STRUCTURE OF THE ORE DEPOSITS
AT SANTA BARBARA, CHIHUAHUA, MEXICO

A THESIS
SUBMITTED TO THE FACULTY OF THE UNIVERSITY OF NEVADA
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF
GEOLOGICAL ENGINEER

By
James B. Scott
1959
Submitted by  

James B. Scott  
Candidate for Degree

Approved by 

Verner E. Overland  
Dean, Mackay School of Mines

Accepted by 

J. E. Mood  
Dean, Graduate School
STRUCTURE OF THE ORE DEPOSITS AT SANTA BARBARA, CHIHUAHUA, MEXICO

J. B. SCOTT

CONTENTS

Abstract ................................................................. 1004
Introduction .............................................................. 1005
Geography .................................................................. 1005
Previous geological work ........................................ 1006
Purpose and methods of present investigation .......... 1006
Acknowledgments ...................................................... 1006
Geology of the Parral mining district ....................... 1008
General Geology of the Santa Barbara district .......... 1009
Shale ........................................................................ 1009
Andesite .................................................................. 1010
Rhyolite .................................................................... 1011
Conglomerate ............................................................ 1011
Diabase, basalt, and scoria ....................................... 1011
Unconsolidated stream sediments ............................ 1012
Structure ................................................................... 1012
Pre-mineral structure ................................................ 1012
Post-mineral structure ............................................... 1014
Geologic history ........................................................ 1015
Ore deposits .............................................................. 1015
History and production ............................................ 1015
Mineralogy ................................................................. 1016
Primary sulfides and other metallic minerals ............ 1016
Primary gangue minerals .......................................... 1017
Oxide zone minerals ................................................. 1017
Zoning ...................................................................... 1017
Veins ........................................................................ 1018
Surface outcrops ....................................................... 1018
Arrangement and pattern of veins ............................. 1018
Structure of veins ...................................................... 1020
Application to Santa Barbara district ....................... 1021
Simple vein structure ............................................... 1023
Complex vein structure .............................................. 1023
Location, shape, and rake of ore shoots .................... 1028
Vein-shale structure .................................................. 1030
Internal vein structure .............................................. 1031
Paragenesis ............................................................... 1035
References .................................................................. 1037

ABSTRACT

The Santa Barbara mines are grouped in a circle around the village of Santa Barbara located in the Parral mining district, in southern Chihuahua, Mexico. The mines are operated by American Smelting and Refining Company and the bulk of the mineral production comes from eleven vein systems.

The pre-mineral rock types consist of a thick calcareous shale formation and andesite flows. The post-mineral rock types consist of dikes and sills of rhyolite and diabase, a thin conglomerate formation, basalt flows, and unconsolidated stream sediments. Pre-mineral faulting took place in two stages, forming four fault systems. Any fault within one system is similar in both strike and dip to another fault within that system. Movement along these faults, vertical in the first-stage faults and horizontal in the second-stage faults, formed openings, breccia zones, and in places horses and wedges of country rock in the faults. The location and explanation of these openings, breccia zones, horses and wedges are the main topic in this paper.

Hydrothermal solutions, emanating from depth, were introduced into the faults. The walls and breccia fragments within the faults were silicified and silicified and the high-temperature silicates, garnet, pyroxene, epidote, and idocrase (?) were formed. Accompanying and following the formation of the silicates, the sulfides sphalerite, galena, chalcopyrite, pyrite, and arsenopyrite, with associated gold and an unknown silver mineral were introduced with quartz, calcite, and fluorite. Most of these minerals replaced the silicates and altered shale. The parts of the faults where wide pre-mineral openings, horses or wedges were formed, were filled with quartz and a higher ratio of sulfides than the narrow portions of the faults. Quartz, calcite, fluorite, and barite were among the last minerals deposited. The veins are assigned to the hypothermal class of hydrothermal deposits.

INTRODUCTION

Geography.—The Santa Barbara district mines form a circle around the village of Santa Barbara in the Parral mining district, which is in the southern part of the state of Chihuahua, Mexico (Fig. 1). The Santa Barbara district, as it is commonly referred to, is an area about 6.5 km long north-south and about 5.0 km wide (Fig. 2). The mines are operated by a subsidiary of the American Smelting and Refining Company. Other mines in the Parral mining district are the La Prieta mine at Parral, also operated by a subsidiary of the American Smelting and Refining Company; the Esmeralda mine near Parral operated by a subsidiary of the Eagle-Picher Company; and the Frisco mine at San Francisco del Oro, operated by San Francisco Mines of Mexico, Ltd. Besides these major producers, a number of small companies and groups of miners are operating small mines in various parts of the Parral mining district.

Santa Barbara is located about 25 km, by oil surface road, southwest of the city of Parral and is connected to Parral by a branch line of the National Railways of Mexico. The north and west boundaries of the Santa Barbara district are located adjacent to the south and east boundaries of the San Francisco del Oro district.

The topography around Santa Barbara is that of mesa tableland cut by deep arroyos, which is typical of late youth. The average altitude is about 1950 m above sea level. Vegetation is sparse, consisting of scrub oak, desert type brush, and wild grass. The average precipitation is about 22 inches per year. About 10 km to the south of the district, the Sierra de Santa Barbara is characterized by steep cliffs of andesite flow rock.
Previous Geological Work.—Geological work was started in the early 1900's, soon after American Smelting and Refining Company formed a unit at Santa Barbara and began operations. J. E. Spurr was the first geologist to visit the mines and was followed by Basil Prescott, J. G. Barry, W. M. Davy, and Harrison Schmitt. In 1937 the position of resident geologist was created at the Unit and a formal program of surface and underground geological mapping was started by W. P. Hewitt and F. W. Farwell, under the direction of T. P. Clendenin. This work has been continued, intermittently, up to the present time by various geologists and mining engineers. Published work on the Santa Barbara geology consists of an article by Harrison Schmitt (23); an account of the geology, accompanied by a surface map and two vertical sections, by M. D. Kierans (10); and more recently a discussion of high temperature minerals by V. T. Allen and J. J. Fahey (1).

Purpose and Methods of Present Investigation.—This paper was written during the fall of 1957. The field work was done, intermittently, over a period of seven months in conjunction with the regular duties of the resident geologist at the Santa Barbara Unit. The purpose of this study is to describe the structure of the veins and the relation it has to the location of ore shoots.

Acknowledgments.—The author is indebted to Mr. C. F. Jordan, former General Manager, and Mr. W. J. Nock, present General Manager for the
Mexican Mining Department of American Smelting and Refining Company, for permission to undertake the work and publish the results. He is also indebted to Mr. A. B. Williams, Unit Superintendent of the Santa Barbara Unit, for his aid and support during the preparation of this paper. Gratitude is expressed to Mr. T. P. Clendenin, Chief Geologist for the Mexican Mining Department who read and criticized the paper and offered much helpful information. Mr. David Wortman, Chief Engineer at the Santa Barbara Unit, gave many hours of critical discussion when the paper was still in the planning stage, and read and criticized the first draft. The writer has used the underground and surface maps prepared by the earlier geologists and mining engineers, and the great help these maps contributed toward the writing of this paper is acknowledged.

Geology of the Parral Mining District.—The most recent map showing the geology of northern Mexico that has been published is the Twentieth International Geologic Congress Map of Mexico (7). An earlier geologic map of northern Mexico was published by P. B. King (12). This map has been included, but at a smaller scale and with less detail, in a map of North America by the Geological Society of America (27). The geology of northern Mexico has been covered in papers by V. R. Garfias, and R. C. Chapin (6), E. O. Hovey (8), L. B. Kellum (9), P. B. King (11), and R. E. King (13).

