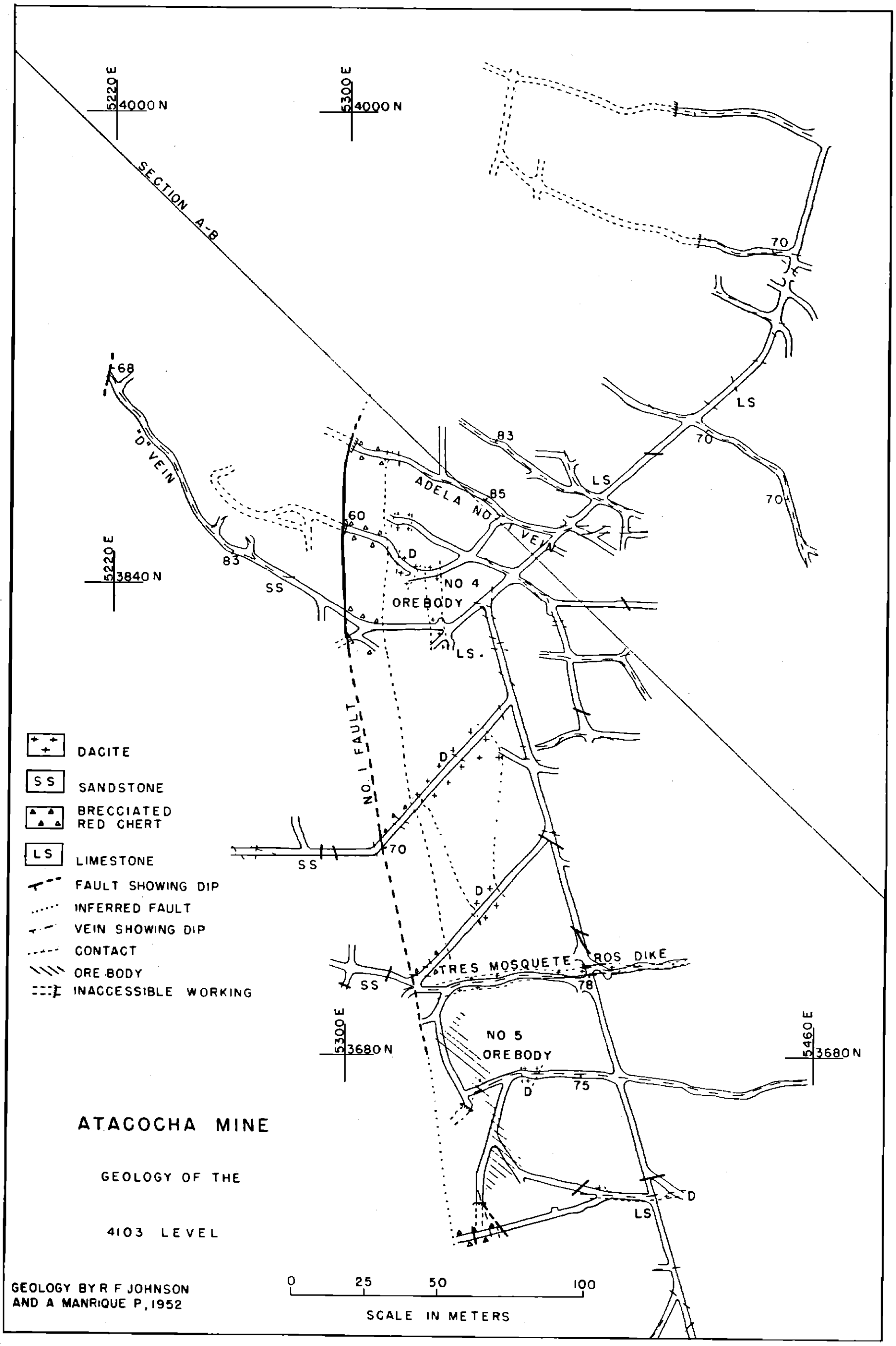

FIG. 6. Geology of the 4,103 level, Atacocha mine.

The dacite does not seem to have been important in the formation of ore bodies, except for the Tres Mosqueteros dike, which forms the northern limit of the No. 5 ore body. The contact-metamorphic area on the 4,103 level in which garnet and wollastonite were formed is not ore bearing.

