GEOPHYSICAL EXPLORATION OF THE EL ARCO-CALMALLI MINING DISTRICT, BAJA CALIFORNIA, MEXICO

by

Ramón Farías García

A Thesis Submitted to the Faculty of the

DEPARTMENT OF GEOSCIENCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCES

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 7 8

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: _____

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

John S. Sumner

JOHN S. SUMNER
Professor of Geosciences

December 27, 1977
Date

ACKNOWLEDGMENTS

I owe special thanks to Dr. John S. Sumner, my thesis adviser, whose advice and patience are highly appreciated. I also wish to thank Drs. William C. Peters and Kenneth L. Zonge, who served on my thesis committee. Appreciation is expressed to Dr. Paul E. Damon for permission to use data on ages of rocks from Choix, Sinaloa.

I also wish to thank the following persons from Industrial Minera Mexico, S. A., Mexico, D.F., for their help and encouragement: Ings. Juan Holquin, Director of Mines; Amador Osoria, Manager of Exploration; and David Gomez Ruiz. Dr. D. F. Coolbaugh, Mexico, D.F., is acknowledged for his help and guidance. I thank the Welch Company of San Diego, California, for permission to use the Ifex International aeromagnetic map of the El Arco-Calmalli area.

I greatly appreciate the effort made by my wife Lourdes during our stay in Tucson.

TABLE OF CONTENTS

TABLE OF CONTENTS—Continued

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS—Continued

LIST OF TABLES

ABSTRACT

Since 1935 mineral production has been active in the El Arco-Calmalli mining district located in the center of the Baja California peninsula. Based on the geologic favorability of the area, Industrial Minera Mexico, S.A., formerly Asarco Mexicana, S.A., has recently carried out geological, geophysical, and drilling programs to evaluate the area. Results of the surveys are presented, also available geological and geophysical information gathered from other sources.

Geologic mapping shows that the district is underlain by a volcaniclastic complex correlative with the Alisitos Formation of middle Cretaceous age. A granodiorite porphyry intrusion is responsible for the copper mineralization within the area. Mafic and ultramafic rocks seem to be the oldest rocks of the region, while younger volcanics are also common.

An induced-polarization survey was very useful for delineating disseminated mineralization and locating the first drill holes in the El Arco porphyry copper deposit. Turam electromagnetic surveys were run to locate and delineate the volcanogenic massive mineralization at Calmalli. Geologic models interpreted from resistivity and gravity surveys were useful for water exploration. Aeromagnetic and ground magnetic surveys were also useful. Interpretation of the geophysical anomalies and the geologic work done give a clearer picture of the district for further exploration and development.

INTRODUCTION

The El Arco-Calmalli district is located at the midpoint of the boundary between the states of Baja California. The district lies between the geomorphologic provinces of Desierto Vizcaino and San Borja. The village of El Arco, with a population of 200 people is located within the district at about lat 28°02' N., long 113°30' W. (Fig. 1).

The elevation of the village of El Arco is about 300 m. The local drainage is southwest into the Vizcaino Desert. Elevation increases to the north, reaching more than 600 m in the northwestern portion of the district.

The climate is dry, with an average yearly rainfall of 120 mm. Temperatures range from 3°C to 42°C. During the winter season foggy weather coming from the Pacific Ocean is common most of the time. Surface water is not available, but the water table is close to the surface in several localities within the district and a large natural reservoir of water exists south of El Arco in the Guerrero Negro basin. Vegetation includes several types of cacti and the unusual boojum (Idira columnaris).

A paved 40-km road connects the village of El Arco with the transpeninsular highway. There is access from mainland Mexico by way of a ferryboat to Santa Rosalia, which lies 130 km distant, or by scheduled airline service to Guerrero Negro, a 40-minute drive from El Arco. In addition there are airfields located in the northwest and southwest

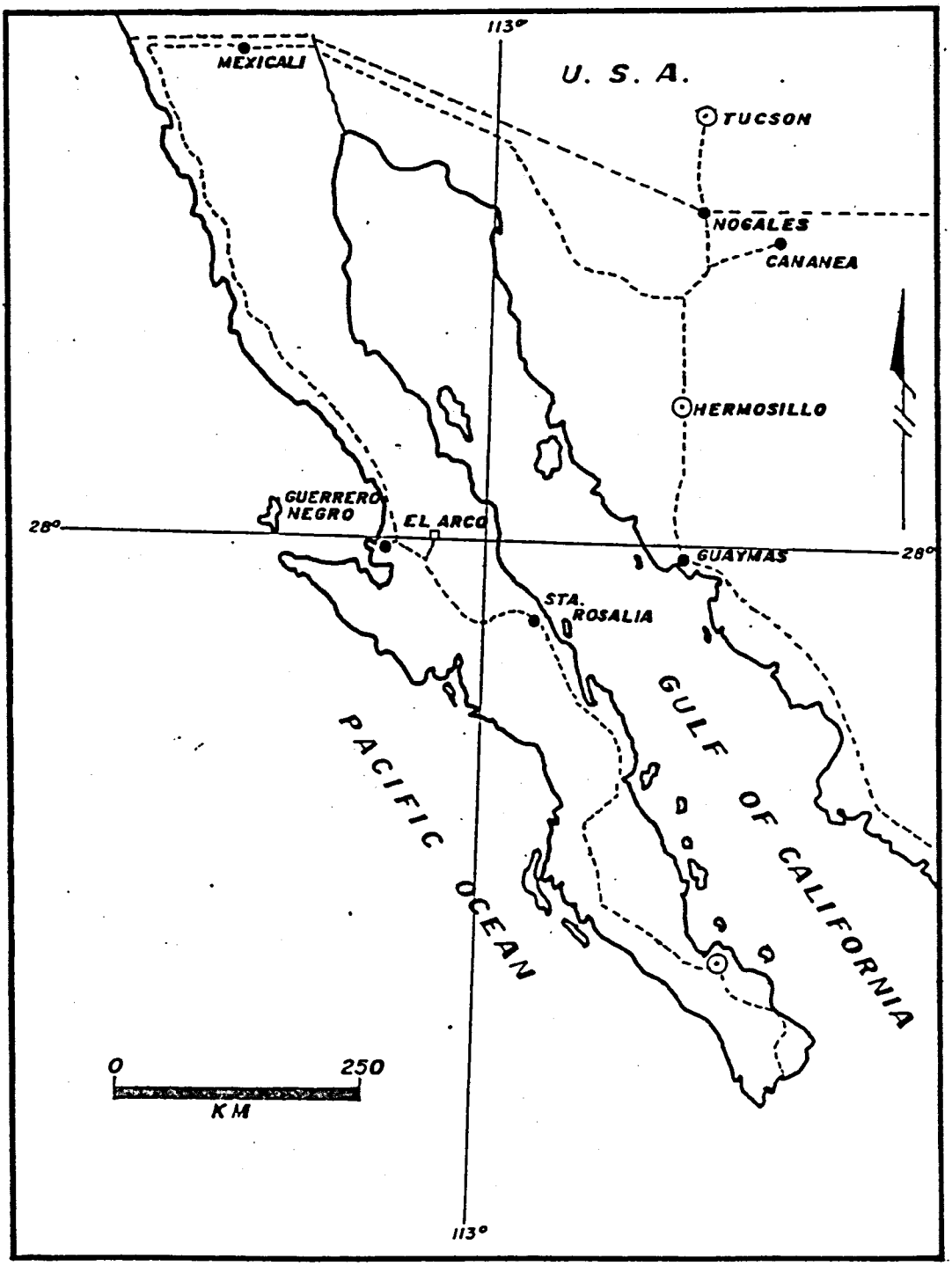


Figure 1. Location of the El Arco-Calmalli district

corners of the district. The airstrip within the village of El Arco will not be used anymore because of the growing population in the area.

Production History

Production in the El Arco-Calmalli district began in 1883 when gold placers were discovered. During the first half of the present century several small mines in the northwestern portion of the district, such as the Calmalli and Don Carlos mines, were developed and worked for gold and copper and were still operating at the beginning of the 1930's. El Arco was also an important mine worked for gold and copper between 1930 and 1940. Other small mines of lesser importance within the district are the Otilia, Nogales, El Tigre, and El Aguila, but not all of these prospects were formally worked. A large amount of placer activity also existed near the streams of Pozo Aleman at the center of the district.

The El Arco-Calmalli district became important in 1968 when Industrial Minera Mexico, S.A., formerly Asarco Mexicana, S. A., began a geological and geophysical reconnaissance of the district followed by a drilling program. This exploration led to the discovery of the El Arco porphyry copper deposit.

Purpose of Work

Since the discovery of the El Arco deposit, the district has been the subject of intense geological and geophysical exploration. The purpose of this thesis is to review the geological setting of the district and to gather, present, and interpret the geological and geophysical information available from different mining companies and institutions, such as Petroleos Mexicanos, Ifex International, San Diego State College, and

others. The geological work presented here was done by the exploration team of Industrial Minera Mexico, S.A., Hermosillo, Sonora. New concepts have been added by the writer, who has been responsible for the exploration geophysical work done for minerals and water in the El Arco-Calmalli district.

It is hoped that this thesis on the El Arco-Calmalli district will be of help to geologists in future exploration of this area and of similar districts north of the El Arco area where identical geological conditions are expected to exist.

REGIONAL GEOLOGY

The most recent and complete geological study of the northern half of the Baja California peninsula has been published by Gastil, Phillips, and Allison (1975), who divide the geological history of the peninsula into three stages: prebatholithic, batholithic, and postbatholithic. Rocks of all three stages can be recognized within the El Arco-Calmalli district.

Prebatholithic Rocks

Outcrops of prebatholithic terrain within the district show two different types of rocks: mafic to ultramafic rocks and a belt of volcaniclastic and other sedimentary rocks.

Mafic and ultramafic rocks crop out in an area of about 10 square kilometers in the northwestern part of the district. Gabbros, peridotites, pyroxenites, and amphibolites are common. They show an advanced degree of serpentinization. Magnesite, although less common, is found in veins and fracture fillings. The ultramafic rocks appear to have oceanic characteristics and underlie the volcaniclastic sequence.

The volcaniclastic sequence, which includes sedimentary rocks, crops out from the 28th parallel through the northern half of the peninsula and cross the U.S. border to the Santa Ana Mountains in California (Gastil et al., 1975). The rocks of this belt were deposited

in an oceanic trench (Ernest, 1965) in Late Jurassic and Early Cretaceous time. At El Arco they serve as host for the porphyry copper mineralization.

The most abundant rocks within the district (Fig. 2) include andesitic-dacitic flows, volcanic breccias, agglomerates, tuffs, limestones, shales, and graywackes. These rocks underwent a period of regional metamorphism, and there is a greenschist facies with a well-developed foliation. Osaria (1971) divides these metamorphic rocks into well foliated, moderately foliated, and massive. The foliation has two main directions, N. 30° W. and N. 65° W. and dips 75°-80° N. The N. 65° W. is the dominant direction in the district. The area surrounding the porphyry copper deposit at El Arco has N. 10°- and N. 45° W.-trending foliations, suggesting different stresses in this area, probably produced by the intrusion of the granodiorite. Rocks with less foliation are found at the El Arco deposit, and as a rule, foliation in the district increases to the north.

Several occurrences of limestone are found within the volcaniclastic sequence. The largest outcrop of carbonaceous limestone is found 4 km northwest of Pozo Aleman (Fig. 2). The content of carbonaceous material in this limestone ranges between 40 and 50 percent and is responsible for the high background level found in the IP response of this area. Other small lenses of limestone interbedded with andesitic agglomerates also occur north of El Arco and south of Pozo Aleman.

Graywackes are common in the Fontes area northeast of Pozo Aleman. Massive volcanic rock with greenschist facies and without foliation are found from El Arco to the south.

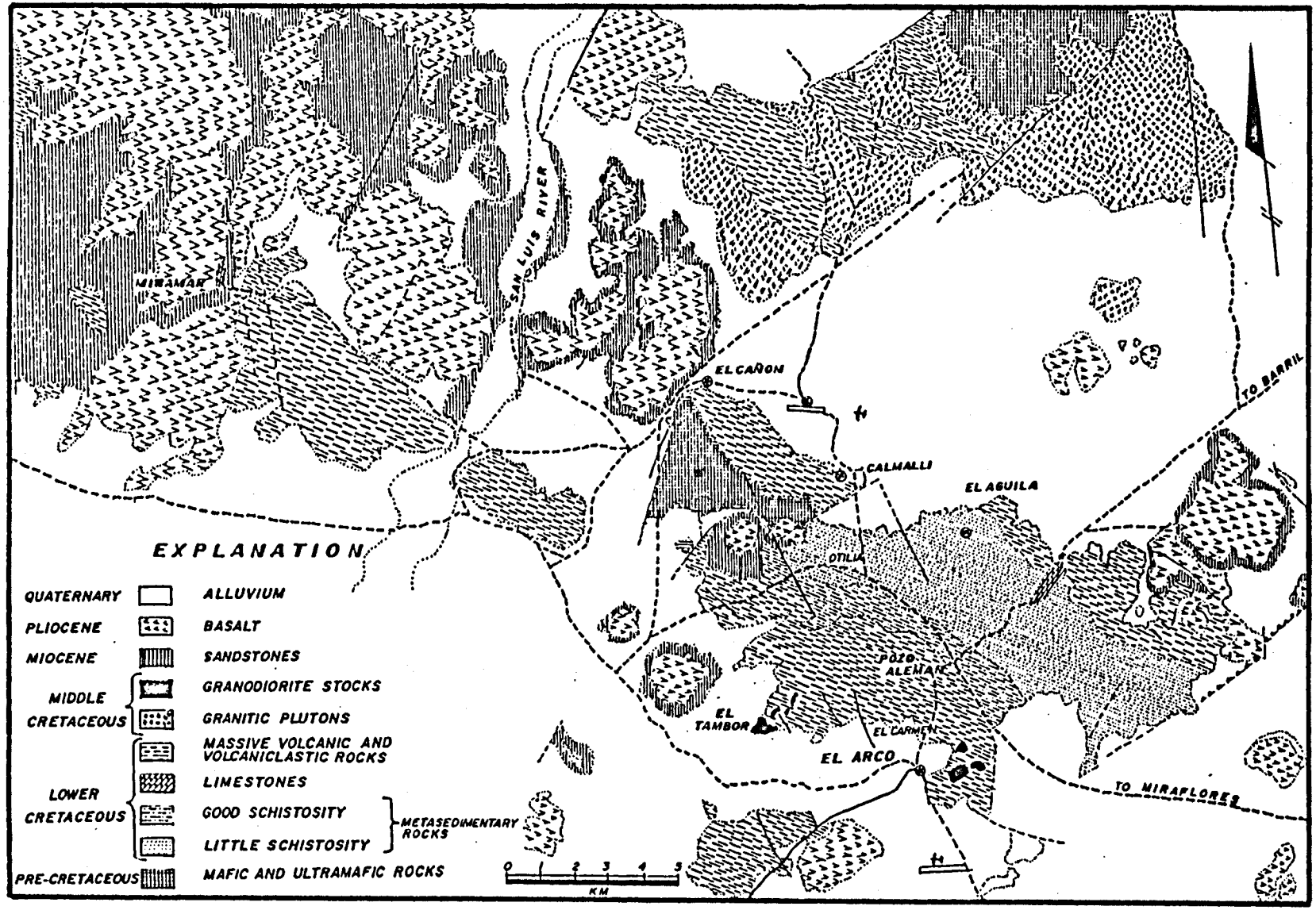


Figure 2. Geologic map of the El Arco-Calmalli district

In general, it can be said that the prebatholithic volcaniclastic formation in the El Arco-Calmalli district is composed of three different members which overlie a sequence of andesitic flows and pillow lavas outcropping near the Calmalli mine.