The Parral mining district is in the border zone between the physiographic provinces of the Central Plateau and the Sierra Madre Occidental (9). The Central Plateau is equivalent to the Mexican Highland division of the Basin and Range province of the southwestern part of the United States, and has the characteristic isolated mountain ranges generally trending north, separated by wide alluvium covered basins. The Sierra Madre Occidental is a heavily dissected lava plateau, composed of a great thickness of bedded volcanic rocks of Tertiary age, which have suffered faulting and deformation at places but in many areas remain practically undisturbed. Greatly deformed Mesozoic rocks underlie the Tertiary volcanics along the eastern and western margins of the Sierra Madre Occidental.

No description of the entire Parral mining district has been published; however, Paul Waitz (28), Harrison Schmitt (23, 24), G. S. Koch (14, 15, 16), M. D. Kierans (10), G. C. Marlow and J. M. Smith (20), G. K. Lowther and G. C. Marlow (19), and G. K. Lowther and E. B. Bell (18) have written about the districts near the cities of Parral, Santa Barbara, and San Francisco del Oro. Other accounts of nearby areas have been written by W. H. Weed (29), Ezequiel Ordoñez (22), F. W. Smith (26), and I. E. Wilson and V. S. Rocha (31).

A thick series of folded sediments of probable Cretaceous age are the oldest known rock types in the Parral mining district. These sediments consist mostly of shale and limestone, but some arenaceous lenses are found within the formation. Clendenin (4) reports a "light colored, highly silicified shale, almost like a fine grained quartzite" in the deepest horizons of the La Prieta mine at Parral. A similar occurrence, a highly silicified arenaceous shale, which resembles a fine grained quartzite, has been found below the deepest workings at Santa Barbara. These sediments are overlain by a thick series of gently dipping volcanics of probable Tertiary age. Schmitt (24) states that near Parral, both the volcanics and sediments are broken by great faults that generally strike north; are cut by a variety of dikes, and intruded by a small stock of quartz monzonite. Some of the veins follow these faults and dikes.

In the San Francisco del Oro-Santa Barbara portion of the Parral mining district, the veins are almost totally confined to fault zones within the shale. The only exception is in the southern part of the Santa Barbara district where a vein, outcropping in andesite, extends down into the shale. Also, in contrast to certain veins near Parral, the veins do not follow dikes, but instead are cut by the dikes. The veins at San Francisco del Oro are found in a system of relatively short fractures; whereas at Santa Barbara they are found along very long and persistent fractures.

A discovery of ammonites near the La Palmilla mine by Dr. J. Friedlander in 1906 (3, p. 174), dates the shale in the Parral district as middle Cretaceous (Gault-Vraconnien stage). No ammonites have been found in recent years and since the circumstances of the original find are uncertain the age assignment is regarded as tentative. A find of poorly preserved Aptychus close to Parral in some thin beds of limestone indicates that the age might be upper Jurassic (2), but this dating has not been used because of the poor condition of the fossils.

General Geology of the Santa Barbara District

The surface geology of the Santa Barbara district is shown in Figure 2. The veins occupy fault fissures of small to large displacement that cut shale and, in the southern part of the district, andesite flow rock. The shale, andesite, and veins are cut by dikes and sills of rhyolite and diabase. These rock units are overlain unconformably by a gravel formation and basalt flows. The andesite to the south, unconformably overlies the shale. Several kilometers beyond the southern edge of the district, basaltic scoria plugs are present and cut through the andesite flows. The shale within the Santa Barbara district is folded into what appears to be an anticlinorium, and the veins are found on both limbs of the structure. The geology of the Santa Barbara district is closely related to that of the San Francisco del Oro district. Both districts have the same formations, except for the andesite which is lacking in the latter, and the structure is quite similar.

Shale.—The oldest known rock type, and the most widespread, is a thick calcareous shale formation. While this formation has not been traced into the shale known at and around Parral (Fig. 1), the two are lithologically similar and are thought to be the same or nearly the same in age. The shale, as Koch (14, p. 4) mentions, might better be called argillite if the name shale were not already so well established locally. In contrast to the behavior of most shales, the shale at Santa Barbara is strong enough to stand for long periods of time without support, even at long distances from the veins, where it has not been subjected to intensive silicification and silication. Very little
timbering is required and then only in fault zones and some broken zones found at sharp folds. Many open fractures are found in the shale, which give further indication of the rock strength.

The shale is hard, nonporous, impermeable, and highly indurated. The color ranges from blue-grey to black, and the composition varies from non-calcareous shale to almost pure limestone. The proportion of calcareous beds is not known, but it varies both laterally and stratigraphically. In general, the proportion of calcareous shale increases with depth, there being places at the deeper horizons where white calcareous bedding makes up about ten percent of the shale. Most of the shale is very fine grained and in places it is so massive that it has the appearance of hornfels. However, in other places it becomes quite granular, but this is due to arenaceous lenses or to recrystallized calcite. Pyritiferous bedding planes are common throughout the formation.

No marker beds are known to exist within the formation. The arenaceous lenses are not continuous enough to serve as marker beds. Neither the top nor bottom of the formation is known. Some deep drilling from the lowest workings would indicate that the base of the beds lies in excess of 700 m from the surface, but it is not known whether or not some of the beds are repeated by folding or faulting. Downward drill holes from the lowest mine levels in the Alejandria and La Paz mines have cut sections of a highly silicified arenaceous shale, resembling a fine grained quartzite, interbedded with black shale. This is the only known occurrence at Santa Barbara. With depth, as a rule, the shale tends to exhibit more pronounced metamorphic characteristics. Bedding planes are smooth and show slickensides in many places. The beds range 1 to 40 cm in thickness. Cleavage is generally visible, but is not strongly developed except where it stands at a large angle to the bedding. Near the crests and troughs of folds, the shale assumes a slaty appearance.

In several localities within the district, especially just north of the village of Santa Barbara, a large number of carbonate concretions have been found in the shale. The concretions have diameters of 5 to 50 cm and are generally oblong and slightly flattened parallel to the bedding. The concretions are dense and hard, black in color, and composed of calcium carbonate. Reports of fossils in concretions in other Cretaceous shales in the Western Hemisphere indicate that the concretions are fossiliferous. The concretions have diameters of 5 to 50 cm and are generally oblong and slightly flattened parallel to the bedding. The concretions are dense and hard, black in color, and composed of calcium carbonate. Reports of fossils in concretions in other Cretaceous shales in the Western Hemisphere (30), prompted the writer to examine hundreds of the concretions for possible fossils. To date, the results have been negative.

Andesite.—The next rock type is a series of andesite flows, located in the south-eastern part of the district. These flows are probably Tertiary in age, about the same age as the andesites found near Parral. They range in color from dark green to dark grey where unaltered and light brown to violet in the weathered zone. The flows rest unconformably on the shale. The contact between the shale and andesite is very uneven, suggesting that the erosion surface on the shale had much the same type of rough topography as is now present. The shale shows baking, alteration, and silicification ranging up to five meters in thickness at the contact. The andesite at the contact is very fine grained and shows vivid colors due to oxidized iron. The andesite assumes a porphyritic texture upward and becomes quite massive. At one place, a rhyolite dike was found to cut up through the andesite establishing that the andesite is older. A vein that outcrops in the andesite was found by drilling to extend down into the shale. This vein is thought to be a continuation of one of the major vein systems of the district, but this has not been established. However, it appears that the shale was covered by the andesite when vein filling took place.