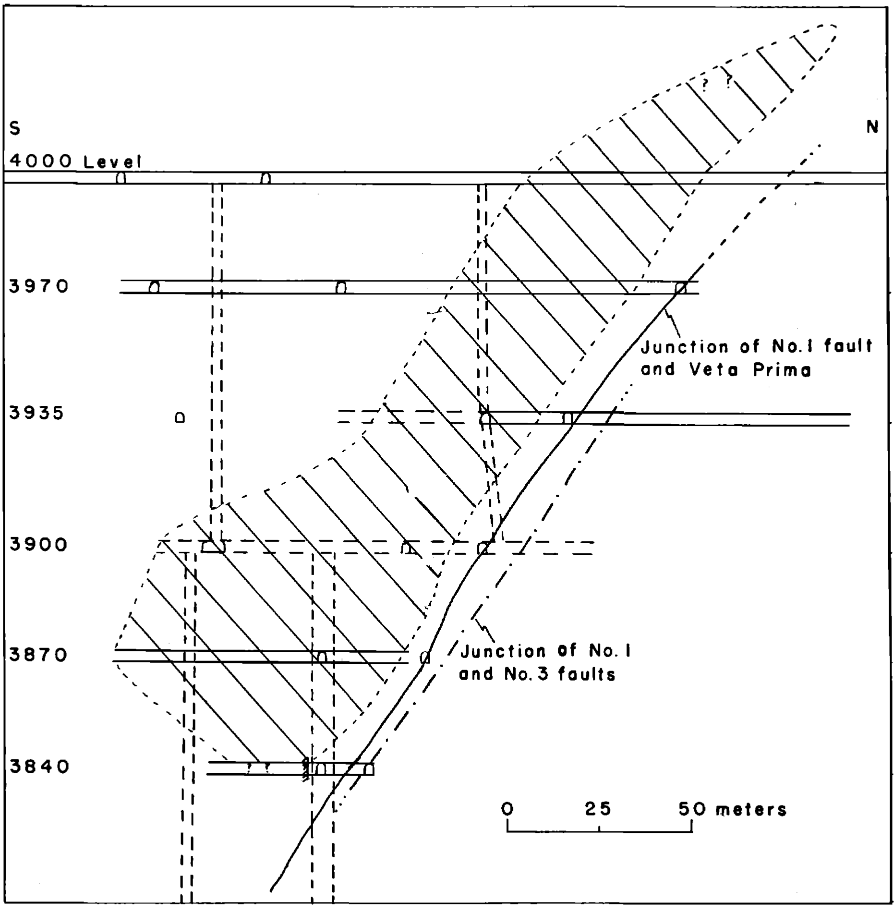

FIG. 7. Longitudinal section of a portion of the No. 1 fault, showing the projection of the No. 1 ore body to the fault plane, and the relation of the ore body to the Veta Prima and the No. 3 fault.

*Veins.*—Veins are found throughout the mine in any rock type. They range in size from irregular stringers to large veins, such as the "D" vein, which has been followed for over 150 m along the strike and for over 300 m vertically. The veins now being mined are usually less than 1 m in thickness, but locally may be 3 to 4 m thick.

Veins of minable width are found in limestone and thin-bedded shale above the 4,000 level, and east of the No. 1 fault. They are most numerous and largest near the axis of the cross fold shown by the bend in the No. 1 fault (Fig. 6). The veins narrow and pinch downward and have not been found below the 3,970 level. The reason for their pinching is not known; the curve in the No. 1 fault is not as pronounced on the 4,000 level as it is above, so possibly the cross fold dies out in depth. Very little work has been done along the No. 1 fault below the 4,000 level. The veins in limestone range in grade from 15 to 28 percent combined lead and zinc, with zinc generally slightly in excess of lead.

Veins in quartz sandstone and chert breccia are found on all levels; below the 4,000 level they are the principal source of ore. The Veta Prima and the "C" and "D" veins are the largest of this type. The Veta Prima has been found on every level from the 4,000 to the 3,775 and it still continues downward. The No. 1 and No. 2 faults form the east and west limits of the Veta Prima, which strikes northwesterly and has a steep southwest dip. The vein is 80 to 100 m long and 1 to 4 m wide.

The "C" vein strikes nearly east and dips 50 to 70° N. It is limited on the east by the No. 1 fault and on the west by the "D" vein or by the No. 4 fault. The segment between the No. 1 and No. 3 faults is missing below the 3,935 level. The "C" vein wedges out above the 4,000 level against the intersection of the "D" vein and No. 1 fault, but lengthens rapidly down dip reaching a length of about 100 m on the 3,935 level. Below the 3,900 level only segments of the fault are known, but it has been followed to the 3,840 level. The vein is from 0.5 to 2 m wide.