The lower member is composed of folded metasedimentary rocks with a high degree of foliation. These rocks are exposed in a 3,000-m-thick belt, which trends N. 65° W. throughout the district. Volcanic agglomerates, graywackes, limestones, diabase dikes, and andesitic flows are the most common rocks. The Fontes area is located within this belt.

The second member is a shaly formation with a very fine, well-developed foliation. This member is folded and exposed in a belt more than 1,000 m thick at Pozo Aleman.

What seems to be the upper part of the formation is composed of massive volcanic rock with a greenschist facies and a small degree of foliation. These rocks are located in the southern part of the district and serve as host to the mineralization at El Arco.

No fossils have been found to aid in determining the age of the prebatholithic rocks in the El Arco-Calmalli district. However, the volcaniclastic sequence can be correlated with the San Telmo, San Fernando and Alisitos Formations of Early Cretaceous age. Silver, Allen, and Stehli (1969) have dated a volcanic bed from the Alisitos Formation at 127 $\pm$ 5 m.y.

Batholithic Rocks

Batholithic rocks of granitic composition found in the northern part of the district are probably the southern portion of the peninsula range batholith whose main outcrop terminates about 20 km north of El Arco. These rocks are related in time to the emplacement of large batholiths and plutons along the western coast of North America from Alaska to Baja California and Sinaloa in Early and middle Cretaceous time. The mineralization in the El Arco-Calmalli district is a phenomenon directly related to this stage.

In the southern part of the district and close to El Arco are several small outcrops of intrusive rocks, which range in composition from monzonite in the El Tambor area to granodiorite porphyry at El Arco. The mineralized granodiorite porphyry at El Arco has been dated from whole rock analyses at 93.4 $\pm$ 2.1 m.y. (Shafiqullah, 1974). Barthelmy (1974) has dated the same rocks at 107 $\pm$ 2.5 m.y. by using unaltered phenocrysts of orthoclase. Probably because of alteration in the granodiorite porphyry, the age given by Shafiqullah is younger than that given by Barthelmy. The Instituto del Petroleo (1974) gave an age of 127 $\pm$ 7.0 m.y. for the mineralized intrusion. This age seems too old when compared with the age of the intruded rocks. A list of rock ages for the district is given in Table 1.

Postbatholithic Rocks

The emplacement of plutons along the Baja California peninsula, completed about 85 m.y. ago (Larson and Pitman, 1972), was followed by a period of uplift, cooling, and erosion (Gastil et al., 1975).

Table 1. Ages of rocks in the El Arco-Calmalli district

Sample	Age (m.y.)	Mineral	Rock and Locality
UAKA 74-3	93.4±2.1	Whole rock	Granodiorite porphyry from El Arco intrusion; feldspar phenocrysts removed (Shafiqullah, 1974)
UAKA 74-2	96.5±2.1	Whole rock	Diorite porphyry from the El Arco area (Shafiqullah, 1974)
UAKA 74-1	103.9±2.3	Whole rock	Host rock for UAKA 74-3, El Arco area (Shafiqullah, 1974)
1173-K-A	107 ±2.5	Orthoclase	Granodiorite porphyry from El Arco intrusion, lat 28°01'11" N., long 113°25'09" W. (Barthelmy, 1974)
RGC-21-73	127 ±7.0	Feldspar	Rhyolite porphyry from El Arco intrusion (Instituto del Petroleo, 1974)
518	19.8±0.5	Biotite	Rhyolite tuff, basal volcanic unit, Mision Sta. Gertrudis (Gastil et al., 1975)
UA ?	[a] 58.6±1.3	?	Granodiorite from La Reforma mine, Choix, Sinaloa (P. E. Damon, written com., 1975)
UA ?	[a] 55.8±1.2	?	Granodiorite phase of the Choix, Sinaloa, batholith (P. E. Damon, written com., 1975)

a. These dates were obtained as part of a cooperative research project between the Consejo de Recursos Naturales no Renovables and the Laboratory of Isotope Geochemistry at the University of Arizona.

Lithologic remnants from this period in the El Arco-Calmalli district are Miocene sandstones and volcanic tuffs, which crop out in the northern and southern portions of the mapped area (Fig. 2). Volcanic rocks of basaltic and rhyolitic composition cover some of the Miocene sedimentary rocks.

Several postbatholithic rock units are associated with volcanoes. These units include lava flows and ash beds located in the northern half of the district. The age of the postbatholithic volcanic rocks in the area is not exactly known. Osaria (1971) gives a Pliocene age for these rocks, and Gastil et al. (1975) report an age of 19.8 $\pm$ 0.5 m.y. for a rhyolitic tuff exposed near Santa Gertrudis, approximately 40 km east of El Arco. The youngest rock within the district is a fluvial conglomeratic sequence of Quaternary age which covers the southern portion of the district.

Tectonic Framework

According to the new global tectonics theory (Isacks, Oliver, and Sykes, 1968), it is now accepted that the widespread emplacement of batholiths and plutons that took place along the Pacific Coast from Alaska to Baja California and Sinaloa between 110 and 85 m.y. ago (Larson and Chase, 1972) was produced by an increase from 5 to 18 cm/yr in the velocity of subduction of the Farallon plate beneath the North American plate. Figure 3 shows the distribution of lithospheric plates during middle Cretaceous time and the trench along the west coast of North America in which the prebatholithic rocks were deposited. Melting through frictional heating of the descending lithospheric plate

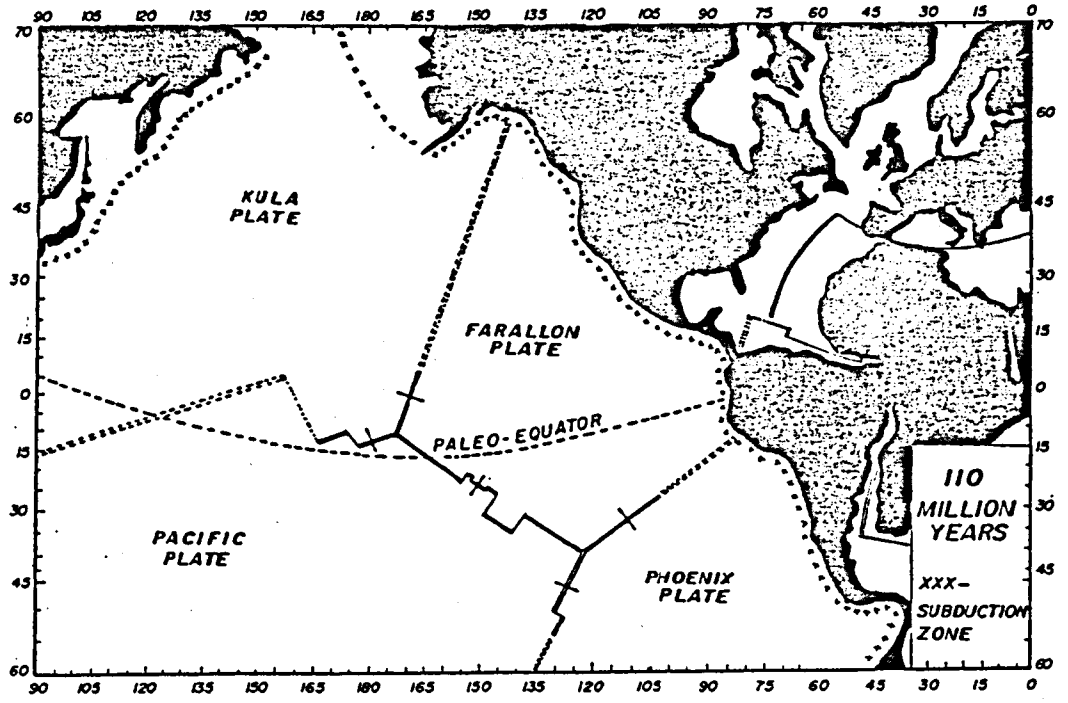


Figure 3. Pacific Ocean plates at 110 m.y. ago—After Larson and Chase (1972)

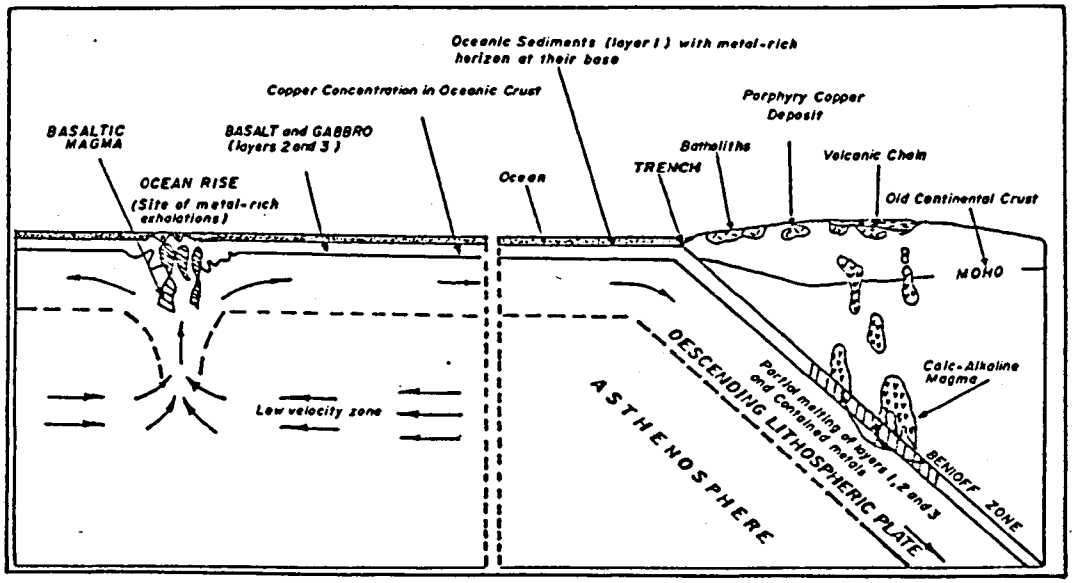


Figure 4. Plate tectonics concept of the genesis of porphyry copper deposits—After Sillitoe (1972)

and uplift of magmas, as shown in Figure 4, were probably the mechanism that produced mineralized intrusions in the El Arco-Calmalli district.

Underthrusting of the Farallon plate was completed 30 m.y. ago (Larson and Pitman, 1972) after the subduction of several thousand kilometers of lithospheric plate. The collision and consumption of the ridge in the trench near Mazatlan, Sinaloa, put the American plate in direct contact with the North American plate to the north of Mazatlan. The last manifestation of the Farallon plate are the Rivera and Cocos plates located at the right margin of the East Pacific rise. The subduction of the Cocos plate beneath Mexico has produced young mineralized intrusions in Chiapas (Damon and Montesinos, 1975). Young mineralized intrusions may also be found south of Mazatlan where the Rivera plate is subsiding underneath the states of Jaliso and Michoacan.

The El Arco-Calmalli district was originally located at the margin of the North American plate. The transfer of Baja California from the American to the Pacific plates (Normark, 1971) and the translation of the peninsula along the San Andreas fault system have changed the original position of this district with respect to mainland Mexico. Since 5 m.y. ago the rate of displacement of 6 cm/yr (Atwater, 1970) has rafted Baja California 300 miles (482.7 km) to the northwest (Hamilton, 1969). By projecting the peninsula back to its original position, it can be readily seen that the El Arco-Calmalli district was originally located in the vicinity of Mochis, El Fuerte, and Choix, Sinaloa, where mineralized intrusions are also known and important porphyry copper prospects are

being investigated. This evidence suggets a common magmatic source for the cluster of mineralized plutons.

The intrusive rocks in the Choix, Sinaloa, area have been dated at 58.6 ± 1.3 m.y. for the biotite granodiorite from La Reforma mine and 55.8 ± 1.2 m.y. for another granodiorite at a fairly great distance from La Reforma (P. E. Damon, written communication, 1975) (Table 1). The ages of the Choix plutons are younger than 93 m.y., the age of the granodiorite intrusion found at El Arco. This difference in age can be easily explained by considering a magmatic front formed by partial melting of the descending Farallon plate that migrated toward the continent. The location of El Arco near the western part of the subduction zone was the first to be intruded by the uprising magmas. The rate of magmatic migration has been calculated to be 0.45 cm/yr by Henry (1975) in an area north of Mazatlan, Sinaloa. This low speed of magmatic migration is probably due to the angle of subduction and the reduction of motion of the plate beneath the mantle. By taking the same rate of magmatic migration for the Choix area and by considering the difference in age between the intrusive rocks at El Arco and Choix, it is possible to consider that the El Arco-Calmalli district was originally located at about 160 km west of the Choix area in northern Sinaloa.

Structural Geology

Local structures in the El Arco-Calmalli district trend northwest and are semiconformable to the foliation of the volcaniclastic rocks. The strike of the structures ranges from N. 10° W. in the southeast portion of the district to N. 65° W. in the northern portion.

The Santa Rosalia fault is the principal major structure that passes through the district. This transpeninsular fault is the continuation of the western Gulf fault zone (Fig. 5). The fault coming from the Gulf of California touches the peninsula at Mulege, passing near Santa Rosalia and then through El Arco and Guerrero Negro. It follows parallel to the Pacific coastline along the magnetic anomalies reported by Krause (1965).

According to Minch (1975) this fault was probably active from Cretaceous to recent time and has a major strike-slip displacement. A direct relationship between this transpeninsular feature and the mineralization in the El Arco-Calmalli district has not been found, but it is possible that the uprise of mineralized plutons in middle Cretaceous time was influenced by this fault. Evidence of recent volcanism is found at Santa Maria and Tres Virgenes.

The Santa Rosalia fault is clearly distinguished near El Arco by its topographic expression at the boundary of the geomorphologic province called Llano del Berrendo or Desierto de Vizcaino. Also, the peninsular batholith appears to be controlled by this major fault, with nongranitic rocks observed to the west of the structure. Gravity anomalies (see Fig. 21, p. 50) define the dip of this fault, which is also the border of the Guerrero Negro basin located southeast of El Arco.

Other major linear structures can be located at Bahia de Los Angeles. Linear features with a north-south direction intersect the Santa Rosalia fault in the El Arco-Calmalli district. Several other minor active linear structures exist in the region that indicate that the zone has a complex structural setting.