Rhyolite.—The next younger rock type in the sequence is rhyolite, which is found as dikes and sills throughout the district. The classification “aplite” might better be used if the name rhyolite was not so firmly established locally and in the literature in both the Santa Barbara and San Francisco del Oro districts. The rhyolite is pink, brown, and white. It contains about 5 percent quartz phenocrysts averaging 2 mm across in a fine-grained groundmass. The dikes and sills are persistent in both the vertical and horizontal sections. In surface expression, the dikes form bold outcrops. One of the most prominent topographic features of the district is the “bufa,” a high knob formed by a very wide dike located near the western edge of the district. The dikes vary in both dip and strike, but most strike north. However, some of the dikes show a S 70° W trend, which is not parallel to any veins, but is almost parallel to the strike of one of the post-mineral fault groups. The dikes are found to be rather constant in width, with the exception of the dike that forms the “bufa.” This dike is about 200 m wide at the surface, but in the lowest workings, some 500 m below in the Tecolotes-Hidalgo mines it is only 20 m wide. Schmitt (23) comments that the structure of the dikes indicate a possible intrusive at shallow depth. As a rule, the dikes parallel the vein systems and therefore it seems possible that the dikes are an expression of fractures. In the northern part of the district, narrow veins are found adjacent to the dikes, and even within a dike zone. This relationship is not clear. One dike beyond the southern border of the district was traced from shale up into andesite. The character of the dike changed markedly at the shale-andesite contact and then the dike dies out after extending about 25 m up into the andesite.

Conglomerate.—In several places within the district, a thin formation of cemented gravel or conglomerate is found between the shale and overlying basalt. At most points on the surface, the formation is covered by basalt talus and is, therefore, very inconspicuous. In other places, the formation is completely absent. This unit is not mappable and is not shown on the surface geology map of the Santa Barbara district. The formation consists of pebbles, small boulders, some sand, and has been cemented by calcite. The fragments are composed of shale, limestone, rhyolite, and several types of andesite.

Diabase, Basalt, and Scoria.—These rock types have been grouped together because of similar chemical composition and because the types are thought to be nearly the same in age. The diabase is found throughout the district in the underground workings as scattered dikes and sills. The diabase is fine grained, but in some of the wider dikes and sills, becomes slightly granular and shows needles of augite. In a few of the dikes, disseminated pyrite is quite prominent. These dikes mainly follow post-mineral cross faults and cut
the veins in many places. It is thought that the dikes are the feeders of the basalt flows found on the surface.

In general the basalt is only found in areas of high elevation as a cap rock. However, to the east of the district, basalt has been found at relatively low elevations. The basalt is dark grey to black in color, is hard and dense, and breaks with a conchoidal fracture where it does not have a high ratio of vesicles. Koch (14, p. 9) reports that the basalt in the San Francisco del Oro district consists of “85 percent feldspar and pyroxene, in the ratio of 3:1, 10 percent olivine phenocrysts, and 5 percent vesicles, most of which are partly filled with calcite.” The bases of the flows show that at the time of extrusion, the erosion surface was one of very gentle topography.

About three kilometers south of the southern edge of the Santa Barbara district, three basaltic scoria plugs are present. The scoria cinders have an average diameter of 10 cm, are red in color, and are highly vesicular. Erosion has removed all traces of any scoria cones, but the diameters of the plugs, which range from four to seven meters, indicate that a large volume of material might have issued from these vents. The plugs cut through andesite. No basalt flows are found adjacent to the plugs, but a large amount of basaltic float is found in the general area, indicating that flows may have been present at a higher elevation, but have disappeared through erosion. It is thought that these plugs might be one type of feeder for the basalt flows found within the district.

Unconsolidated Stream Sediments.—The youngest formation found within the district consists of unconsolidated sediments occurring along the drainage courses. The sediments include boulders, gravel, and sand. These sediments were derived from shale, limestone, rhyolite, several types of andesite, basalt, welded tuff and from the veins in the district, the latter contributing quartz and minor amounts of heavy minerals, including gold.

STRUCTURE

The structure will be discussed under two headings, pre-mineral and post-mineral, to conform with the major periods of structural activity.

Pre-Mineral Structure.—Soon after deposition and consolidation of the shale, horizontal forces began to be applied in a northeast-southwest direction. These forces resulted in the formation of an anticlinorium. Work by Koch (14, p. 4) on the north end of the structure, at San Francisco del Oro shows that it had a N 28° W trend and a 12° north plunge. At the south end of the structure at Santa Barbara, no definite surface interpretation could be made except that a very complex anticlinorium is present and has a N 30° W trend. The detailed structure is very complex because the individual shale beds are thrown into complicated drag folds and are broken by numerous small faults. However, underground mapping in a crosscut 2.7 km long, that extends from the Segoviedad shaft to the Cobriza shaft area, gave a very definite picture of an anticlinorium. The west limb seems to dip more steeply than does the east limb. Examples of reverse movement along the bedding planes or as faults are very common in the underground workings.
some of these fractures might have extended up into the overlying andesite. The shear fractures, known as the Alpha and Beta, which formed the first stage of fracturing, both have an average strike of north—south, but the first has an average dip of 75° east, while the latter has an average dip of 70° west. According to the fracture theory, both of these fracture systems should have been normal faults, and ample evidence has been found in the field to confirm this. Since there are no marker beds within the district, it is not possible to determine the amount of the fault movement, but it is thought to be only moderate. One feature of these systems is their very regular strike. Another feature is that both appear to occur only in zones. Only two well-defined zones are present within the district and they are separated by a width of 2.5 km.

The shear fractures, known as the Gamma and Delta, formed the second stage of fracturing. The Gamma set had an average strike of N 31° W with a dip of 58° west. The Delta set had an average strike of N 23° E, with a dip 51° west. Both of these systems are characterized by having an uneven strike, but are strong and extend over long distances. The Gamma system, having a strike of N 31° W, is parallel to the trend of the anticlinorium. Both surface and underground evidence indicate that the Seca fracture of the Gamma fracture system is located along the axis of the anticlinorium. What possible effect that might have had on the Gamma and Delta systems, will be discussed in the section on Veins. Again referring to the fracture system theory, the second stage shear fractures, instead of moving as normal faults, should have moved as strike-slip faults with a minor amount of vertical movement. Thus, the stresses of the second stage would have been relieved by movement along the fractures of the first stage where they were conveniently oriented. This would mean that some secondary movement, in a horizontal direction, would have taken place in some fractures of the first stage. Conclusive evidence has been found in the field to confirm the horizontal movement in the second stage fractures and the secondary horizontal movement in the first-stage fractures.

Post-Mineral Structure.—Following vein filling of the fractures, a series of faults and joints were formed. These are post-mineral since they cut or displace the veins. Much like the pre-mineral fractures, the post-mineral faults and joints fall within strike trend groups. The first has an average strike of N 50° E and contains most of the major faults while the second with an average strike of N 45° W contains both faults and joints. It has been noted that three types of faults are present:

1—Quartz filled faults
2—Calcite filled faults
3—Gouge filled faults

Strike-slip displacement along these faults is moderate, having an average of about 10 m. The maximum known strike-slip displacement is 60 m in a fault that cuts the Los Hilos-Coyote vein system. Vertical displacement in general is quite moderate, but in a few places it is known to be large. In the Clarines mine, it has been reported that a vertical movement of 90 m took place on one fault (16). In most cases, a fault zone consists of a crushed zone 1 to 12 m wide with a center zone 0.1 to 1.0 m wide filled with quartz, calcite or gouge. Many of the gouge faults have diabase dikes in the center.

Some of the faults are very persistent and have been traced from the surface to the lowest levels of mining. Most have right-hand strike-slip displacements, but there are many known exceptions to this rule. Some hinge reefs are known to exist, but they are few in number. It is thought that this series of post-mineral faults and joints extended over a considerable period of time, beginning soon after mineralization and continuing beyond the time when the diabase dikes and sills were intruded. In a number of places, diabase dikes and sills are cut by faults. About 4 km east of the southern part of the district, an escarpment of recent age has been found. The escarpment extends along the base of some steep hills, cutting through the basalt andesite and small alluvial fan deposited at the mouth of a canyon. The escarpment is mostly covered by alluvium, but the break in the slope is very pronounced and can be traced for about 300 meters along the strike.