The "D" vein has been followed from above the 4,192 level down to the 3,900 level. It has a nearly vertical dip and the strike varies from N 40–70° W. The No. 1 fault is the eastern limit on most levels. On the 3,900 level, however, the vein has been found only west of the No. 3 fault; a diamond-drill hole drilled east of the fault failed to locate the vein. The vein dies out in chert breccia to the west on some levels, but on others it has not been followed beyond a large fault. On the 3,900 level the vein has not been found west of the No. 4 fault. The "D" vein has a maximum length of about 150 m and a width of from 0.5 to 2 m.

The grade of the veins in sandstone or chert breccia ranges from 10 to 17 percent lead and from 2 to 3 percent zinc. The reason for the difference in the lead-zinc ratios in ores from the siliceous rocks and those from the limestone is not known.

Veins in dacite are mostly small, but ore-bearing fractures are widespread. Many of the dacite contacts are mineralized. The Tres Mosqueteros dike is found on all the levels above the 4,000 level in the hanging wall of the No. 1 fault. It contains veins of minable width, and the No. 5 ore body extends south from it. The dike has not been explored to see if it crosses No. 1 fault; a dacite dike mapped on the surface west of the fault may be the same as the Tres Mosqueteros dike.

A suggestion of a radial pattern can be seen in the plan of the veins on the 4,103 level (Fig. 6). The veins in and near the Tres Mosqueteros dike strike nearly east, but those farther north strike a little north of west. This pattern could be due to tension fractures formed during the formation of the cross fold. Fracture filling seems to have been the principal process in vein formation; replacement is of minor importance.

## MINERALOGY AND CLASSIFICATION

A brief description is given of the mode of occurrence and paragenesis of the ore and gangue minerals noted during the Atacocha study. A detailed mineralogic study of the ore was not attempted so the list is probably not complete.

### *Sulfides and Sulfosalts*

*Arsenopyrite.*—Small amounts of arsenopyrite are found intergrown with and replacing pyrite, and in turn being replaced by sphalerite and galena. The arsenopyrite is massive; crystal faces were not noted.

*Chalcopyrite.*—Copper is a minor constituent of Atacocha ore and is not of economic interest. Chalcopyrite, the most common copper mineral, is found throughout the mine in scattered small grains and as blebs in sphalerite.

*Galena.*—Galena is one of the principal ore minerals. Small crystals are found but the usual occurrence is in granular masses with typical cubic cleavage. The cubes in a specimen from the 4,263 level are oriented so as to give the specimen a banded appearance. Cleavage fragments are small and cubes over 5 mm on an edge are rare. Galena was deposited after most of the pyrite and probably contemporaneously with the sphalerite. Galena-bearing veins can be seen cutting pyrite veins. The "D" vein has a galena-rich center bordered by sphalerite and pyrite so at least some of the galena seems to be younger than sphalerite.

The silver content of the ore varies directly with the galena content. No silver minerals were seen, so probably the galena is argentiferous.

*Jamesonite.*—A lead-antimony sulfide, tentatively identified as jamesonite, was found on the 3,900 level. The mineral shows a good cleavage in one direction. It is associated with galena, sphalerite, and pyrite.

*Marcasite.*—Marcasite from Atacocha is listed in the Catálogo Mineralógico Nacional, but none was noted during the mine mapping.

*Orpiment.*—Bladed and micaceous yellow orpiment is found associated with realgar. Orpiment is more abundant than realgar, but most of it seems to be an alteration product.

*Pyrite.*—Pyrite is the most abundant sulfide in the area, and with sphalerite and galena forms the characteristic mineral assemblage. Pyrite, however, is found over a much wider area than the other sulfides. Concentrations of pyrite are commonly present along intrusive contacts, and barren pyrite veins occur. Massive and crystalline pyrite are both common. Pyrite in the ore bodies is massive or forms small striated cubic crystals, but in the hydrothermally altered zones the disseminated pyrite is generally found as small pyritohedrons. Crystals over 2 cm in diameter are rare. Pyrite was probably the earliest sulfide to form, and it continued to be deposited throughout most of the period of sulfide deposition.

*Realgar.*—Realgar and orpiment are abundant on the 4,240 level and were noted in seams in the gouge of No. 1 fault as far down as the 4,103 level. They are also found in fractures in limestone on the 3,600 level between 1,200 and 1,300 m from the portal. Large specimens of realgar and orpiment were obtained from a vein in limestone on the 4,240 level. The realgar occurs as orange platy masses enclosed in orpiment, and as small red crystals that resemble cinnabar. The larger realgar-orpiment veins are not found associated with lead-zinc minerals, but realgar fills fractures in a small body of ore.