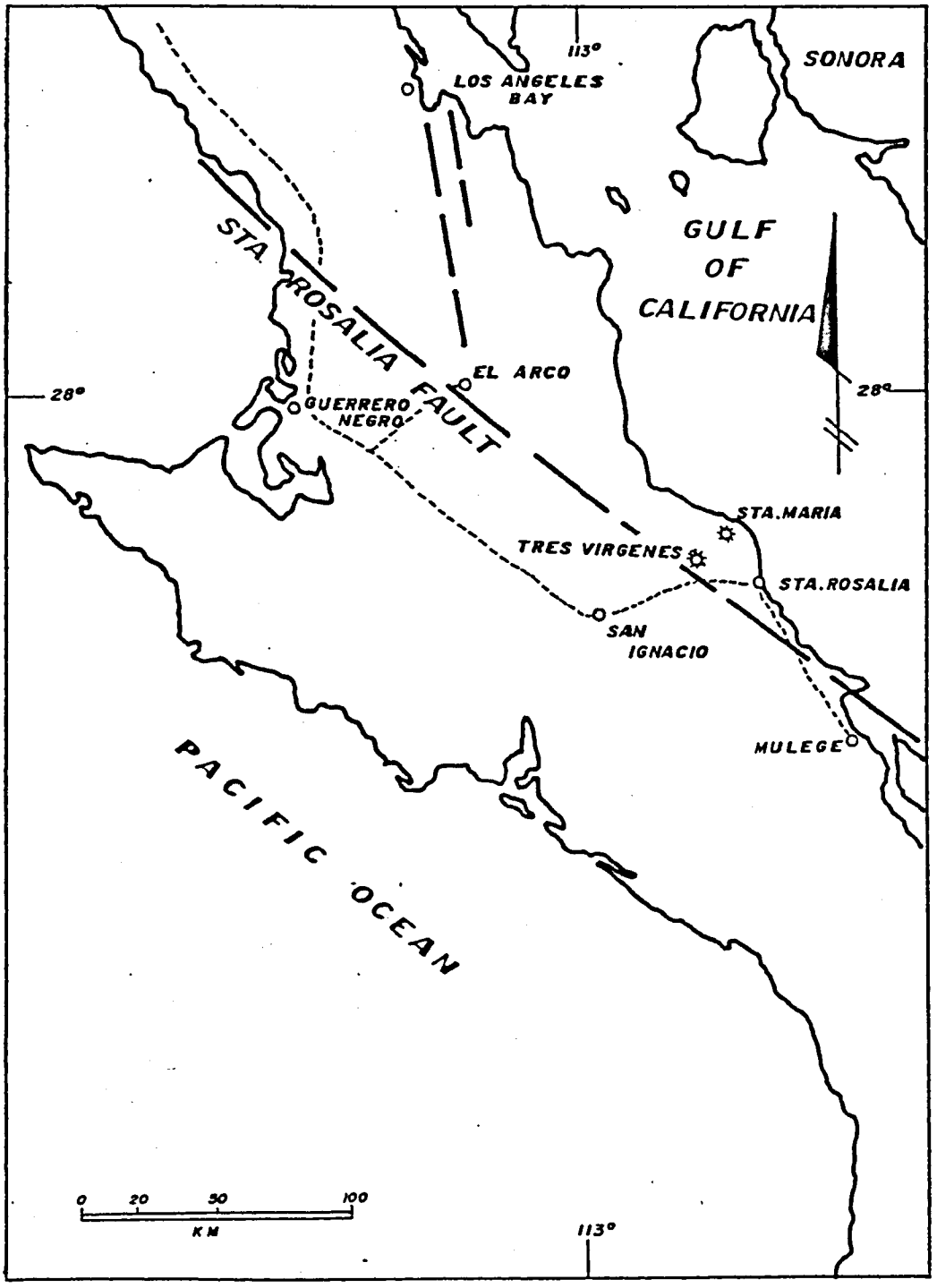


Figure 5. Major structures passing through the El Arco-Calmalli district—After Sumner (1972)

GEOLOGY OF THE EL ARCO PORPHYRY COPPER DEPOSIT

Figure 6, a geologic map of the El Arco porphyry copper deposit, shows the rocks that crop out within the mineralized area. There are two preore rock units: a sequence of andesitic rocks altered to the greenschist facies by regional metamorphism and a granodiorite porphyry genetically related to the economic mineralization. The postmineral rocks exposed in the mine area are a mafic rock petrographically identified as a diabase, aplitic dikes, and a conglomerate, which covers 75 percent of the mineralized area.

All of these rocks have been cut by drill holes. The drill core generally shows well-defined contacts between rocks, but some of the rock changes graduate from andesite-diorite to granodiorite. Although the rocks are extremely well fractured in a random fashion, the dominant structural trend is northwest. No important faults were mapped in the area, but there is some indirect evidence to support the theory that a fault of at least moderate displacement follows the trace of the central drainage. In addition, drill core shows numerous faults with small displacement.

Andesitic Rocks

The andesitic rocks were the host for the mineralized porphyritic granodiorite. Three types were petrographically identified: porphyritic andesite, hornblende andesite, and andesitic breccias (Echavarri, 1975). There is also a rock identified by thin section as diorite which is

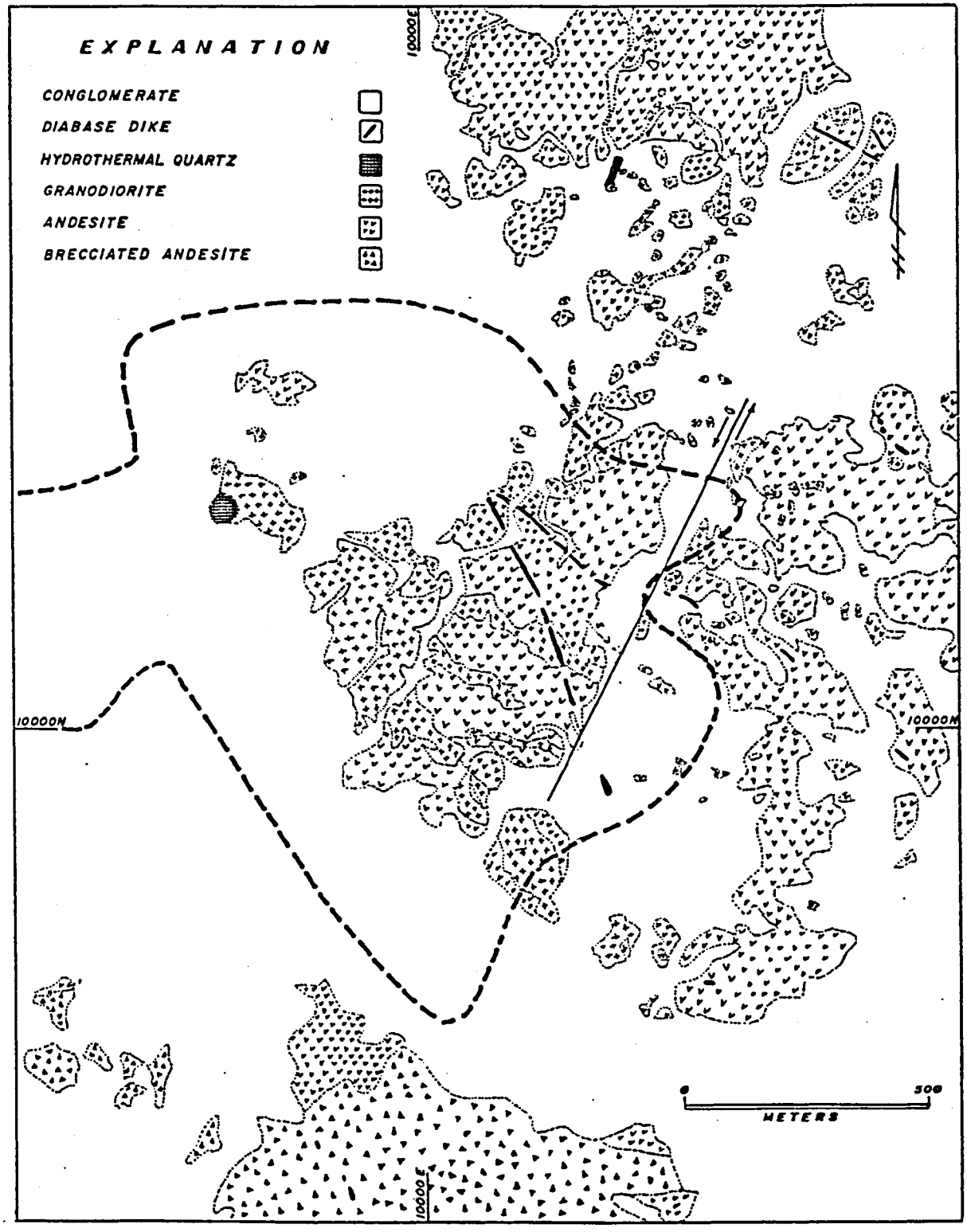


Figure 6. Geologic map of the El Arco porphyry copper deposit

possibly genetically associated with the andesites. All these rocks belong to the Alisitos Formation (Santillan and Barrera, 1930) and make up the Telolopan Alisitos arc described by Campa and Oviedo (1976). At El Arco these rocks have undergone metamorphism, but the foliation and schistosity is not as well developed as in rocks in the northern part of the district.

Small lenses of limestone found in the andesites indicate a marine environment of deposition. The brecciated andesites were possibly formed by steam explosions in a subaqueous environment.

Granodiorite Porphyry

The granodiorite porphyry has medium-grained phenocrysts and a fine-grained groundmass. Outcrops vary from from cream to brown. Potash feldspars as large as 1 cm can be seen in hand specimen. The plagioclases vary in size from 1.2 to 3 mm. Quartz and hornblende are found in crystals with a length of 2.5 mm. Granodiorite porphyry constitutes 40 percent of the outcropping rocks, and the mineralization is genetically associated with it. Outcrops of massive milky quartz are found embedded within the granodiorite porphyry (Fig. 6). A hydrothermal origin has been proposed for this quartz in contrast to a metamorphic origin for that found outside the intrusion.

Diabase

Barren dikes of light to dark gray diabase are found cutting all the rocks. Some dikes are more than 10 m thick. They have been penetrated in drilling throughout the deposit.

Conglomerate

The youngest rock unit is a conglomerate made up of rounded to subrounded boulders and pebbles of andesite, granodiorite, and diorite. It is cemented by sand and clay. The thickness of this unit is greatest in the western portion of the mineralized area where more than 300 feet have to be drilled before basement rock is found.

Alteration

Most of the rocks within the El Arco deposit show only weak hydrothermal alteration. Significant alteration occurs in irregular patches ranging in diameter from 3 to 100 m. On the surface, the only observable alteration product is silica and sometimes kaolin and minor sericite. There are several small areas of strong silicification. One area of significant size, around 100 m in diameter, occurs at the center of the mineralized area (Fig. 6). The drill core shows the presence of secondary potash feldspar in veinlets found in the granodiorite, while propylitization is observed in the andesites. The propylitic assemblage is more intensely developed in the outer zone of the deposit, while the K-feldspar is found at the center.

The classic Lowell and Guilbert (1970) alteration zones for porphyry copper deposits are not well developed in the El Arco orebody. Potassic and propylitic zones are found telescoped and overlapping. The argillic zone is not well developed.

Alteration from regional metamorphism is also present. Veinlets of epidote, calcite, chlorite, and quartz are the main representatives of this type of alteration. Some minerals from the hydrothermal

alteration assemblages were destroyed by regional metamorphism and are not found in regular concentric zones. The more unstable hydrothermal minerals, such as biotite, were transformed into more stable minerals. For these reasons it is possible to conclude that mineralization at El Arco is older than the regional metamorphism.

Mineralization

The mineralization at El Arco is found filling fractures and disseminated in the rocks. The primary sulfides are pyrite and chalcopyrite, with minor amounts of magnetite, gold, bornite, and molybdenite. Minerals from the oxidation zone are chrysocolla, dioptase, malachite, and wad.

Pyrite and chalcopyrite are the most abundant sulfides. At the center of the economic ore the total pyrite content is less than 1 percent by weight, increasing toward the periphery of the deposit where it makes up a halo with more than 5 percent pyrite. Distribution of total sulfide content is shown on Figure 7. Chalcopyrite content is 1.5 percent at the center of the mineralized area, diminishing toward the periphery. The pyrite-chalcopyrite ratio is approximately 1:1 at the center, and it increases to 8:1 at the border of the economic mineralization.

Bornite appears sporadically and in small quantities throughout the deposit. Molybdenite occurs in quartz veinlets, generally in the zone of potassic alteration at the center of the body. Magnetic occurs in veinlets or small blebs throughout the deposit. Galena and sphalerite have been identified in trace amounts at the margins of the intrusion.

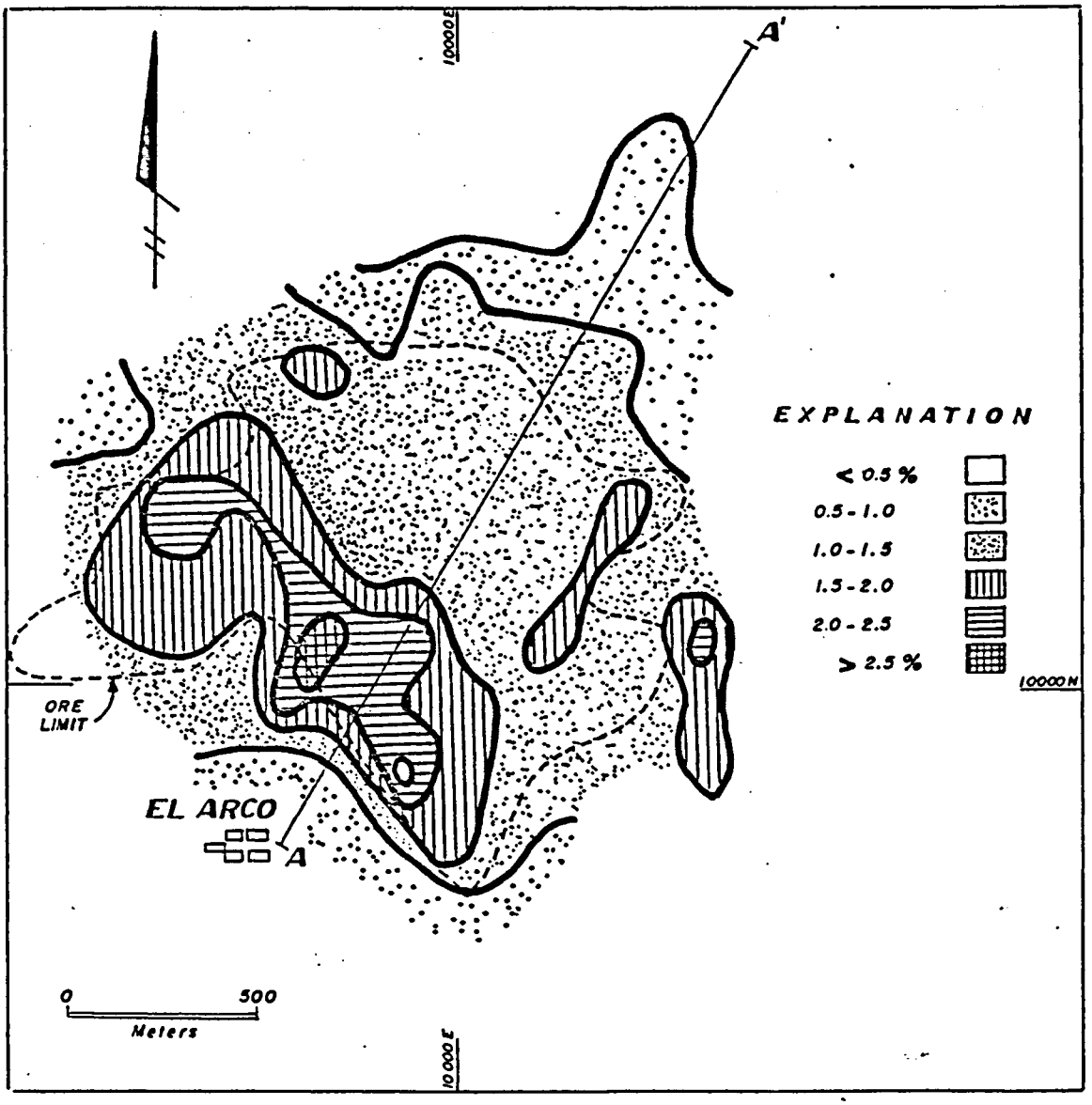


Figure 7. Total sulfide distribution in volume percent at the El Arco porphyry copper deposit—After Echavarri (1975)

Figure 8 is a cross section through the economic orebody. It shows an oxidation zone with an average thickness of 30 m. Underlying this oxidation zone is a transition zone ranging in thickness from 1 to 15 m containing a mixture of copper sulfides and oxides. No significant secondary enrichment exists at El Arco. The sulfide zone, which has been drilled to a depth of 360 m, constitutes the most important economic zone.