Geologic History

Although the sequence of geologic events in the Santa Barbara district is relatively clear, the lack of age determinations makes it difficult to assign each event to its correct position in the geologic time-scale. The oldest rocks are the shale formation, probably Cretaceous in age. After the shale was folded a period of erosion followed in which deep canyons with steep cliffs were formed. Andesite flows of probably Tertiary age were extruded filling the canyons first, then completely covering the shale erosion surface to a possible depth of 900 m. Next, the shale and the lower portion of the andesite were fractured in two stages, not necessarily separated by any real length of time. Simultaneously or soon after the formation of the second fracture stage, hydrothermal solutions entered the fractures to form veins. The rhyolite dikes and sills were then intruded into the shale and lower portion of the andesite. After a period of time, sufficient for erosion to strip away most of the andesite and reduce the surface to a gently rolling plain, gravel was deposited. Then another period of erosion followed during which most of the gravel together with more of the older rock was removed. After mineralization, a series of faults and joints were formed in two strike trends. Diabase dikes and sills were intruded, some in the faults, and previously led the basalt flows that covered most of the Santa Barbara district. After cones, to the south of the district, might have supplied part of this material. Another cycle of erosion followed, accompanied by more faulting until all the present topography was formed.

ORE DEPOSITS

History and Production

Evidence is available that the veins at Santa Barbara were being worked in the pre-colonial period by Indians. This could be the reason why the first
Primary Sulfides and Other Metallic Minerals.—The most common minerals in this zone are sphalerite, galena, chalcopyrite, pyrite, and arsenopyrite. Small amounts of bornite, native copper, and hematite are found in the lower levels of some of the veins. The ore minerals sphalerite, galena, and chalcopyrite are found from the top of the sulfide zone to the lowest levels. The mineral referred to as sphalerite is really the iron-rich variety, marmatite. Generally the marmatite is quite massive and has a coarse crystal form. Galena occurs in two forms, the first very massive and showing a coarse crystal form. The second, while massive, has a fine crystal form and tends to be closely associated with pyrite. Chalcopyrite is rather fine grained and occurs as masses associated with pyrite or arsenopyrite. The arsenopyrite, although in small amounts near the surface, tends to increase with depth and in some of the lowest workings is very abundant. In general, all sulfides and gangue minerals become more coarse with depth. Schmitt (23) mentions this in his paper on Santa Barbara and Koch (14, p. 28) reports a similar condition at the Frisco mine.

Silver and gold are associated with the sulfides. The silver is closely associated with the galena and is probably carried mainly as an impurity in that mineral, though a little argentite may be present. The highest silver values occur with the fine-grained variety of galena. Gold is generally present in very minor amounts, but in recent years rich gold concentrations have been found in a portion of the Seca vein.

Schmitt (23) recognizes three distinct kinds of primary ore at Santa Barbara. The first is a silicious lead-silver-zinc type, characterized by massive galena and sphalerite and containing minor amounts of chalcopyrite and pyrite. The second is a silicious gold-silver ore, distinguished by the absence of massive sulfides and the presence of silicate minerals such as pyroxene and garnet. The third variety, like the first, carries much massive sulfide, but in addition a large amount of silicate minerals.

Primary Gangue Minerals.—Quartz and calcite are the most common and widespread of the gangue minerals and are found in all the veins. Minor amounts of fluorite are found in all the veins, but in the lower levels of the Alejandro and La Paz mines in the northern part of the district, the amount increases and in places becomes the main gangue component. The quartz ranges from clear colorless, grey, to greenish in color. Most of the vein quartz is massive and dull in color. Lining the walls of vugs, the quartz is clear colorless to white and has a comb structure. Calcite is white to colorless, but in two places a violet variety has been found. Fluorite ranges from white to green in color and is fine grained.

Occurrences of orthoclase have been noted in several of the veins. Barite is found as narrow stringers within the veins, or in places as masses associated with calcite and quartz. The high temperature silicates belong to the garnet, pyroxene, and epidote groups. Schmitt (23) made the following identification of the silicate minerals:

- Garnet (isotropic and birefringent)
- Pyroxene (clino-enstatite)
- Epidote (epidote and zoisite)
- Idocrase (vesuvianite ?)

Allen and Fahey (1) report the presence of manganiferous hedenbergite from the 1,400-level of the Hidalgo mine.

Oxide Zone Minerals.—Above the water table, which is 50 to 120 m below the surface, the veins are vuggy, earthy, and show residual boxworks. The oxide portions of the veins are no longer being mined except on a minor scale by independent operators in the northern part of the district. The secondary minerals are anglesite, azurite, malachite, cerussite, jarosite, and “limonite.” Additional secondary minerals as reported by Schmitt (23), are bornite, chalcocite, plumbojarosite, mimetite, pyromorphite, smithsonite, calamine, planerite, and hisingerite.

Zoning.—Schmitt and others have discussed the possibility of zoning in the district, but no definite conclusions have ever been presented on the district as a whole. C. A. Lee (private report) made the observation, “that the mineralogy of the veins suggests a semi-circular outline elongated N 45° W with more length than width.” Schmitt (23) discussed zoning with depth and made the observation that copper increases somewhat with depth.

Although the mineralogy of the veins suggests something like a semi-circular outline, too many cases were found where the mineralogy does not
increases with depth. Copper, in the form of chalcopyrite along with arsenopyrite increases with depth.

Veins

All of the veins in the Santa Barbara district fill fractures in shale and andesite and have dips from 35° to vertical. Most veins, some of which are quite long, are longer than they are deep. The longest known continuous vein complex starting from the south at the San Martin mine and extending north to the Palo Blanco mine is 5.5 km in length. The average width of the veins is about 1 m, but in the ore shoots, widths of 4 to 5 m are common. In several of the wider ore shoots, veins of 15 m width have been mined.

Surface Outcrops.—Along the surface outcrops of the major veins in shale, it has been found that silicification and silication in places extend 10 to 15 m on each side of the vein. In the andesite, the degree of replacement and alteration is less, only extending out about 5 m on each side of the vein. Most of the veins have prominent outcrops and stand above the shale or andesite. In places they form ridges and, thus to some degree, control the topography of the district. In a number of places where the vein outcrops are not prominent, the silicified and silicated country rock adjacent to the veins, give rise to conspicuous topographic forms that have made it easy to locate the veins. Blind veins, having no surface outcrop, as yet have not been found in this district. However, there is no reason why such veins could not be present.

Arrangement and Pattern of Veins.—The surface arrangement of the veins is shown in Figure 2. Of the veins shown, the majority fall into eleven vein groups, from which the bulk of the mineral production is obtained. The remainder of the veins are quite narrow, have very limited surface expression along the strike, and are seldom of ore grade. Grouping the veins according to strike and dip, discloses that they all fall within four strike-dip systems, any one vein within a system being similar in both strike and dip to any other vein within that system. In Table 1, all of the veins are listed according to systems. It will be noted that many of the veins shown in Figure 2 are not listed. This is because no data is available on the vein, or that the vein is in ground under control by other mining companies, or that the vein is only of minor importance and would not contribute to the geologic picture of the district. Since the four vein systems are the expression of pre-mineral fractures, they fall within the same strike-dip pattern of the fractures.

All of the vein groups show intersections within their own group, indicating wedges or horses of country rock causing vein splits. The vein groups are discussed below.

The Alpha group veins have an average strike of N 2° E and dip 75° E. Within a single vein the strike is constant, but the dip is uneven. The veins show intersection at depth with veins of the Beta group in the eastern part of the district.

The Beta group veins have an average strike of north with a 70° west dip. Within a single vein, the strike tends to be slightly erratic and the dip is very uneven. An extreme case of uneven dip is found in the Santiago vein. The dip changes from west to east for a short distance, then back again to the west. This is repeated, to some degree, in the Cabrestante vein, which becomes vertical for a short distance. The veins in the western part of the district show intersections with veins of the Delta and Gamma groups.