*Sphalerite.*—Light-brown to nearly black sphalerite occurs in varying proportions with galena. It occurs as a massive mineral with good cleavage, as rounded grains, and as crystals that may show multiple twinning. Age relations of the sphalerite are not well known. Specimens from the ore bodies are difficult to secure as the ore crumbles readily. In the veins, sphalerite and galena are later than some of the pyrite.

*Tennantite.*—Tennantite was identified in one polished surface of Atacocha ore. It was found replacing pyrite, but its age relation to adjoining galena and sphalerite could not be determined.

*Calcite.*—Veins of calcite are abundant in limestone, and some are found in quartz sandstone, where calcite is a common gangue mineral. The calcite is white or cream and medium grained with rhombohedral cleavage. It is commonly intergrown with rhodochrosite in the ore-bearing veins. These carbonates are among the latest minerals to form; they fill the centers of veins and enclose angular fragments of sulfides. Veins of fibrous calcite 1 to 2 cm wide are common features in the upper mine workings. They are definitely postore and may be supergene in origin.

*Cerussite.*—Cerussite was found in the Curiajasha area as colorless grains in a yellow earthy groundmass.

*Chlorite.*—One or more members of the chlorite group of minerals are present in two areas of the mine. Chlorite is abundant in a sheared zone on the contact of the limestone and chert west of the quartz sandstones on the 3,935 level and also occurs along what may be the same contact on the 3,600 level.

*Clay Minerals.*—White clay minerals are common constituents of the hydrothermally altered rocks close to and in the ore bodies. Positive identification was not possible, but the microscope revealed clay minerals with high and low birefringence, so both the kaolin and montmorillonite groups may be represented.

*Fluorite.*—Violet and green fluorite occurs in carbonate veinlets in the upper mine levels, both in ore bodies and in country rock. Abundant fluorite is reported on the 3,840 level below ore body No. 1, but the area was inaccessible at the time of the examination. Fluorite also occurs in tiny fractures in porphyry and quartz sandstone. Cubes and irregular masses with grains as much as 2 cm in diameter are associated with calcite and rhodochrosite. Fluorite is apparently one of the last minerals to form, as the carbonate veinlets in which it is found cut the ore minerals.

*Gypsum.*—Gypsum occurs as thin scaly crystals in fractures and on exposed surfaces, and in massive granular aggregates in the alteration zone of the ore bodies and veins.

*Limonite.*—Limonite occurs pseudomorphous after pyrite, and as stalactitic and botryoidal forms in old workings. It is a common oxidation product.

*Malachite.*—Malachite was found both in old workings and on the surface. The best occurrence of malachite is along the road about 2 km from the mine, where it is found in old prospect trenches associated with chalcanthite.

*Manganese Oxides.*—Black manganese oxides are common on the walls of some workings, and in vein outcrops in limestone adjoining the mine area. Psilomelane is the most abundant manganese oxide in the vein outcrops with pyrolusite present in small amounts. The manganese-bearing outcrops are not indicators of ore below; some of the larger veins of this type have been explored with discouraging results.

*Melanterite.*—Fibrous green melanterite was found in old workings.

*Muscovite.*—Sericite is present in sheared zones in the hydrothermally altered rocks, but it is not a common alteration product at Atacocha.

*Phlogopite.*—Abundant phlogopite was found in a fault zone on the 3,600 level associated with biotite, hematite, chlorite, and pyrite.

*Quartz.*—Small acicular crystals of quartz are found in vugs in the veins and ore bodies, but veins of quartz are not known. Silicification of the limestone is the common type of alteration near No. 1 fault, but the silica mineral could be either quartz or chalcedony.

*Rhodochrosite.*—Rhodochrosite is a common gangue mineral. It is generally massive, but a scaly form lines vein cavities. The fresh mineral is pink, but it becomes nearly white on exposure to air.

*Serpentine.*—Serpentine nodules occur in limestone south of Gueshgua and west of La Laguia. Massive serpentine and the fibrous variety chrysotile were found in a fault zone on the 4,240 level.

The mineralogy of the Atacocha ores is indicative of deposition under moderate conditions of temperature and pressure. Realgar and orpiment are typical epithermal minerals, but they were deposited after the deposition and fracturing of the other sulfides. The galena-sphalerite-pyrite association is found in all classes of hydrothermal deposits, but the association with jamesonite and tennantite, and particularly with the gangue minerals rhodochrosite and fluorite, indicate moderate to low temperature and pressure. The deposits should probably be classified as leptothermal.