Ore Reserves

To date 160 holes, located on a 100-m triangular grid, have been drilled to evaluate the economic mineralization in the El Arco deposit. Results from more than 50,000 m of diamond drilling indicate a tonnage of 600 million with an average grade of 0.62% Cu, 0.2 grams per ton gold, and 4.0 grams per ton silver. The cutoff grade for this reserve is 0.4% Cu. Values above 1.0% Cu are common at the center of the orebody.

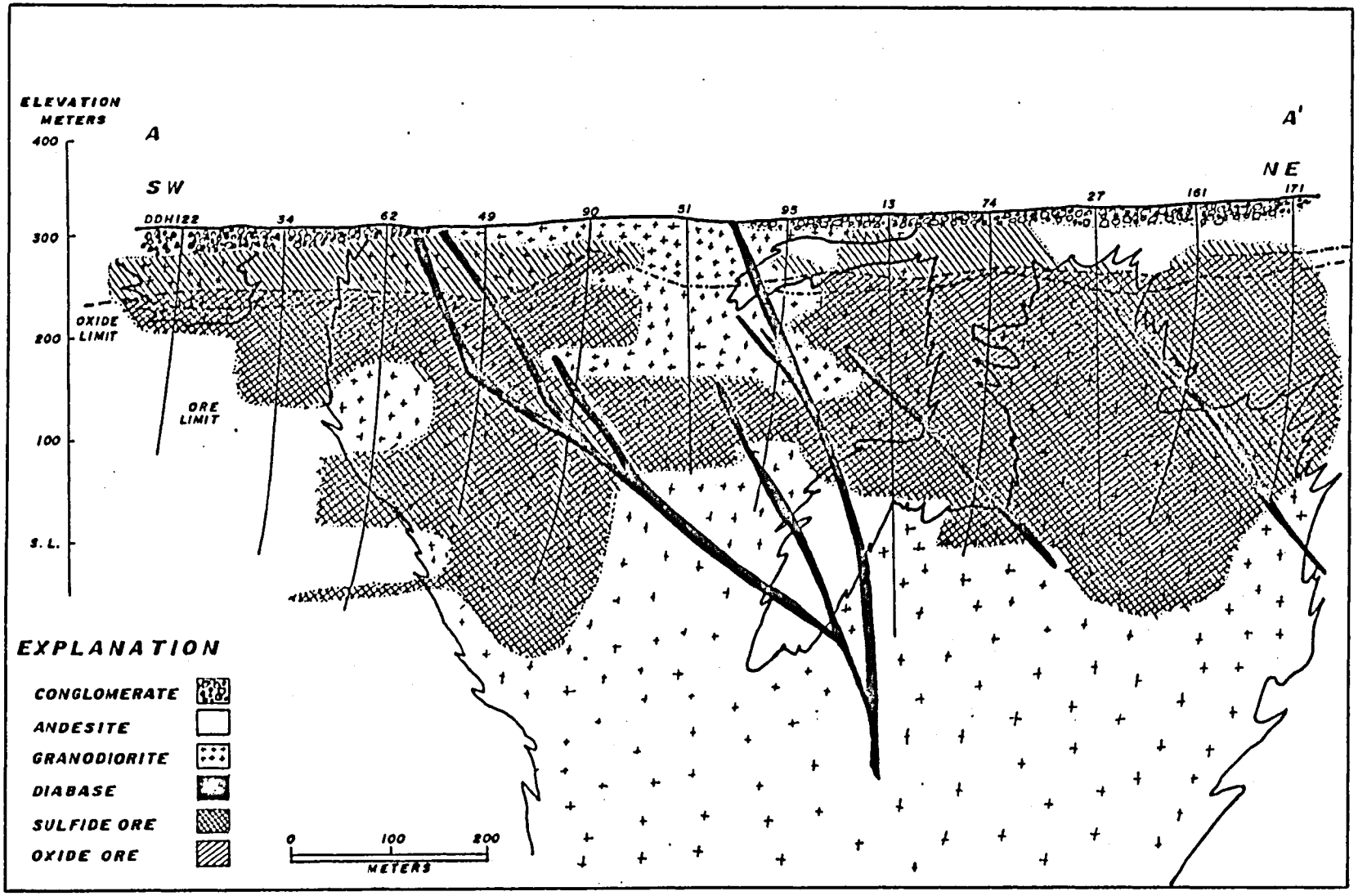


Figure 8. Geologic section through the El Arco porphyry copper deposit

REGIONAL GEOPHYSICAL SURVEYS

Several geophysical methods have been applied in the El Arco-Calmalli district as reconnaissance tools to locate mineralized area. In addition, the Instituto de Geofisica of the University of Mexico, San Diego State College, and Pemex (Petroleos Mexicano) carried out geophysical exploration in surrounding districts at various times. This exploration has been of valuable help in correlating the local geophysics with the regional geophysical context of the peninsula.

Heat Flow

Two heat flow measurements were made in drill holes at El Arco. The values of the heat flux found were 1.23 and 1.22 HFU (1 HFU = 10^{-6} cal/cm^2/s. These values are similar to the low-to-normal values found in the northern half of the Baja California peninsula. Figure 9 shows flow values for the northwestern part of Mexico. Heat flow in Sonora is greater than that of the peninsula. Heat flow measurements in Sonora indicate a high heat flux in the western part of the state a slightly lower heat flux to the east. According to Gastil et al. (1975), the geothermal heat flow through the floor of the Gulf of California is higher than the world average of 1.5 HFU. High heat flow in the Gulf of California is probably the result of sea-floor spreading.

Gravity

In order to process the copper ore at El Arco, 10,000 gpm of water will be required. Therefore, hydrological studies were carried out

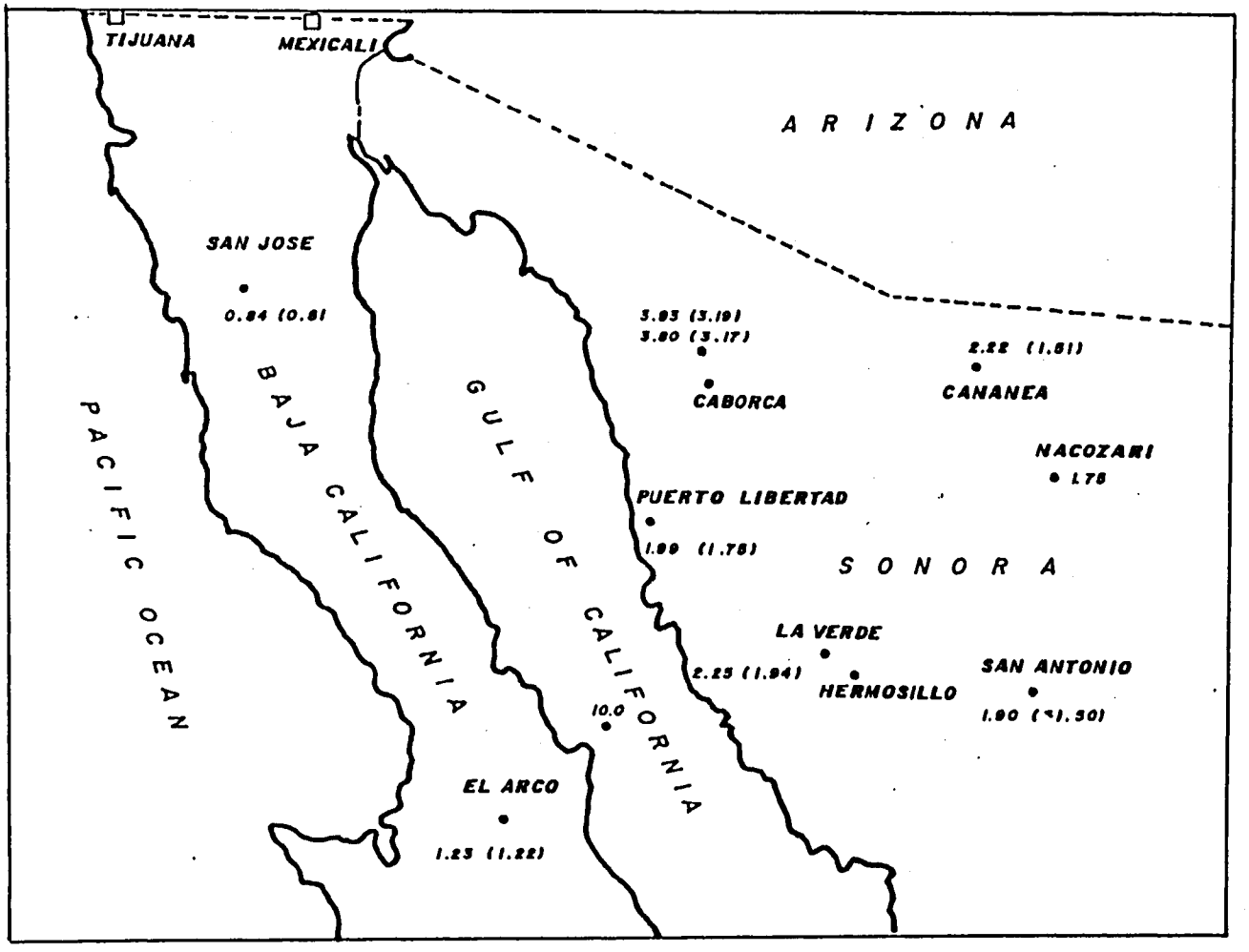


Figure 9. Values of heat flow for northwestern Mexico—After Smith (1972)

All values are given in heat flow units; reduced heat flow in parentheses.

to look for favorable areas. Gravity and resistivity surveys were made as an initial step to detect thicknesses of detrital formations and the depth to bedrock.

Gravity stations were located in an area southwest of El Arco at distances of 2 km and distributed on the lines as shown in Figure 10. For this survey, a total of 400 stations were read. A gravity base located at the weather station in El Arco was used. The value of observed gravity at this point is 979 123.68 mgal. The base station is tied to the U.S. Geological Survey gravity monument at the Los Angeles International Airport (Gastil et al., 1975). Elevation above sea level of the El Arco base is 279.2 m; the geographic coordinates are lat 28°01'4" N. and long 113°24'39" W. The simple Bouguer gravity value given by Gastil et al. for the El Arco base is -8.15 mgal. Gravity measurements were made with a Scintrex prospector-type gravity meter. Stations were located with aerial photographs. Vertical control of the stations was established by means of an altimeter, which gave a precision of $\pm$ 2 m. The accuracy of the gravimetric values is therefore $\pm$ 0.4 mgal, which is acceptable because of the high value of the sought-for anomalies.

The observed gravity values were corrected for drift, free air, Bouguer, and latitude. Table 2 shows the densities of typical rocks from the El Arco-Calmalli district. A density contrast of 0.4 g/cm^3 between sediments and consolidated rocks was used. The calculated average density used for consolidated rock was 2.67 g/cm^3. No topographic corrections were made because most of the stations were located in flat terrain.

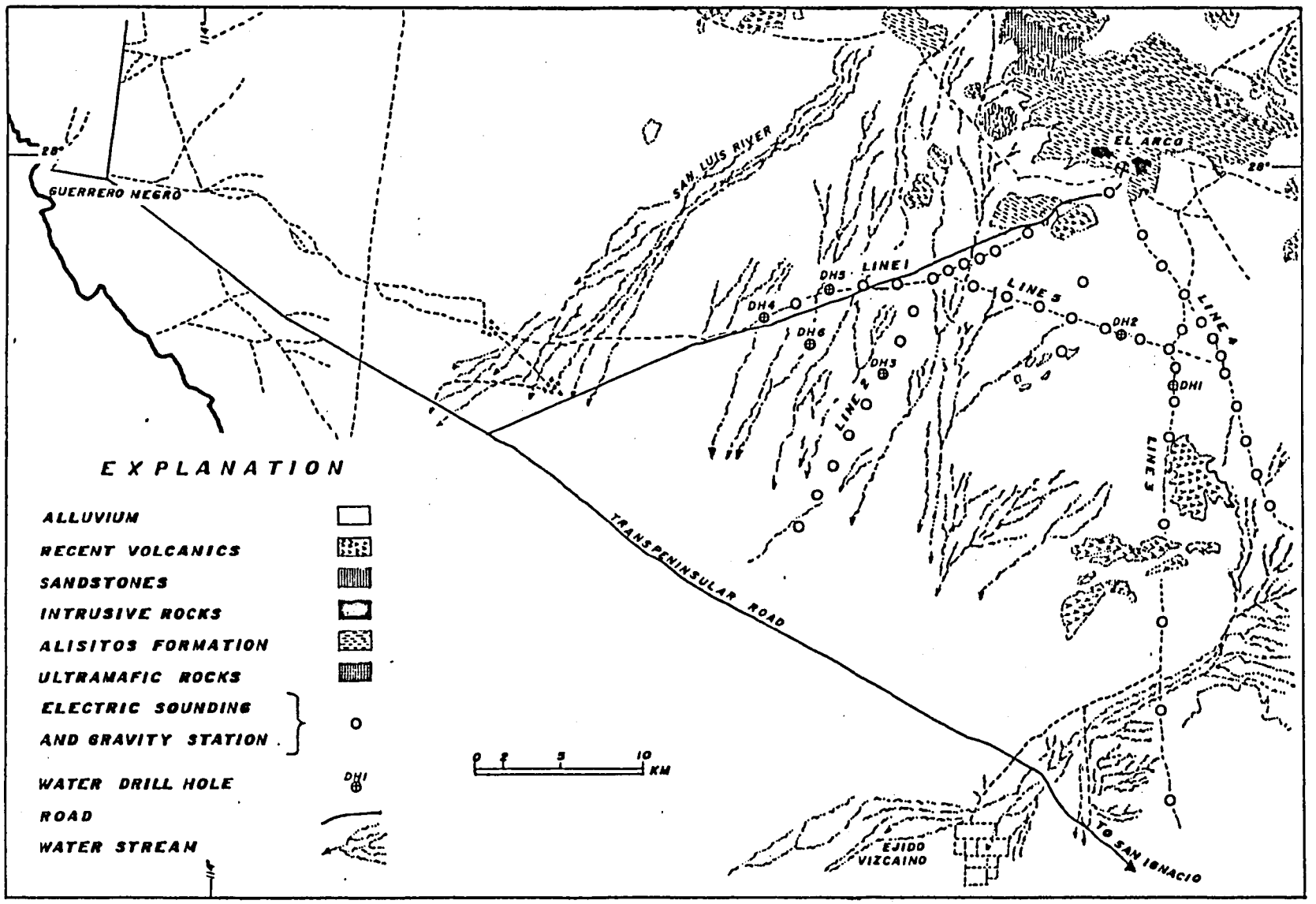


Figure 10. Location of vertical electric sounding and gravity stations

Table 2. Densities of typical rocks from the El Arco-Calmalli district

Type of Rock	Density (g/cm^3)	Location
Granodiorite porphyry	2.69	Intrusive rock at the El Arco deposit
Andesite	2.72	Host rock for the granodiorite porphyry in the El Arco area
Conglomerate	2.4	From DDH 5, 18 km southwest of El Arco
Sandstone	2.2	Miocene sandstone from the Bacatete Formation; from DH-6, 20 km southwest of El Arco
Shale	2.32	Miocene Bacatete Formation from DH-5
Gabbro	2.99	Sample taken near El Canon
Pillow lava	2.4	Sample from Calmalli mine