The Delta group veins have an average strike of N 23° E with a dip of 1 W. Within a single vein, the strike is very erratic and the dip even.

The uneven strike is shown rather well in the Mina del Agua-Palo Blanco vein system. It is suspected that a portion of this vein system will fall within the Beta group, and that the vein complex is a series of linking veins. Inspection of Figure 2 shows that the Mina del Agua-Palo Blanco vein shows two strike trends, one within the Delta group, and then for short distances one vein is the Beta group. Such a condition would result if a series of Beta veins were present along this zone when the second stage of fracturing occurred. The Delta fractures, having a strike-slip movement, would trend within the weak zones represented by the Beta fractures for short distances, then turn back parallel to the direction of shear. To some degree, this is confirmed by intersecting veins, such as the La Reina. The La Reina vein falls within the Delta group, yet the Mina del Agua-Palo Blanco vein turns at a sharp angle and has a north strike for a short distance before turning west again to the general strike trend of the Delta group. Then, at the extreme south end of the Mina del Agua-Palo Blanco vein system, there is a distinct turn in the strike of the vein and it appears to have gone into the Gamma group. However, evidence available at the San Martin mine indicates that the west wall moved north in relation to the east wall, which would indicate that the vein was still within the Delta group. It is thought that the presence of the anticlinorium crest in this area had some effect on the strike and dip of the fractures as they cut across the structure. If this is the case, these fractures would be expected to exhibit the same characteristics, wherever they come into the axial trace of the structure. The fracture of the Delta set

<table>
<thead>
<tr>
<th>Table 1: Vein Group Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha group Attitude</td>
</tr>
<tr>
<td>Cerro N 8 E. 70° E</td>
</tr>
<tr>
<td>Cerro N 7 E. 60° E</td>
</tr>
<tr>
<td>Los Hilo-Coyote N 7 E. 75° E</td>
</tr>
<tr>
<td>Pluma N 7 E. 55° E</td>
</tr>
<tr>
<td>San Carlos N 6 W. 70° E</td>
</tr>
<tr>
<td>San Rafael N 6 W. 70° E</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Delta group Attitude</td>
</tr>
<tr>
<td>Bidalge N 27 E. 42° W</td>
</tr>
<tr>
<td>Mina del Agua-Palo Blanco N 21 E. 55° W</td>
</tr>
<tr>
<td>La Reina N 30 E. 80° W</td>
</tr>
<tr>
<td>San Martin N 20 E. 55° W</td>
</tr>
</tbody>
</table>

below the weak zones represented by the Beta fractures for short distances, then turn back parallel to the direction of shear. To some degree, this is confirmed by intersecting veins, such as the La Reina. The La Reina vein falls within the Delta group, yet the Mina del Agua-Palo Blanco vein turns at a sharp angle and has a north strike for a short distance before turning west again to the general strike trend of the Delta group. Then, at the extreme south end of the Mina del Agua-Palo Blanco vein system, there is a distinct turn in the strike of the vein and it appears to have gone into the Gamma group. However, evidence available at the San Martin mine indicates that the west wall moved north in relation to the east wall, which would indicate that the vein was still within the Delta group. It is thought that the presence of the anticlinorium crest in this area had some effect on the strike and dip of the fractures as they cut across the structure. If this is the case, these fractures would be expected to exhibit the same characteristics, wherever they come into the axial trace of the structure. The fracture of the Delta set
turned parallel to the trend of the anticlinorial axis and possibly followed the reverse faults found on the limbs or the tension fractures that parallel the structure. Another vein that cuts the San Martin vein turns almost normal to the axis of the structure, and the dip is affected. In the western part of the district, this same relationship can be seen where veins of the Delta and Beta groups intersect the crest zone of the anticlinorium. The veins either turn parallel or normal to the trace of the structure axis.

The veins of the Delta group show numerous examples of intersections with veins of other groups. A large number of horses and wedges of country rock are present in this vein group.

The Gamma group veins have an average strike of N 31° W with a dip of 58° W. Within a single vein, the strike is erratic and the dip uneven in places. The Seca vein and the Coyote-Seca vein, the north extension of the Seca, along with the Primavera vein are the only major veins in the district found within this group. The Seca vein is located along the axis of the anticlinorium. In the case of the Seca vein, it is thought that the tension fractures located parallel to the axis of the structure, served as weak zones and confined the strike-slip movement within the tension fracture zone. The tension fractures, having a dip normal to the folded bedding, in some cases, were filled with vein material. This resulted in a zone of veins with parallel strike and with dips ranging from east to west. In other places, it has been noticed that first stage fractures, where they cut across the crest of the structure, influenced the strike and dip of the Seca vein for short distances.

Attention is called to the fact that the grouping of the veins is very similar to that given the veins in the San Francisco del Oro district by Koch.

**Structure of Veins**

In the development of shear fractures such as those described in the section on structure, theoretically the fractures should form as perfect planes that show no variation in either strike or dip. However, since most rock units vary in chemical composition, physical properties, attitude, and have pre-existing joints and fractures that are zones of weakness, the resulting shear fractures will also vary in both strike and dip. Thus it might be said that all fractures are warped planes to some degree. Fault movement along these fractures, in either a vertical or horizontal direction, depending on the competence of the rock, would result in openings. A very brittle rock like andesite might become so brecciated during movement that any void would be filled with breccia. Even so, the fractured rock would give more area of contact to any possible mineral solutions that might be introduced at a later date and would, therefore, be especially favorable for replacement. In the case of a less brittle rock, such as a tough calcareous shale, the opening would have some brecciation around the margins, but the cavity might stand open indefinitely. A non-competent rock such as tuff, would be so plastic that any opening caused by faulting would be almost immediately filled.

Of course, much would depend on the depth below the surface and the consequent heat and pressure, but in an ideal situation and with the conditions defined, a warped plane would result in openings on the steeper portions of normal faults, on the flatter portions of reverse faults, and on changes in strike or curves along strike-slip faults (Fig. 3). Any mineral solutions introduced in such faults should result in the wider portions of the veins being in brecciated or cavity zones. The important feature of this discussion on the location of the wider portions of the veins, is that within the Santa Barbara vein system, the width of the veins is roughly proportional to the grade of the ore. In other words, the wider the vein, the richer the ore.

Emmons (5) and Newhouse (21) report many deposits that show a warped plane condition. Schmitt (23) noticed a relationship between brecciated zones and width of vein at Santa Barbara and commented, “the widest part of the veins were areas of greatest brecciation along the pre-mineral fault planes, and thus the most favorable places for hypogene enrichment.”

![Fig. 3. Diagram showing openings formed by movement along faults.](image-url)
In turn, movement on the second stage of shear fractures, the ture theory. In turn, movement on the second stage of shear fractures, the Gamma and Delta, should have formed openings at changes in strike, or curves, along the trace of the vein since they would necessarily have been strike-slip faults to again follow the theory. A slight amount of vertical movement would also be expected on this second set of fractures, since according to the theory, the compressive stress was not wholly horizontal in direction. Of course, minor strike-slip movement would also take place in the fractures of the first stage from the stresses of the second stage, and the fractures of the Alpha set would be opened wider. This would to some degree form openings on changes in strike, or curves, along the trace of the veins. Therefore, in sum-

mary, in the first stage of shear fractures most movement would be in a vertical direction with minor movement along the strike, but in the second stage of shear fractures most movement would be strike-slip with minor movement in a vertical direction.

The field evidence to support the warped plane theory will be discussed under two headings, simple vein structure and complex vein structure. The simple vein structure designates a single vein uncomplicated by splits caused by horses or wedges of country rock or by vein intersections, which come under the complex vein structure classification.