## HYDROTHERMAL ALTERATION

Well-defined alteration envelopes around the ore bodies are not found at Atacocha. Alteration of the carbonate wall rocks is nearly everywhere present, but it varies greatly in intensity and shows no consistent relation to known features. The sandstone and chert seem to be little affected by hydrothermal alteration.

The limestones have been altered for varying distances from the ore bodies and veins, and alteration is nearly continuous in the hanging wall of No. 1 fault. Silicification is the commonest type of alteration. Argillization is prominent near some ore bodies but may be weak or absent near others. Disseminated pyrite is present in both types of alteration.

The first alteration effect is a bleaching of the limestone, which may be slight and may be the only change noted outward from the ore. With more intense alteration the limestone becomes nearly white and loses its distinctive structural features. Highly altered limestones are difficult to distinguish from fine-grained quartz sandstone, but chert lenses that resemble those in unaltered limestone may be present. In one area on the 4,000 level, north of coordinate 3,760 N, and east of No. 1 fault, alteration is so intense that the original rock type could not be determined; the fault is shown as the contact because of similar relations elsewhere.

Zones of hydrothermal alteration are favorable for exploration at Atacocha, but additional factors need to be considered. Alteration near the veins in sandstone is negligible, and some ore in limestone is found in only slightly altered rock. On the other hand the limestones near No. 1 fault are nearly everywhere altered, so alteration alone is not an infallible guide to ore. Detailed microscopic examination of altered rocks may show an association between certain alteration minerals and ore, but without equipment and trained personnel this is of doubtful practical aid in prospecting.

## DEPOSITIONAL HISTORY

The events leading up to the deposition of metallic sulfides at Atacocha are not well understood, but a possible sequence is offered. The major fault zone east of the mine, and the subsidiary thrust faults such as No. 1 fault, may have originated during the period of orogeny in which the strong folding took place, probably prior to the porphyry intrusions. The intrusions may have accompanied renewed movements on the faults during which the cross fold that localized the ore bodies was formed or accentuated. No. 1 fault is conformable in strike with the sediments in the cross fold, so it may have been folded with them and would thus predate the cross fold. The fractures in which the veins formed seem to have developed as a consequence of the cross folding. They could not have remained open for a long period so it seems probable that they were formed after the porphyry intrusions. Silica and pyrite were then deposited from hydrothermal solutions from an unknown source. The porphyry contacts were favorable channelways at this time, as most of them are mineralized with pyrite. Later solutions carried lead and zinc sulfides that filled accessible fractures and replaced favorable limestone beds. The replacement ore bodies may have formed from local concentration of solutions guided by the gouge zones of the thrust faults, or in areas where intense fracturing permitted the access of abundant solutions to the favorable limestone horizon. Arsenic sulfides were deposited as a later phase of hydrothermal activity. Their occurrence in the upper mine workings, or at some distance from known lead-zinc ore on the 3,600 level, suggests zoning, but where arsenic and ore minerals occur together, the arsenic minerals fill late fractures in the crystallized lead and zinc sulfides, and are not found intergrown or replacing them.

Postmineral movements appear to be minor. The "D" vein has been offset as much as 10 m, and a larger displacement may have taken place on a strong fault that cuts off the vein on the west. Many veins terminate against the gouge zones of the thrust faults, but as there is no evidence of faulted ore and no known correlation between veins on either side of the faults, the vein fissures may have ended in the incompetent gouge zones.

Supergene enrichment is of minor importance inasmuch as the veins do not have much surface expression, and the ore bodies did not reach the zone of oxidation. An exception is at San Gerardo, and there because of rapid erosion, sulfide ores are found on the surface.

## CONCLUSION

Structural relations are of prime importance in the Atacocha mine. Knowledge derived from the mapping, such as the location of the major ore-bearing area near the axis of the cross fold and the location of the largest ore bodies near the hanging wall of the No. 1 fault, should be of assistance in the laying out of future exploration.

The area surrounding the Atacocha mine has been well prospected. Several small ore bodies have been mined, and other ore bodies will probably be discovered. An adit was driven in the Curiajasha area in late 1952 to explore mineralized faults that crop out there. The faults were not found to be of economic interest at depth, but further work is planned to explore the contact of the limestone and chert breccia in that area. A small amount of ore was found along a contact of the dacite and lava near coordinates 3420 N and 5,110 E (Fig. 2). Further work is also being done in that area.

U. S. Geological Survey,
Washington, D. C.,
*Aug. 10, 1954*

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