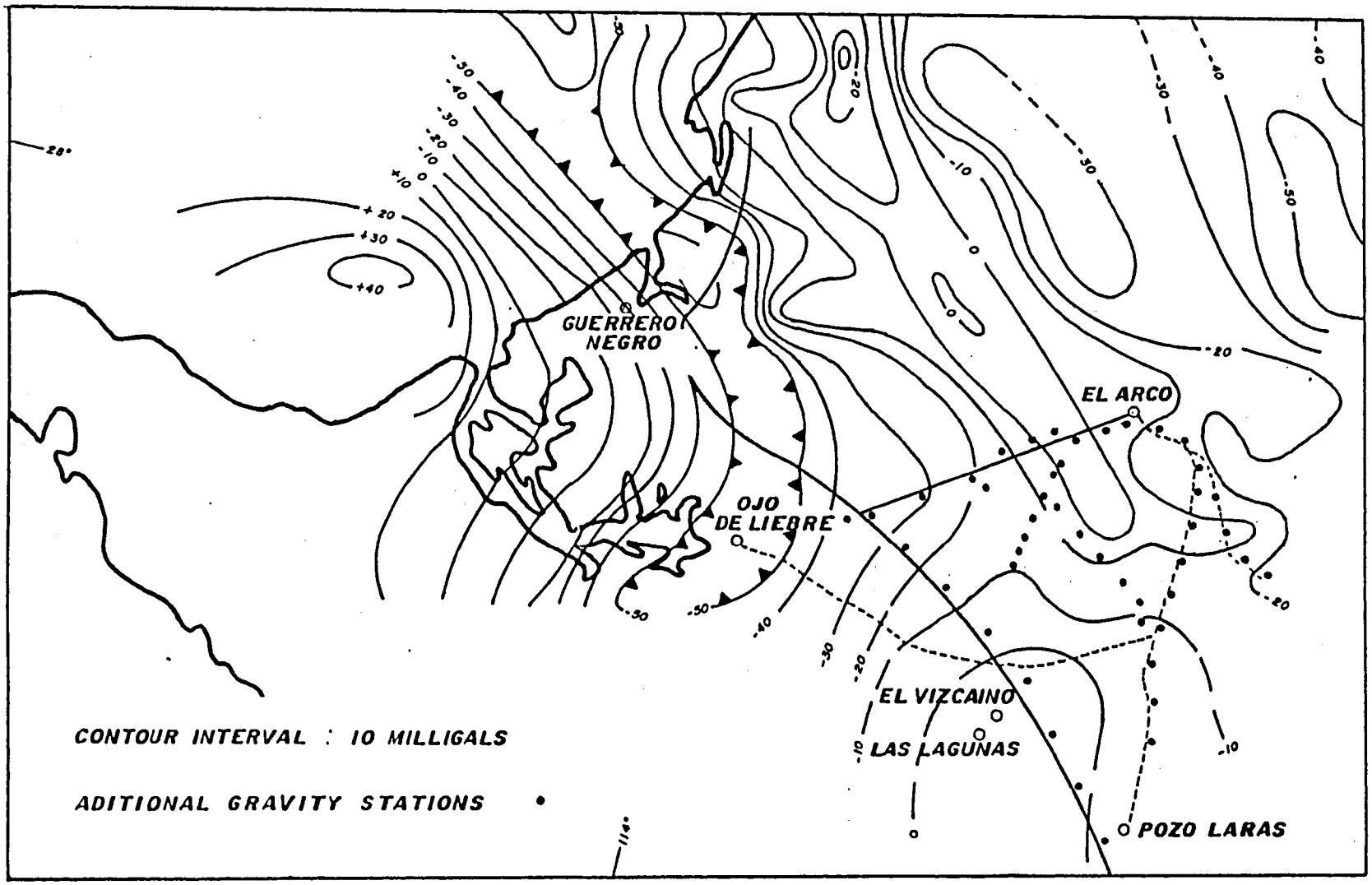


Figure 11. Bouguer gravity map of a portion of the Baja California peninsula

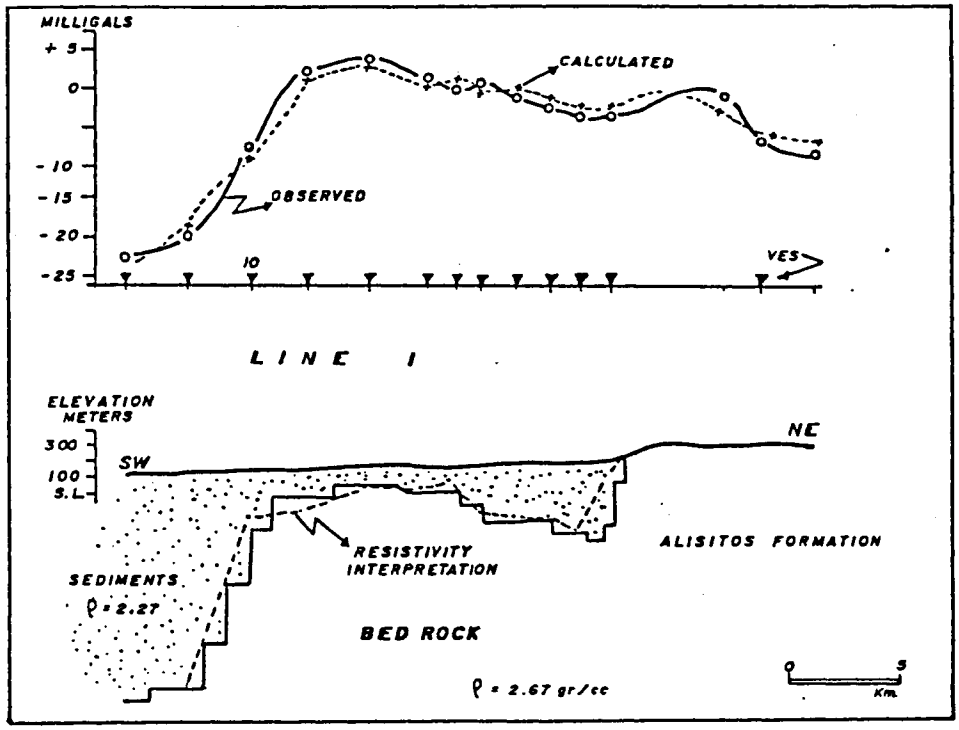
Results of the gravimetric survey were used to complement the Bouguer anomaly map of Gastil et al. (1975) south of El Arco (Fig. 11). In this figure it is possible to observe the end of the gravimetric high of the Alisitos Formation, which runs from the northwestern coast of the peninsula to the El Arco district and lies in the eastern part of a gravimetric high. It can be seen from Figure 11 that the gravity anomalies have a northwesterly trend showing the structural trend of the peninsula.

Figure 10 shows the location of the three gravity profiles modeled by the Hubbert (1948) method. Interpretation was made to determine the thickness of sediments and to outline the basement to detect favorable areas for water exploration drilling. Gravity profiles and model geological sections for profiles 1, 3, and 4 are shown together with the basement relief detected with vertical electric soundings on Figure 12.

Profiles 1, 3, and 4 show gravity highs associated with bedrock exposures or associated with a thinning of sediments. Gravity lows indicate a thick cover of sediments as was proved by six holes drilled to test the hydrologic conditions of the area. Gravity profiles and model geologic cross sections 1 and 4 indicate anomalies greater than - 20 mgal along the border of the Guerrero Negro basin, which is filled with more than 15 km of sediments. This basin produces a gravity low of - 60 mgal near Guerrero Negro. The basin is also called the Baja California syncline (Beal, 1948). It has been recently drilled by Pemex, who have found good indications of oil and gas.

Resistivity

As a step for hydrological studies and also as a complement to the gravimetric interpretation, 100 vertical electric soundings (VES) were



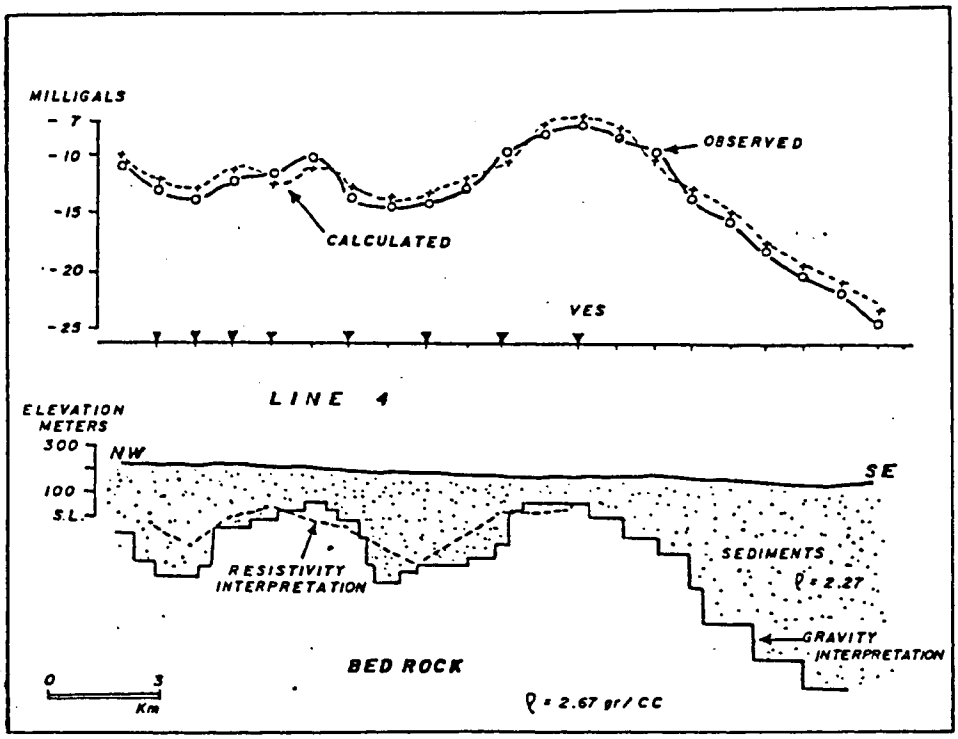


Figure 12. Gravity profiles and modeled geologic sections for lines 1, 3, and 4 (Fig. 10)

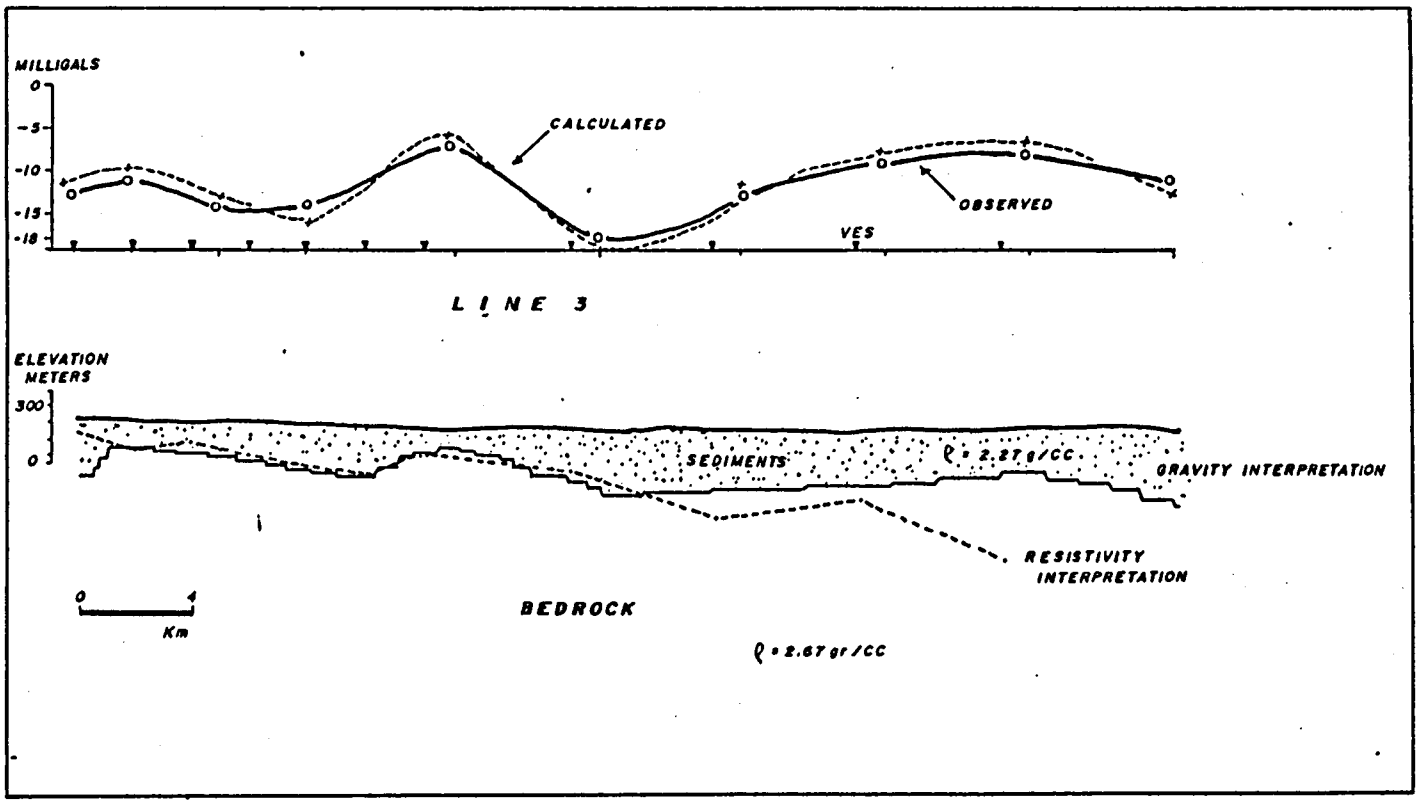


Figure 12, Continued

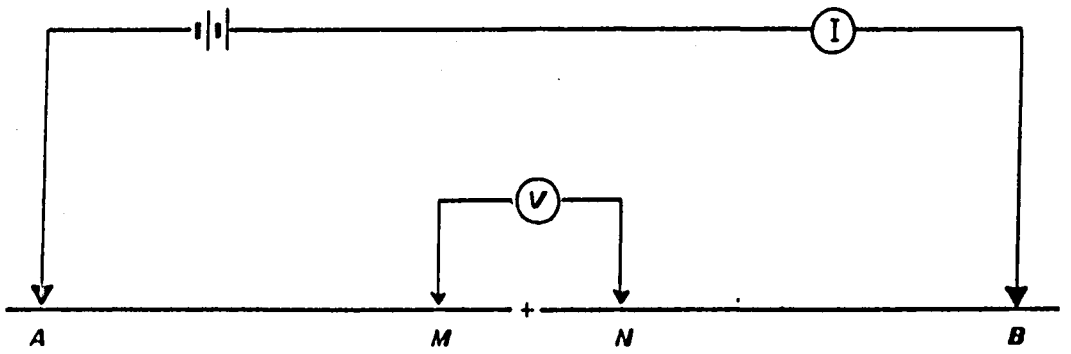
made in the Vizcaino Desert; locations are shown on Figure 10. The electric soundings consisted of a succession of apparent resistivity measurements made with an increasing electrode separation while the center of the configuration and its orientation remained fixed. Four electrodes are commonly used; two current electrodes to inject current into the ground (points A and B in Figure 13) and two potential electrodes to measure the voltage between the two points M and N.