**Simple Vein Structure.**—The proposed theory of warped fracture planes can be tested in a number of ways. One would be to try and find simple vein situations in the field and then apply the theory. Examination of vertical sections of simple veins, falling within the first stage of shear fractures, should show that on the steeper portions of the veins the veins widen. In Figure 4 are shown typical sections on two of the major veins in the district that fall in this fracture stage. It is not practical to show all the possible vertical sections, but as shown in the vertical sections illustrated, the ore zones in the simple veins are consistently found on the steeper portions of the veins.

For the simple veins, falling within the second stage of shear fractures, the changes in strike, or curves along the trace of the veins, should show widening of the veins. A portion of the underground geology on one level along the Mina del Agua-Palo Blanco vein is shown in Figure 5. On the portions of the vein that curve toward the west, surface or underground workings along the whole length of the vein shown, disclose ore at these locations and only at these locations. The reason for the location of the wide pre-mineral openings being in the vein curves to the west, and not in the curves to the east, cannot be explained. Along the Hidalgo vein, also in the Delta group, the wide pre-mineral openings occur in curves to the east.

It is thought that the location of pre-mineral openings in curves of one direction and not in the other might be due to the amount of horizontal movement along the fractures, but this is not clear. However, once it has been established that a pre-mineral opening occurs in a curve of a certain direction, then all the other zones of wide vein, in that vein system, will also be found in similar curves.

**Complex Vein Structure.**—As was shown, in the case of simple vein structures, the thicker portions of the vein are found in the locations as defined by the theory. However, many places exist where the thicker portions of the veins are located in places that seem to be contrary to the theory. Examination of these places shows that they occur where a horse or wedge of country rock is present or where veins of different vein systems intersect. Analysis of each case has reduced the rather complex structure to a simple classification: That the thicker part of the vein is due to an opening formed by either vertical or horizontal movement. An example of each type of complex structure will be taken and a case history given on each.
Horses and Wedges.—This type of complex structure is the most common and economically the most important in the district. Movement of one wall against another in either a vertical or horizontal direction will cause sections of the hanging wall to break parallel to the direction of movement. This would tend to be the case, especially where there are marked changes in the dip or strike of the fracture. In general, most of the horses are small enough that they can be easily recognized for what they are. However, some of the wedges are so large, that the hanging wall and footwall veins have been classed as individual veins. The San Rafael-Clarines and Cobreza-Pilares veins are thought to be separated by a wedge. If such is the case, then it is the largest structure of that type in the district since it would be about 300 m wide and 1,500 m long.

Where a horse or wedge is encountered, invariably the hanging wall branch of the vein tends to be the wider and higher grade, whereas the footwall portion tends to pinch and becomes quite narrow. In several hanging wall branches, associated with both horses or wedges, the width of ore has exceeded 15 m. Gravity is thought to be the factor that controls this condition. However, it is known that during movement along the faults, especially those that had horizontal movement, some rotation of the horses or wedges took place. This would, to some degree, affect the location of the wider openings. Therefore, there are exceptions to the rule and it is sometimes necessary to make a detailed geologic study of each case to determine whether the footwall or hanging wall portion is the more favorable. A good example of such an exception is found in the Segovedad section of the Mina del Agua-Palo Blanco vein. This horse has been completely outlined by mining. The top of the horse is first encountered between the 500 and 700 levels and the bottom lies just above the 1,100 level. The horse is located slightly off the center of a vein curve. The hanging-wall vein is relatively narrow, while the footwall vein becomes quite wide. All of the footwall vein has been mined, while only a portion of the hanging-wall vein has been mined. At the top and bottom of the horse, where the two veins rejoin, the vein becomes very wide. An example of a horse showing the typical wide hanging wall and narrow footwall veins is found in the Seca vein. The horse has been almost completely outlined by mining and diamond drilling. Only a small portion of the footwall vein has been mined. The feature of this horse, is that the hanging wall becomes quite wide toward one end of the horse, showing that some rotation took place.

In most cases when a horse is encountered during the driving of development drifts, the splitting of the vein is so prominent that it is hardly overlooked. However, in a vein where horizontal movement took place along the fracture, the horse tends to pull toward one end or the other of a curve, and a more than average amount of rotation normal to the strike of the fault might have pressed the edge of the horse very tightly against the footwall and the resultant footwall vein might be so obscure that it would be overlooked. When the other edge of the horse is reached, if the development drift is not driven along the footwall side of the hanging-wall branch of the vein, it could again be overlooked. It is possible that such situations exist, especially where no horse or wedge has been found on a major vein curve.

An example of a wedge, that was thought for a time to represent two intersecting veins, is the Mina del Agua-Novedad section of the Mina del Agua-Palo Blanco vein. The south end of the wedge starts at about the middle of the Mina del Agua ore shoot and continues north to about the middle of the curve toward the east that separates the Mina del Agua and Segovedad ore shoots. The length of the wedge at the surface is about 400 m. The hanging-wall vein of the wedge is called the Novedad and the footwall vein Mina del Agua. In Figure 6, it can be seen that the hanging-wall vein, as a whole, is much wider than the footwall vein, except in the southernmost section, where the footwall attains a width equal to that of the hanging-wall vein. From this, it is thought that slight rotation of the wedge took place, pressing the hanging-wall side of the wedge against the hanging-wall fracture to the south and the footwall side against the footwall fracture to the north. The hanging-wall vein assumed width up to 15 m in this wedge zone.

Horses and wedges, similar to the type just described, have been found in almost every major vein or vein system in the district. In several cases, it has been found that a horse and wedge may exist on the same change-of-strike curve along a vein.

Many excellent examples of intersecting veins exist in almost every vein in the district, especially the Mina del Agua-Palo Blanco vein. However, about the best example in the district, and also the area with the most complex structure, is that where the Seca vein of the Gamma group intersects the Tecolotes and San Albino veins of the Beta group. Figure 7 shows four
underground levels in the intersection area to give an idea of the other factors involved. The Tecolotes and San Albino veins appear to be separated by a wedge, but the veins, though approaching each other, have not yet been found to intersect at the lowest level of mining, so this is only inferred. A portion of the possible wedge appears to have been displaced by the Seca fracture. Since the west wall of the Seca fracture, to follow the fracture system theory, would have moved toward the north, it might be possible that the displaced portion of the wedge is to the north along the hanging-wall extension of the Seca vein. To further complicate the structure, the Seca vein is located on or slightly to the west of the N 30° W trending axis of the anticlinorium.

A detailed examination of the Seca and Tecolotes-San Albino intersection area discloses that the locations of the wider zones of vein conform to the warped plane theory, with the exception of the possible wedge zone between the Tecolotes and San Albino veins. Figure 7 shows that the Seca vein has a curve toward the east, south of the intersection, and that north of the intersection in the Rica and Seca-Coyote veins other curves are present. The curves to the east in the Seca and Seca-Coyote and the curve to the west in the Rica, are zones of wide vein. Vertical sections taken along these curves show that the wide vein zones also are confined to portions of the veins that show a steeper dip.

Of interest is the fact that vein intersections do not appear to be especially favorable for wide vein zones. A number of examples of intersecting veins can be shown where the vein does not widen to any degree. The Seca and Tecolotes-San Albino are the best example. However, an example can be shown where the older of two intersecting fractures was wedged open by movement on the second fracture, but this did not form a wide opening directly at the intersection, but only along the wedged fracture. Also this wedging open of a fracture tends to occur only in the portion of the fracture located in either the footwall or hanging wall of the second fracture, but never in both. Therefore, strike-slip and vertical movement in the second fracture, while wedging open the first fracture on one side, tends to pinch it tight on the other side. At the San Martin ore shoot, located on a portion of the Mina del Agua-Palo Blanco vein, mining between the 700 and 900 levels disclosed what appeared to be a double splitting vein (Fig. 8).