A Schlumberger configuration of electrodes was used because it was the most suitable to detect horizontal inhomogeneities of the ground. In this array, the potential electrodes were moved a minimum number of times during a given electrical sounding. The apparent resistivity (ρ_a) of the ground is given by the following equation:

$$\rho_a = \frac{\overline{AB}^2 - \overline{MN}^2}{MN} \frac{\pi V}{4I}$$

in which V is the voltage measured and I the current intensity in amperes. The depth of exploration is controlled by AB/2 (half the current electrode separation). Separation between soundings was 2 km, and they were located on different lines southwest of the El Arco deposit in order to locate the nearest favorable area with appropriate thickness of sediments. An Elliot 1.5 kW transmitter was used. This equipment is capable of injecting 3,000 V at 0.5 A into the ground and it reads voltages as small as 0.01 mV. Electrode separations ranging between 3 and 3,000 feet were used to investigate the ground to depths up to 1,500 feet.

Apparent resistivity readings were displayed logarithmically as shown on Figure 14. Interpretation was made by using a matching



$$\rho_a = \frac{\pi}{4} \frac{(AB)^2 - (MN)^2}{MN} \frac{V}{I}$$

Figure 13. Schlumberger electrode array

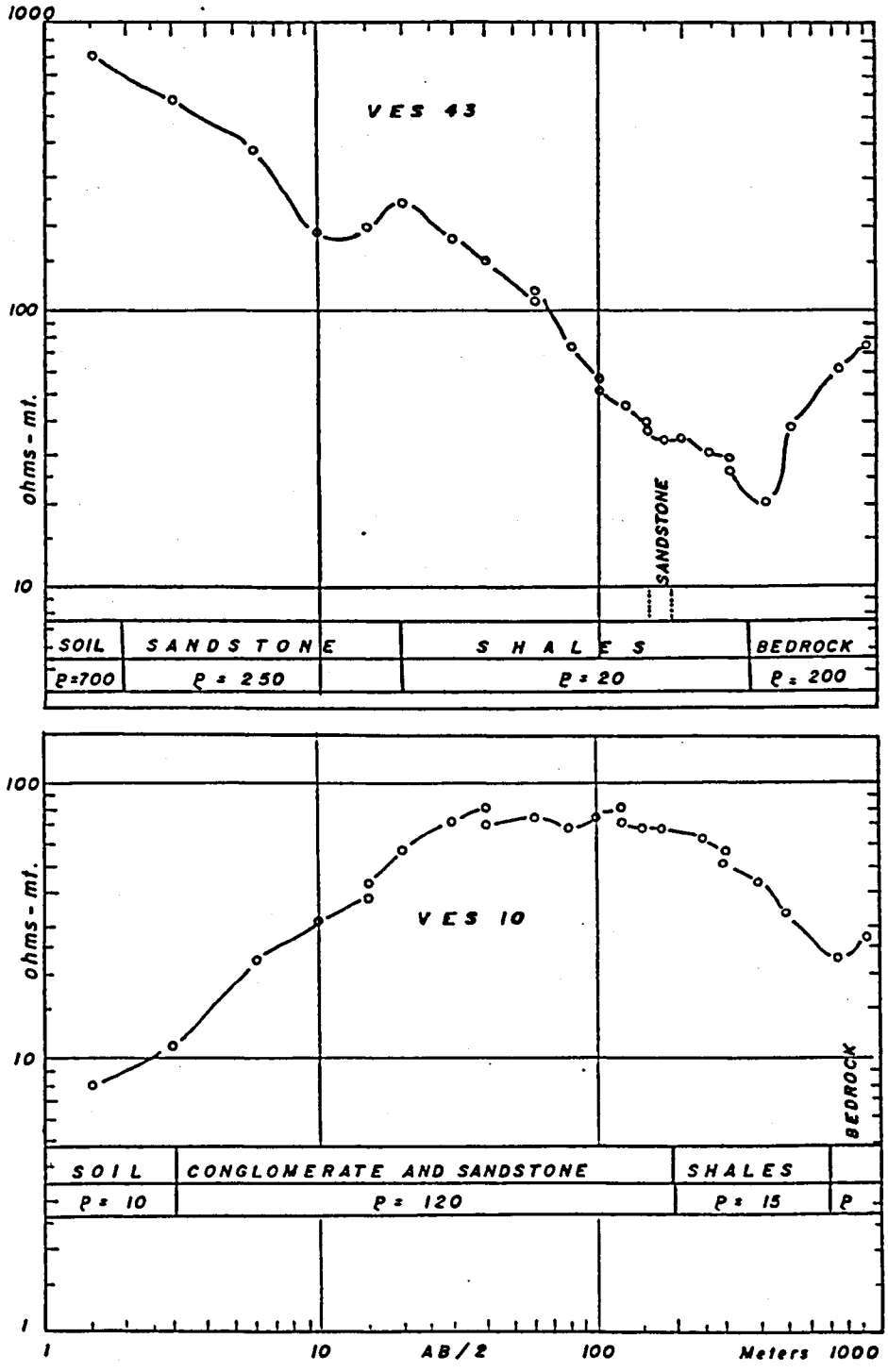


Figure 14. Interpretation of vertical electric soundings 43 and 10 located at drill holes 2 and 4 (Fig. 10)

procedure, comparing the field curve with master curves that give the specific resistivity and thickness for different beds below the surface.

Correlation between the soundings of one line provides a section or profile with the interpreted thickness of the sedimentary units. Figure 15 shows such a section across an area located near the El Arco ore deposit. In this section, thicknesses of the sedimentary units detected with VES range from 0 to more than 1,000 m. Several profiles interpreted by this procedure indicated four areas of interest, and six holes were drilled in these areas for observation wells to investigate the characteristics of the aquifers.

Aeromagnetics

Ifex International flew an aeromagnetic survey for Welch Mining Co. over an area of 225 km^2 covering most of the district. Data were obtained using a Geometrics 803 magnetometer. Flight lines were approximately north-south, 1.3 km apart, and 153 m above ground surface.

Magnetic contours are shown on Figure 16. The contour interval is 100 gammas. The most prominent anomaly, with a total amplitude of 3,560 gammas above the background magnetic level, is located in the northwestern portion of the surveyed area. Ground investigation indicates that this anomaly coincides with an outcrop of ultramafic rocks shown on the geologic map (Fig. 2). A magnetic low of 100 gammas located southwest of the Calmalli airstrip is in volcanic rocks of the Alisitos Formation. Craters and basaltic mesas also coincide with large-amplitude magnetic highs. This coincidence suggests that these anomalies are partly produced by basalt necks and dikes that fed the basaltic

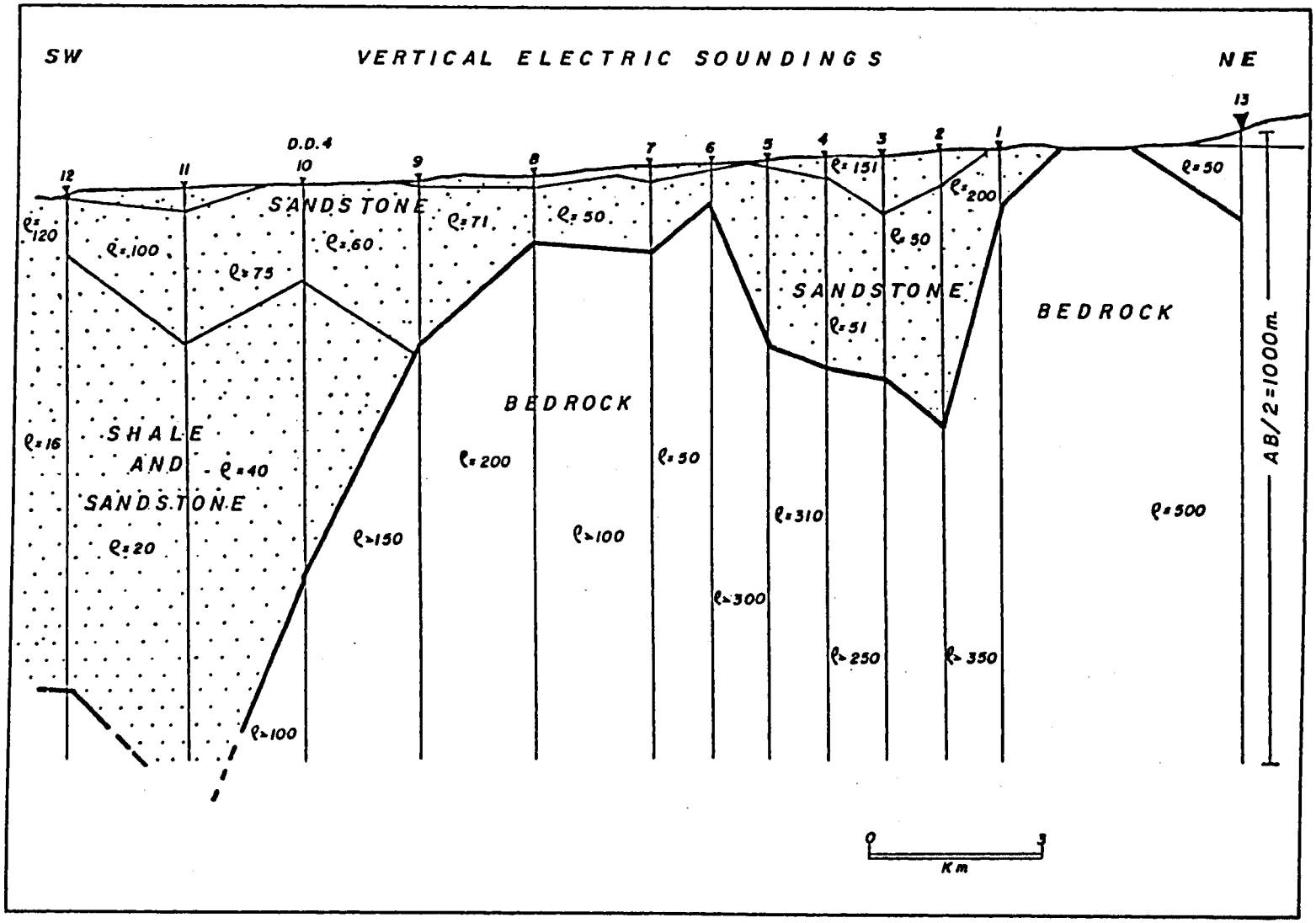


Figure 15. Geologic section interpreted from vertical electric soundings of line 1 (Fig. 10)

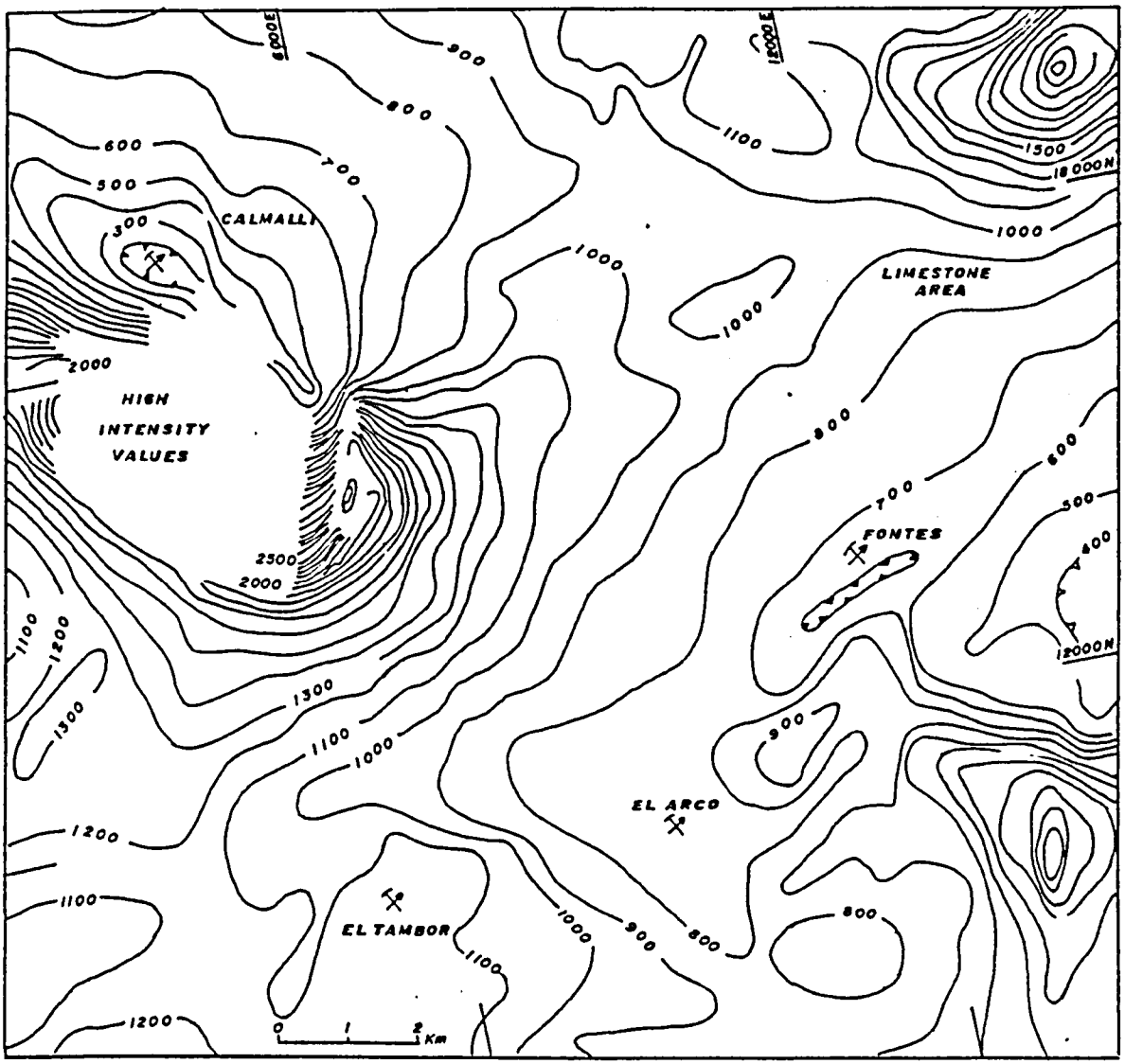


Figure 16. Aeromagnetic contour map of the El Arco-Calmalli district—From Ifex International (1971)

flows such as those located at the northeastern corner of the geologic map.

Known mineralization within the district is associated with magnetic lows. The El Arco mineralized area is located in an anomalous magnetic trend whose intensity ranges from 700 to 900 gammas. Mineralization at Calmalli, El Tambor, and Calizas also coincides with magnetic lows.

It can be said that the magnetic anomalies detected in the El Arco-Calmalli district reflect the composition of two large masses of different composition: (1) ultramafic to mafic rocks, which crop out northwest of El Arco and show a magnetic high of 3,500 gammas, and (2) an intrusive mass of probable monzonitic to granodioritic composition, which crop out in the El Arco area and follows a northeasterly trend as indicated by medium to low intensity anomalies shown on the magnetic map (Fig. 16). This intrusive mass is mineralized, as indicated by IP anomalies.

Induced Polarization

After a reconnaissance geologic survey was made in the district, it was recommended that a regional IP survey be made to confirm the suspected presence of sulfides at depth northeast of the El Arco porphyry copper deposit. For this survey, all the roads in the district were covered with a Wenner electrode array using spacings of 500 m. Several additional reconnaissance lines perpendicular to both sides of the roads were laid out. Anomalous areas found with this survey were resurveyed with equidistant IP lines separated by 500 m and with

electrode stations at 200-m intervals. For this survey a 7.5 kW time-domain Huntec transmitter and a Scintrex IPR-7 receiver were used.

The IP data are displayed in a planar configuration on Figure 17, with contour intervals of 5 ms. The IP background of the rocks in the district was determined to be 4 mV s/v (ms); therefore, all IP values above that value were considered anomalous. Figure 17 shows the location of the five anomalous areas detected by the IP survey: El Tambor, Calmalli, Fontex, Calizas, and El Arco. The IP anomaly at El Arco will be discussed in the section on the geophysics of the El Arco deposit.

El Tambor Anomaly

The El Tambor IP anomaly is located 3.5 km northwest of the village of El Arco. This anomaly has a maximum intensity of 14 ms and is related to a quartz monzonite porphyry.

Calmalli Anomaly

The anomaly located close to the Don Carlos mine south of the town of Calmalli has an intensity of 10 ms. This anomaly is produced by a volcanogenic pyritic body. No disseminated copper sulfide mineralization has been found in the area where this anomaly is located.

Fontes Anomaly

The Fontes anomaly is located 4.5 km northeast of the village of El Arco. It has a maximum intensity of 15 ms and is 1 km long and 600 m wide. The outcropping rock in the anomalous area is a well-foliated schist intruded by dikes with syenite and magnetite veins.

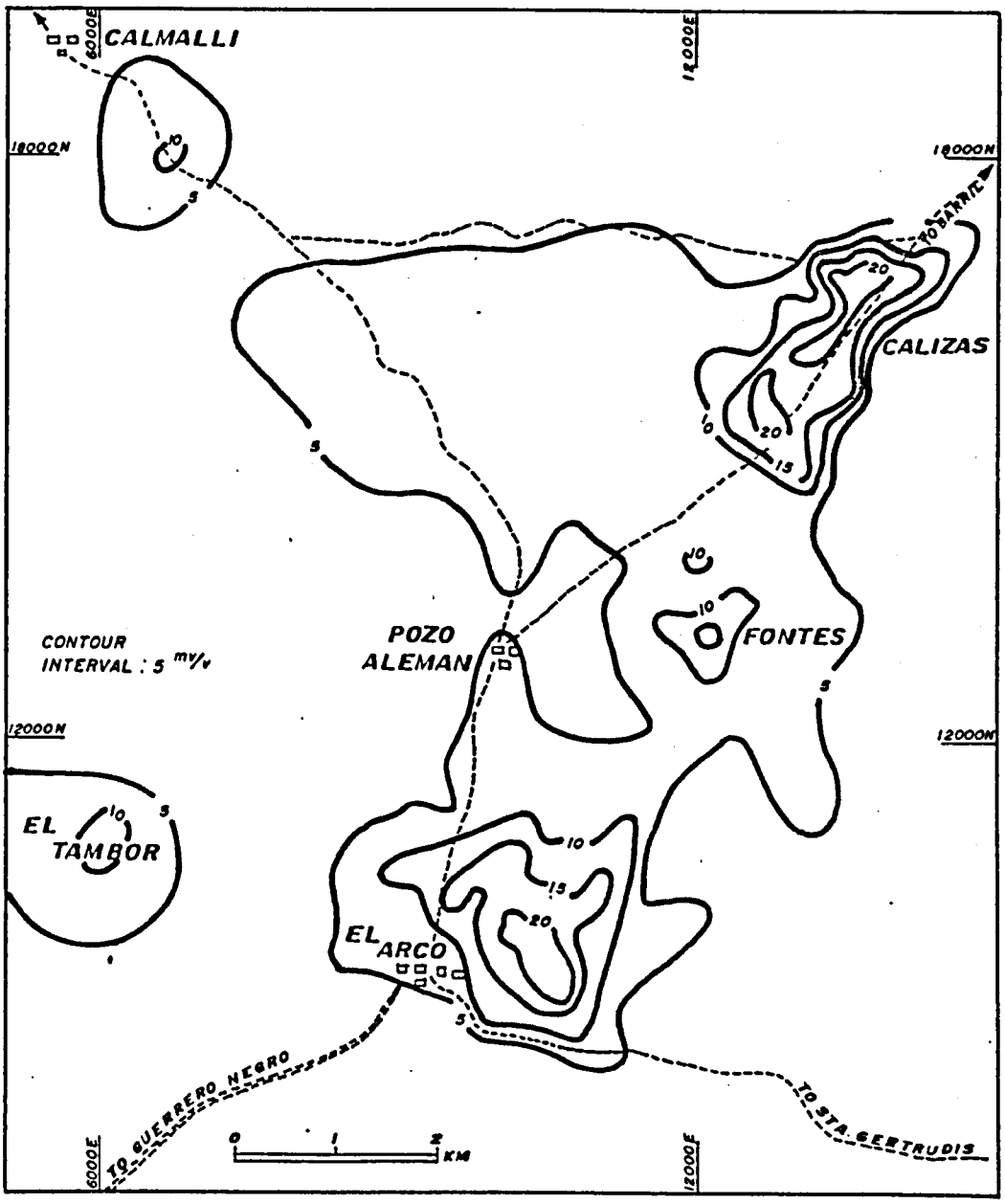


Figure 17. Regional induced-polarization contour map of the El Arco-Calmalli district

The magnetite, which is also found disseminated in the schist, probably produces the IP anomaly.

However, a geochemical survey over the area of the IP anomaly in the Fontes area showed 1,000 ppm Cu, although a hole drilled in the anomalous area showed no significant values of copper. The high geochemical values found are probably produced by small veinlets of copper mineralization between the foliation planes of the schist. These may also in part account for the IP anomaly.

Calizas Anomaly

An IP anomaly is located in the area marked Calizas on Figure 17, where calcareous sedimentary rocks with a high content of carbonaceous material and disseminated pyrite crop out in an area 800 m long and 150 m wide. This area is 7 km N. 35° E. of the village of El Arco. The IP background produced by the carbonaceous material is 17 ms, with a resistivity ranging from 2 to 50 0-m. The length of the anomaly is 2.5 km and its width 1 km; therefore, most of the anomaly is produced by a source other than the carbonaceous material. The IP high is 45 ms, which is found outside the calcareous rock in a schist of probable sedimentary origin. There is also a barren intrusive rock, petrographically identified as a quartz diorite porphyry, that is probably mineralized at depth. This intrusive rock may be the source of the very fine dissemination of pyrite in the limestone. A 100-m hole drilled at the periphery of the anomaly found a content of 15 percent pyrite and pyrrhotite. The mineralized rock was not identified because only powder was recovered from the hole.

The geology, the high sulfide content found in the drilled hole, and the large dimensions of the anomaly make the Calizas area favorable to explore for volcanogenic ore deposits.

Electromagnetics

Because the Calizas area was found geologically interesting for exploration for volcanogenic massive ore deposits, an electromagnetic survey with the Turam method was made. A Scintrex SE-71 Turam electromagnetic system was used. The survey was run using 800 Hz; the line spacing was 120 m, with stations at 30-m intervals. Reduction by the field strength ratio was obtained by dividing the observed ratios by the normal ratios previously calculated. The phase differences were measured between successive stations. Results of the survey are shown on Figure 18. Large anomalies were detected on all lines of the survey. The geology of the area indicates that such anomalies are located in the carbonaceous limestone. Interpretation of the anomalies are obscured by the response of carbonaceous material which accounts for the large electromagnetic values found. Possibilities of finding massive mineralization below the calcareous sedimentary rocks still exist because of the geologic evidences on the surface, such as pyrite dissemination and the alteration of the rocks. A drilling program will be carried out in order to explore the geophysical anomalies.

A Turam electromagnetic survey was also done in the Calmalli area. The volcanogenic massive pyrite mineralization was clearly detected (Fig. 19). All lines of the survey show anomalous values. The anomalous electromagnetic response is caused by a tabular body of

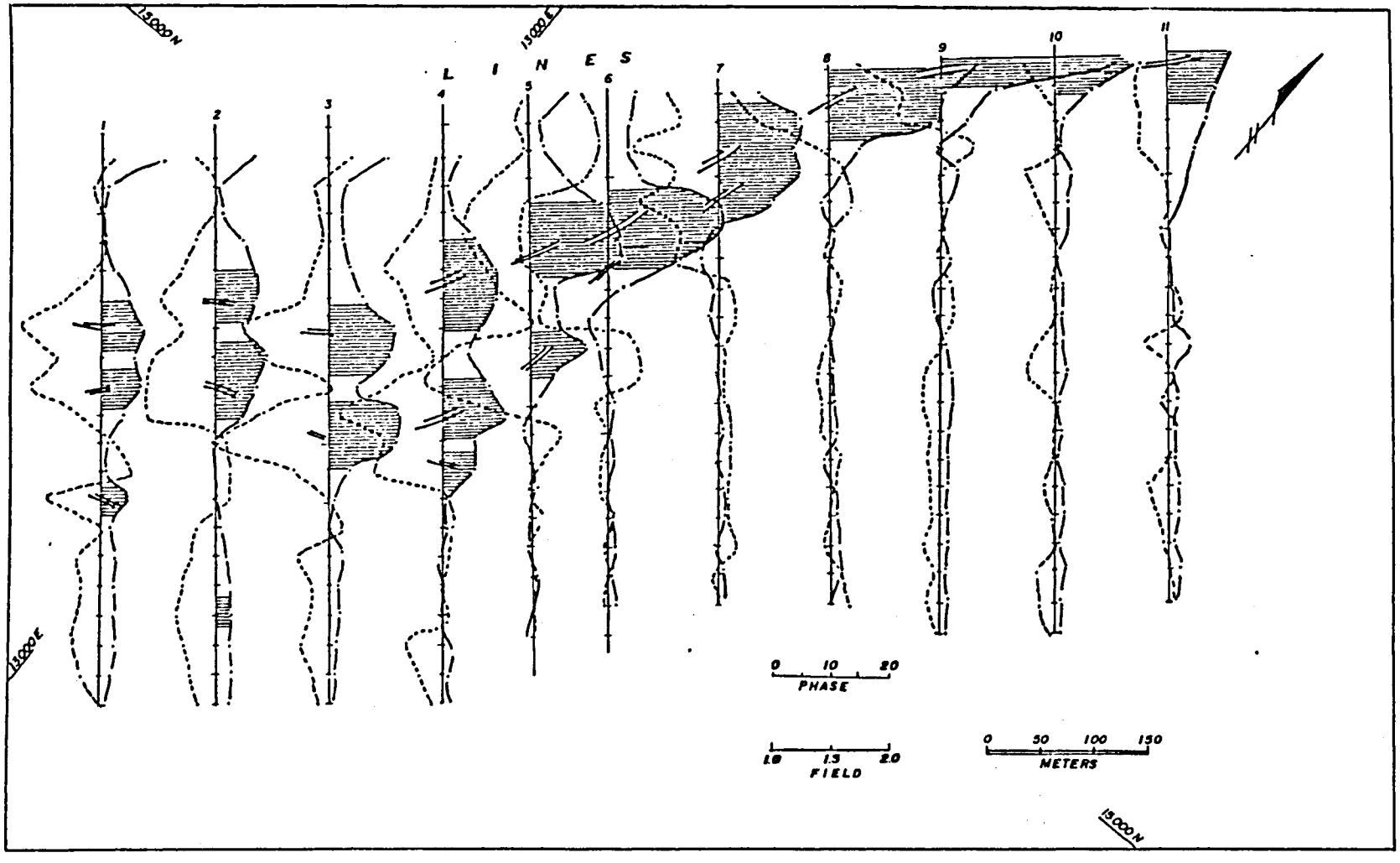


Figure 18. Turam electromagnetic survey of the Calizas area

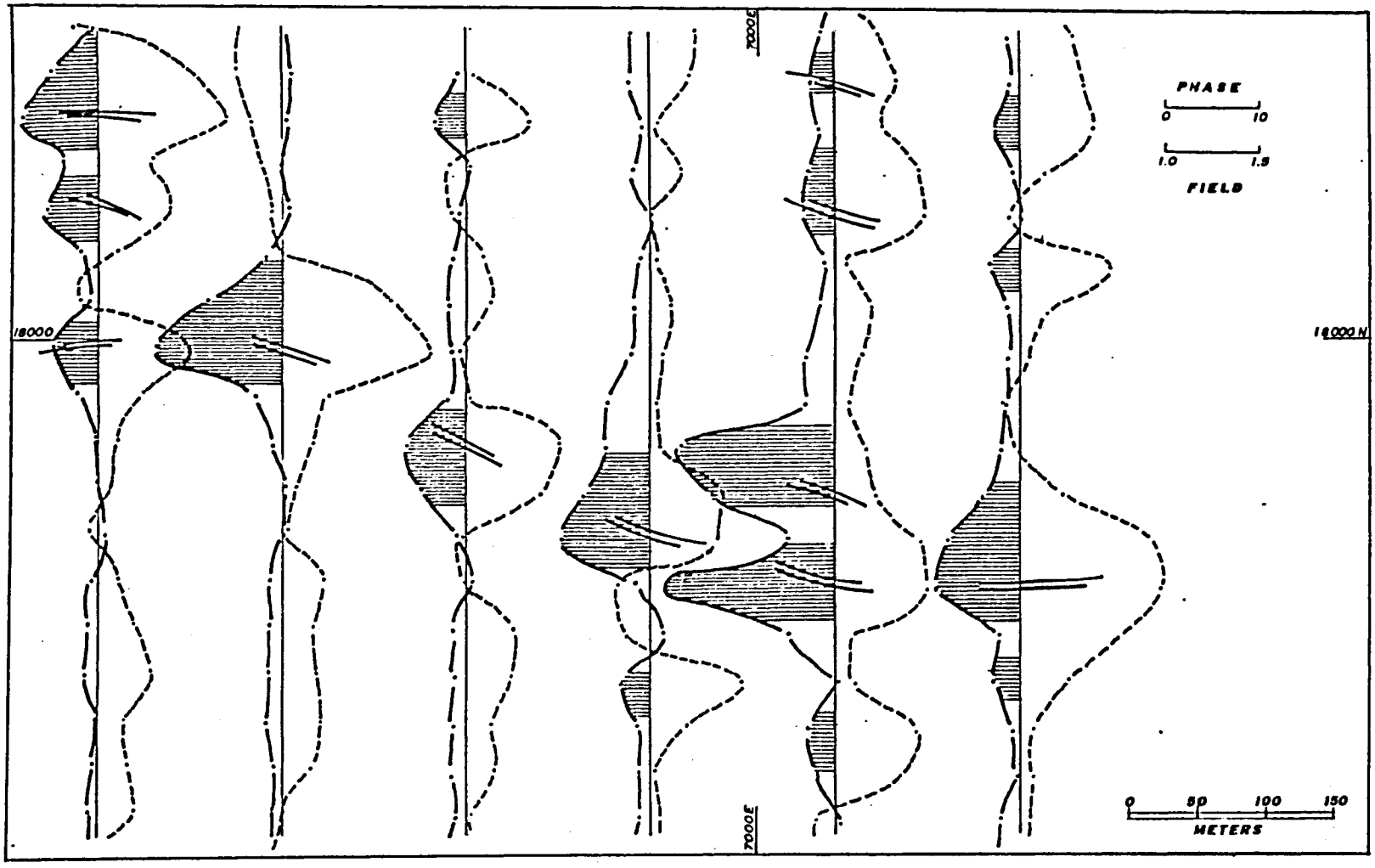


Figure 19. Turam electromagnetic survey of the Calmalli volcanogenic massive sulfide body

pyrite 3 m wide that dips 65° NW. The enclosing rock of the body is volcanic and shows the greenschist facies of alteration. Pillow lavas and sedimentary rocks also crop out near the orebody (Fig. 2).