The location of the N 30° W trending axis of the anticlinorium, as discussed earlier, in the San Martin area is thought to have had some effect on the strike of the fractures. Therefore, while they do not follow the strike of the systems as required in the fracture theory, the San Martin vein is believed to fall in the Delta system, and the splits off the vein, in the Beta system. The San Martin ore shoot is located on a horizontal curve to the west. The hanging-wall split comes into the south end of the ore shoot and the footwall split comes into the north end of the ore shoot. The footwall split was ore grade and was mined 80 m to the north beyond the point where it leaves the San Martin vein. A geological model was made to determine if this was a double splitting vein, caused by spurs formed from the walls moving past each other during faulting, or if it was just a simple fracture intersection, offset by faulting. The model disclosed that the splits were too long along the strike to come under the double splitting vein classification but formed instead...
a single offset. To reconstruct the order of events, the fracture of the Beta system was formed before the fracture of the Delta system. Strike-slip movement along the latter fracture, moved the east wall north in relation to the west wall. This offset the Beta system fracture about 50 m along the strike. Vertical movement tended to wedge the fracture open at the north intersection, and close it at the south intersection. Thus at the start of mineral deposition, the wider openings formed in the horizontal curve of the Delta system fracture and the wedge in the north portion of the Beta system fracture, were available for vein filling.

**Location, Shape, and Rake of Ore Shoots.**—Previously it was stated that all fracture planes are warped to some degree. It was shown that the major warps are the controlling factor in the location of openings along the fractures. But besides the broad warps there are also minor warps along the whole lengths of the fractures, both in open and in tight sections. This accounts for the pinch and swell character of the veins and is very noticeable along the narrower sections, where a slight swell or pinch in the vein is conspicuous. While this condition can be more easily seen in a narrow vein, it is necessary to go to the mined-out stopes where both walls of the vein have been exposed to obtain data on the condition. Figure 9 is an equal vein thickness contour map made of the longitudinal section of an ore shoot.

Figure 9 represents an ore shoot showing simple vein structure. Upon first observation, it appears that the vein pinches and swells at random with no definite patterns of wide and narrow portions of the vein. However, a study of the map (which is sometimes helped by drawing lines connecting the wider portions of the vein) discloses that a pattern is present. This pattern generally consists of a series of circular or elliptical units, each unit consisting of vein of wide character but with a center of narrow character, and with the units linked together like a set of interlocking rings. Two trends in this pattern are apparent, one that is parallel or almost parallel to the rake of the ore shoot and the other normal or almost normal to the rake. The dimensions of the circular zones, although not identical, are similar. This same condition has been found in every equal-vein thickness map made of the Santa Barbara veins. This suggests that the minor warps might have been the result of rather regularly spaced zones, such as weaknesses caused by joints and fractures; these zones, on intersecting with the shear fractures, would have tended to cause rather evenly spaced warps.

Underground mapping in a long crosscut that extends from the Segovedad shaft to the Cobriza shaft area, confirms the regular spacing of fractures and joints. Although the interval is not the same in all cases, it was noticed that groups of fractures and joints occur about every 70 or 140 m. Applying this on a larger scale and comparing Figure 10 (a longitudinal section of a vein with the outline of stoped areas shown) with Figure 9, an interesting similarity between the vein thickness contours and the spacing and linking of ore shoots is seen. The possibility that such a pattern of wide vein zones, shown in Figure 9, could apply to an entire vein system is not only reasonable, but probable. The presence of the major warps in the shear fractures, suggests that strong joints and fractures cut by the shear fractures, could very well have caused the marked changes in the strike found in some of the veins. This condition is well illustrated along the strike of the Mina del Agua-Palo Blanco vein, where the vein is thought to intersect older fractures. Changes in the attitude of the shale bedding and the joints and fractures are very likely the reason for changes in dip. The possibility that there are regular intervals between the ore shoots, because of the spacing of the weak zones intersected by the shear fractures, is very important.

Again, in the Mina del Agua-Palo Blanco vein, a rather constant interval between the major ore shoots is apparent. The average interval between the ore shoots is about 750 m. Along other veins this constant interval condition between ore shoots is not too obvious from the surface geology, but from the underground workings, on some of the veins, a very good constant interval
picture is obtained. Other veins show no interval relationship at all, but this might be due to the presence of complex structure zones.

In the early days of operation at this unit, most of the ore shoots were classed as being longer than they were deep. However, since then, as mining has progressed to deeper levels, the general classification has changed to that of equal lengths in the vertical and horizontal sections. About half of the ore shoots have the shape of the top portion of an hour glass and appear to be shortening with depth; others have vertical sides from top to bottom, and still others have the shape of the bottom portion of an hour glass and appear to be lengthening with depth. About half of the known ore shoots have a vertical or nearly vertical rake. Some of the ore shoots, among those classed as having a vertical rake, appear to have both north and south rakes for short distances where a very narrow spot appears in the vein, but the ore shoot taken as a whole, has a vertical trend. A very noticeable rake to the north is shown by the Los Angeles ore shoot and a noticeable rake to the south is displayed by the Cobriza ore shoot. What appears to be a double raking ore shoot is located along a portion of the Los Hilos-Coyote vein (Fig. 9).

Vein-Shale Structure.—It is to be expected that the attitude of the shale bedding would have a bearing on the width of the veins. A fracture normal to the bedding would necessarily break the shale open with accompanying brecciation. Movement along such a fracture, if it was warped, would form openings. A fracture parallel to the bedding would follow and have movement along the bedding and thus tend to be very narrow. Any openings formed in the fracture would tend to close. At the Frisco mine, this is reported to be the most important factor governing vein strength (14, p. 16).

Contrary to this, at Santa Barbara the bedding appears to have little or no control over the vein width. Isolated examples where it appears that the bedding might govern the width of the veins, are found mostly in the minor veins in the northern part of the district. It is possible that the bedding exercises less control than expected because most of the fractures in the Santa Barbara district crossed the fold trends at angles from 20 to 60 degrees and the attitude of the bedding was, therefore, hardly ever parallel to the fractures. Even though most of the direct evidence seems to be negative, it is suspected that the bedding does exert more control on the veins than is indicated.

Only two major veins, the Seca and Primavera, strike parallel to the trend of the folding. The Seca vein is located near the crest of the anticlinorium. Not much control could have been exerted by the bedding since the vein is almost normal to the bedding, and tension fractures formed along the crest of the anticlinorium, would have provided a weak zone for the Seca fracture to follow. The Primavera vein, while dipping in the direction of bedding, is much steeper, and would have cut across the bedding planes. It seems reasonable that more fractures of the Gamma system should have been formed. The rarity of veins in the Gamma set suggests that the fractures might have been parallel to the bedding and that they were so tight that no hydrothermal solutions were introduced into them. Some of the larger folds on both limbs of the anticlinorium, having also formed tension fractures during folding, might be favorable locations for the presence of blind veins that would have strikes parallel to the trend of the folding.

Detailed geologic mapping of the shale beds will be required to determine this and other questions pertaining to the relation of the vein-shale structure.

Internal Vein Structure.—The internal vein structure varies from vein to vein and also with depth. A typical vein is bounded on both sides by semi-parallel walls that are frozen to the vein. On both sides of the vein, the distance varying from a few centimeters to 15 meters, the country rock is silicified, pyritized, silicified, and in places shows disseminated sulfide replacement. Sub-parallel stringers of quartz and calcite are common. Depending on the vein, but mostly at depth, the vein-wall contacts become vague in places and the contact becomes a zone, several meters wide, of stringers in a matrix of country rock. In the veins the sulfides occur as narrow ribbons or bands, also as massive lumps or layered bands where shale fragments and masses of silicates were replaced. In both silicified and unsilicified country rock adjacent to the veins, and also at long distances from the veins, sulfides occur as disseminated lumps and grains in bedded replacement zones. These replacement zones vary in dip and strike, following the bedding for a distance, then cutting across the bedding until another favorable bedding horizon is encountered. The question as to what constituted a favorable bedding horizon prompted the writer to make a study of drill cores where such replacement zones have been cut. In most cases, the replacement zone follows the more calcareous bedding. When the zone cuts across the bedding, it is in the form of very narrow quartz-calcite or silicate stringers that are generally barren of
sulfides except where a calcareous band is cut, whereupon sulfides commonly appear. This is shown in Figure 11.

Figure 11 suggests that the composition of the country rock might be a factor to be considered in the discussion of the location of ore shoots. If calcareous beds made up a very small portion of the shale formation and are also restricted to a limited number of horizons, their position might have been a very important factor. However, the calcareous content of the whole shale formation is quite high and the beds with a high calcareous content are found everywhere within the formation. Thus, it is thought that any influence of the country rock on ore deposition has been minor. It is thought that the composition of the breccia fragments within the vein might have a bearing on the degree of replacement achieved within that local part of the vein, and might be a reason for the higher than average metal content of zones within an ore shoot.

![Fig. 11. Sketch showing replacement in shale.](image1)

Toward the ends of ore shoots, the veins are mostly filled with irregularly shaped fragments of country rock that have been silicified, silicatized, and replaced around the fringes with sulfides. Towards the centers of ore shoots only half to three-quarters of the vein is apt to contain breccia fragments. These fragments have also been silicified, silicatized, and tend to be more completely replaced by sulfides and quartz. There are places where the fragments have been completely replaced by alternate layers of quartz and sulfides, giving a cockade structure. This cockade structure is common throughout the veins (Fig. 12). The breccia zone is generally along the footwall of the vein, but in places it is in the center and even adjacent to the hanging wall. The portion of the vein where there are no breccia fragments generally has a ribbon or banded structure. In places the quartz is quite massive with little or no structure.

![Fig. 12. Two examples of cockade structure, showing both complete and incomplete replacement of shale fragments. (top)—Part of the back in drift on Cobriza vein, 1,200 level, Cobriza mine; (bottom)—Part of the wall in sill on Cobriza vein, 1,200 level, Cobriza mine.](image2)

All the veins with ribbon and banded structure, indicate that they were subjected to dilation during vein filling (Fig. 13). On the 1,200 level of the Santiago vein there is a good illustration of this feature. A portion of the vein was broken across the ribbon structure three times, each vein filling...
cutting across the previous fillings. Many vugs occur in the veins throughout the district, indicating that many openings were present, even along sections of narrow vein. However, most of the vugs occur within the ore shoots, the largest being between the 800 and 1,000 levels of the Cobriza vein. The vugs are quite large, ranging up to 40 cm wide, and the quartz crystals developed in the walls of vugs show a comb structure. Other gangue minerals and some of the sulfides in the walls of vugs show perfect crystal forms.

The veins generally end either by intersection with other veins or by pinching down until they are very narrow, and then fray out into a number of stringers. Very few examples have been seen of veins pinching down to a knife edge as is reported to be the case at the Frisco mine (14, p. 27).

For a number of years it has been known that the grade of Santa Barbara ore is roughly proportional to the width of the vein (23). Of course, isolated exceptions to this can be found, but they are very few. It is thought that where there were wider openings in the pre-mineral fractures, the decreased velocity of the upward rising mineral solutions as they came into these wider openings was the main factor contributing to the higher metal ratio of such places. It would seem that in zones of narrow fractures, the higher velocity of the solutions would allow little time for precipitation or replacement. Otherwise, all of the veins regardless of width, would show the same metal content.

**Paragenesis**

Hydrothermal solutions, possibly emanating from the intrusive body suspected to be at depth, were introduced into the open fracture systems. The solutions contained ore metals with fluorine, sulfur, and possibly iron, magnesium and other elements. The silicates were formed by the interchange of constituents between the solutions and shale at a high temperature. Quartz and calcite were recrystallized, and fluorite and sulfide minerals were deposited.

Koch (14, p. 36) suggests that the bulk of the mineral matter at the Frisco mine was introduced at one time and not at different periods. Schmitt (23) gives three types of sulfide ore: Type I—Massive sulfide ore. Type II—Sillarous gold-silver ore containing abundant silicate minerals, Type III—Massive sulfide ore with abundant silicate minerals. This, of course suggests more than one period of vein filling at Santa Barbara. Schmitt also cites J.G. Barry’s (unpublished report) observation that the high-temperature or silicate stage cut the low-temperature or solid sulfide stage. This would mean that the temperature rose to the silicate stage and then declined, with
sulfides being deposited in every stage. This seems reasonable, but such occurrences of high-temperature mineralization cutting the lower temperature mineralization must be scarce, because only a few have been seen by the writer. However, there are many occurrences of the lower temperature mineralization cutting the high-temperature stage. Whether this represents two different periods of vein filling or just long time lags between the reopening of the veins to allow more vein filling is not known. Since these occurrences are so numerous, it seems likely that at least two stages of vein filling are represented; however, the question is debatable.

It is the opinion of the writer, except for a minor amount of pre-silicate sulfides, that the high-temperature silicates with associated sulfides constituted the initial stage of vein filling. The veins of the silicate stage are characterized by very coarse crystals, almost pegmatic in size. The best example of this is the Alejandria-La Paz section of the Mina del Agua-Palo Blanco vein. It might be mentioned again that deep drilling from the Alejandria and La Paz mines disclosed quartzite-like lenses at depth. This vein can be followed continuously to the south, passing from this high-temperature silicate stage of mineralization into a region at the south end that shows only epidote, the weakest recognized degree of silication. This, of course, suggests zoning. Schmitt (23) comments about gradation from one stage of mineralization to another in the San Albino and Cabrestante veins.

As vein filling progressed, the temperatures dropped, until at a late stage, deposition took place with little or no silicates. Barite appears to be later than the sulfides. It occurs within the veins, but cuts all sulfides and gangue minerals. Cross stringers of barite are common along a portion of the Los Hilos-Coyote vein. A late stage of fluorite is also present. It has been found where the veins are cut by fluorite-calcite-quartz stringers. Examples of this are found in many places along the Alejandria vein. A very late stage of deposition is represented by barren quartz veins that cut the older mineralized veins.

The birefringent garnet, reported by Schmitt (23), associated with the pyroxenes in some of the sphalerite ore, and the fact of the veins having been formed by replacement of shale suggested to Allen and Fahey (1) that the veins are pyrometasomatic replacement deposits. It is quite possible that a buried intrusive exists a short distance below the veins, and the factor of metamorphism, as indicated by the quartzite-like zones at depth, helps substantiate the presence of an intrusive. However, pyrometasomatic replacement deposits are characterized irregular and bumpy, and seldom have large amounts of quartz gangue. The veins at Santa Barbara, even the high-temperature silicate type, are well defined and regular veins, and have a high ratio of quartz gangue vein material. Therefore, following Lindgren's (17, p. 694) classification, the Santa Barbara deposits are assigned to the hypothermal class of hydrothermal deposits.

Colonia Tecolotes, Santa Barbara, Chihuahua, Mexico, April 15, 1958

References

7. Hernandez Sanchez M. S., editor, 1956, Carta Geológica de la Republica Mexicana, Scale 1:2,000,000: Cong. Geol. Intern., XX Seccion, Mexico.
12. ———, 1947, Carta geológica de la parte septentrional de la República Mexicana: Univ. Nacional Autónoma, Instituto de geología, Cartas geológicas y mineras de la República Mexicana, No. 3.
27. Stose, G. T., editor, 1946, Geologic map of North America, Scale 1:5,000,000: Cong. Geol. Intern., XX Seccion, Mexico.