GEOPHYSICS AT THE EL ARCO PORPHYRY COPPER DEPOSIT

Geophysical surveys at the El Arco copper deposit were run for a period of three years before drilling. Integration of different geophysical techniques was very helpful to locate areas for the first drill holes in the mineralized area.

Induced Polarization

The most effective method used for the delineation of the mineralized zone was induced polarization. Measurements were made using a three-electrode array at spacings of 100 m. Traverses were run in a north-south direction with an electrode separation of 100 m. Figure 20 shows the IP anomaly at the El Arco porphyry copper deposit. The dashed lines show the limit of the economic mineralization, which is smaller than the IP anomaly.

High-intensity values of 22.5 ms are found outside the economic zone. These high values correspond with a halo of pyrite surrounding the economic mineralization as well as a portion of the deposit where the mineralized rocks are exposed. As was mentioned earlier, at least 75 percent of the orebody is covered by a conglomerate which produces its own IP response. The 15-ms curve roughly outlines the limit of economic mineralization in the covered portion of the orebody. It is interesting to note that the total sulfide content obtained from the drilling data shown on Figure 7 coincides with the IP anomaly. Figure 21 shows

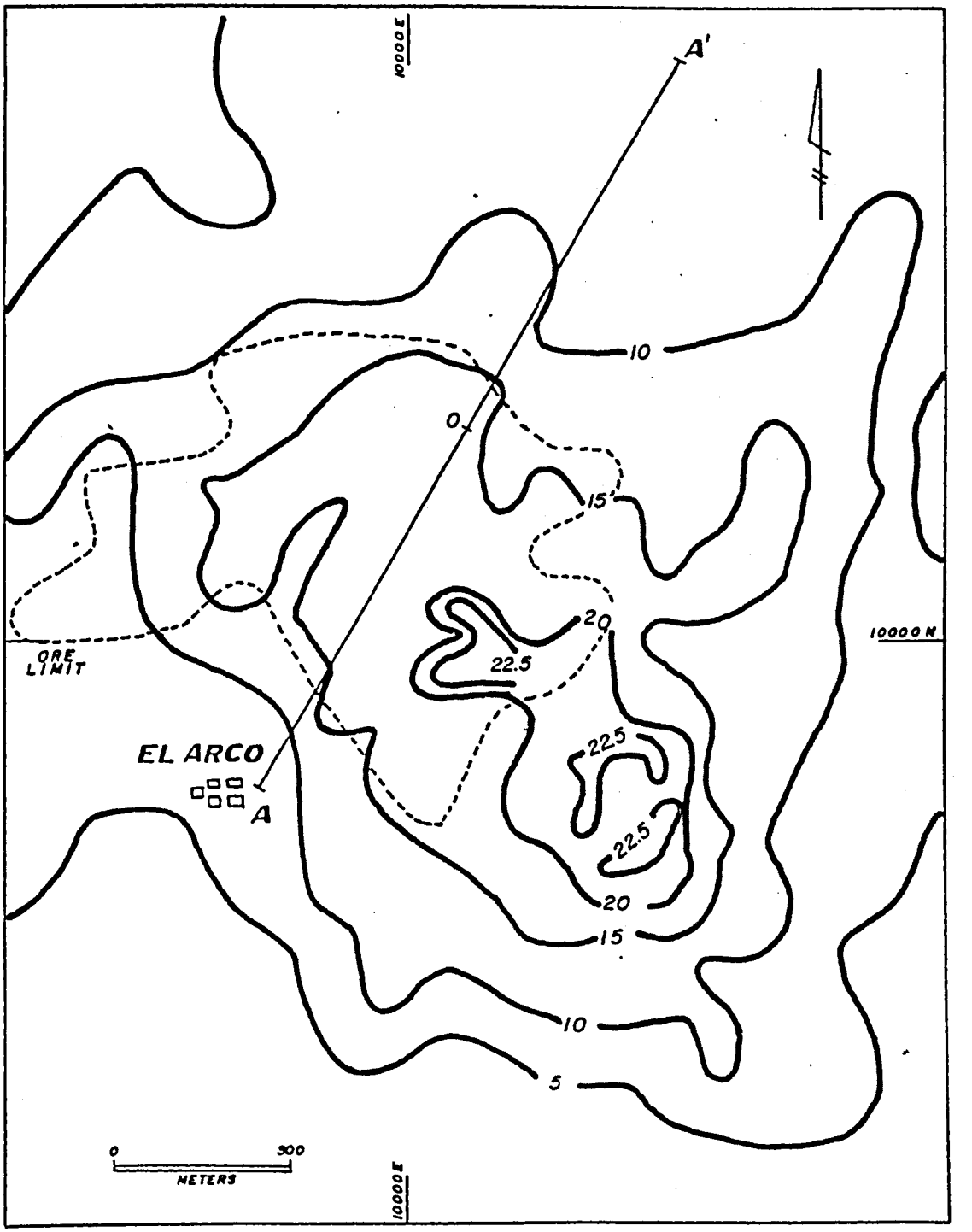


Figure 20. Induced-polarization anomaly at the El Arco porphyry copper deposit

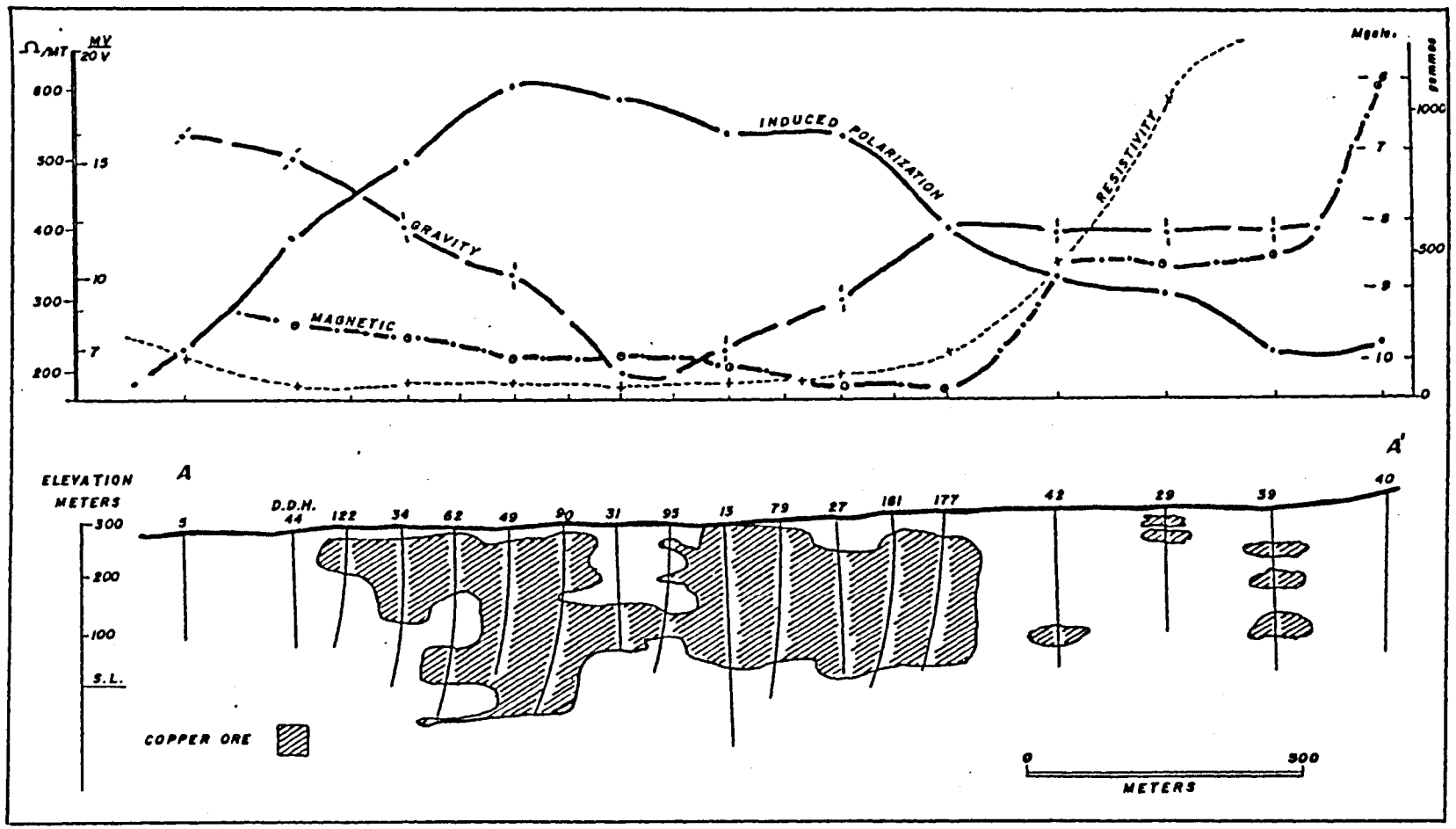


Figure 21. Induced-polarization, resistivity, magnetic, and gravity profiles through section A-A' at the El Arco orebody

different profiles through the orebody. As can be seen, the IP method is the best geophysical method to define the mineralized area. The IP anomaly has a 20 mV s/V value at the center of the deposit.

Resistivity

A resistivity survey of the El Arco area was run simultaneously with the IP survey. Figure 22 shows the resistivity contours every 100 ohm-meters. Lows of 100 ohm-meters correspond with IP high, which also coincide with the known mineralized area. The resistivity survey was required to select locations for the first holes drilled at El Arco. It can be said that resistivity in conjunction with IP proved to be quite successful for detecting disseminated mineralization.

Ground Magnetics

A ground magnetic survey was carried out over the IP anomaly at El Arco to look for magnetic minerals. Results are shown on Figure 23, where magnetic lows are found over the orebody. Localized magnetic highs up to 1,000 gammas are found surrounding the economic mineralization. These highs are explained by the high magnetite content in the andesitic rocks that surround the mineralized intrusive granodiorite. Although magnetite is found in the granodiorite most of it has probably been destroyed by hydrothermal alteration. In addition, the thick cover at the western part of the porphyry deposit also accounts for the magnetic lows found over it. A section with a magnetic profile through the mineralized body is shown on Figure 21.

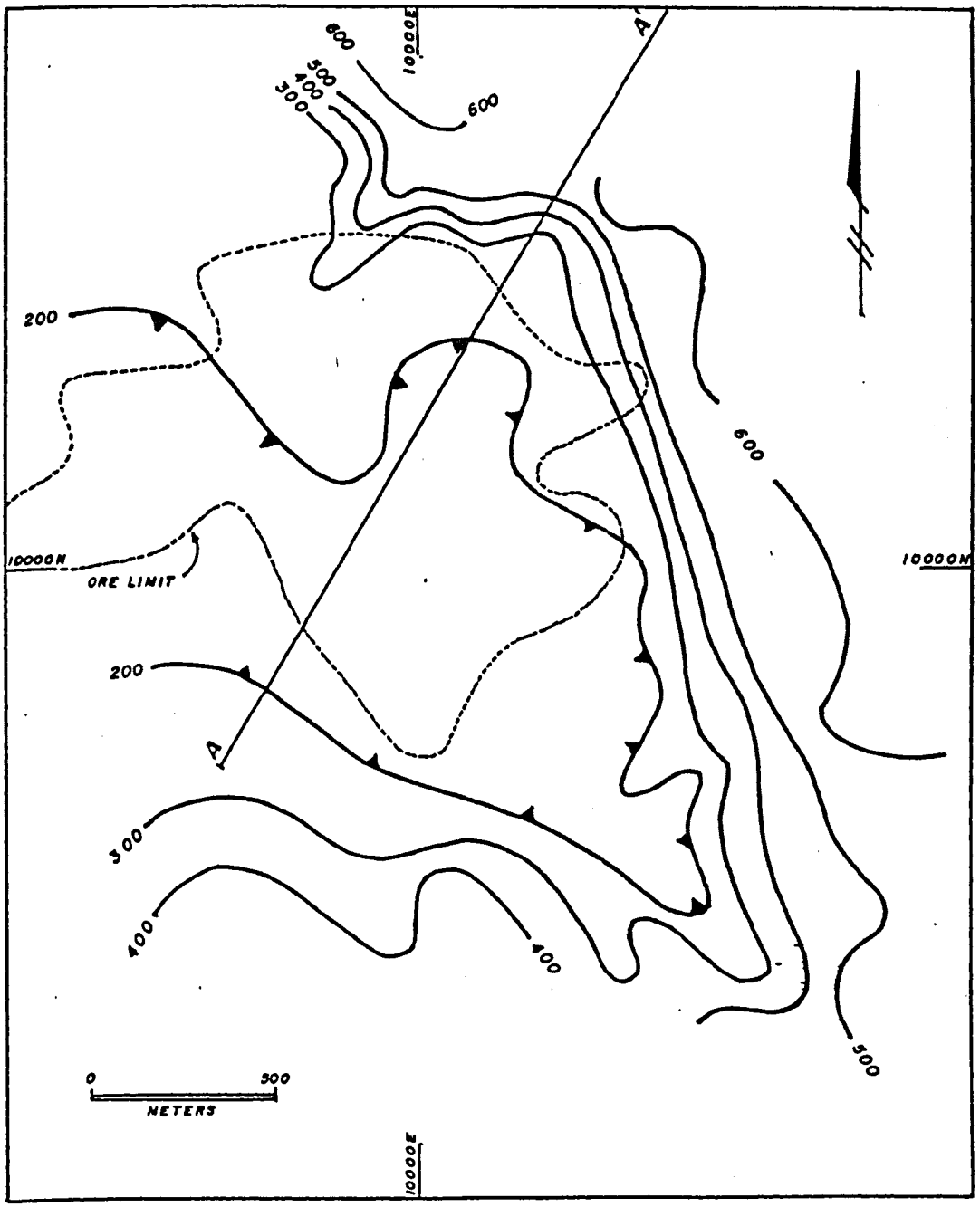


Figure 22. Apparent resistivity contours at the El Arco porphyry copper deposit

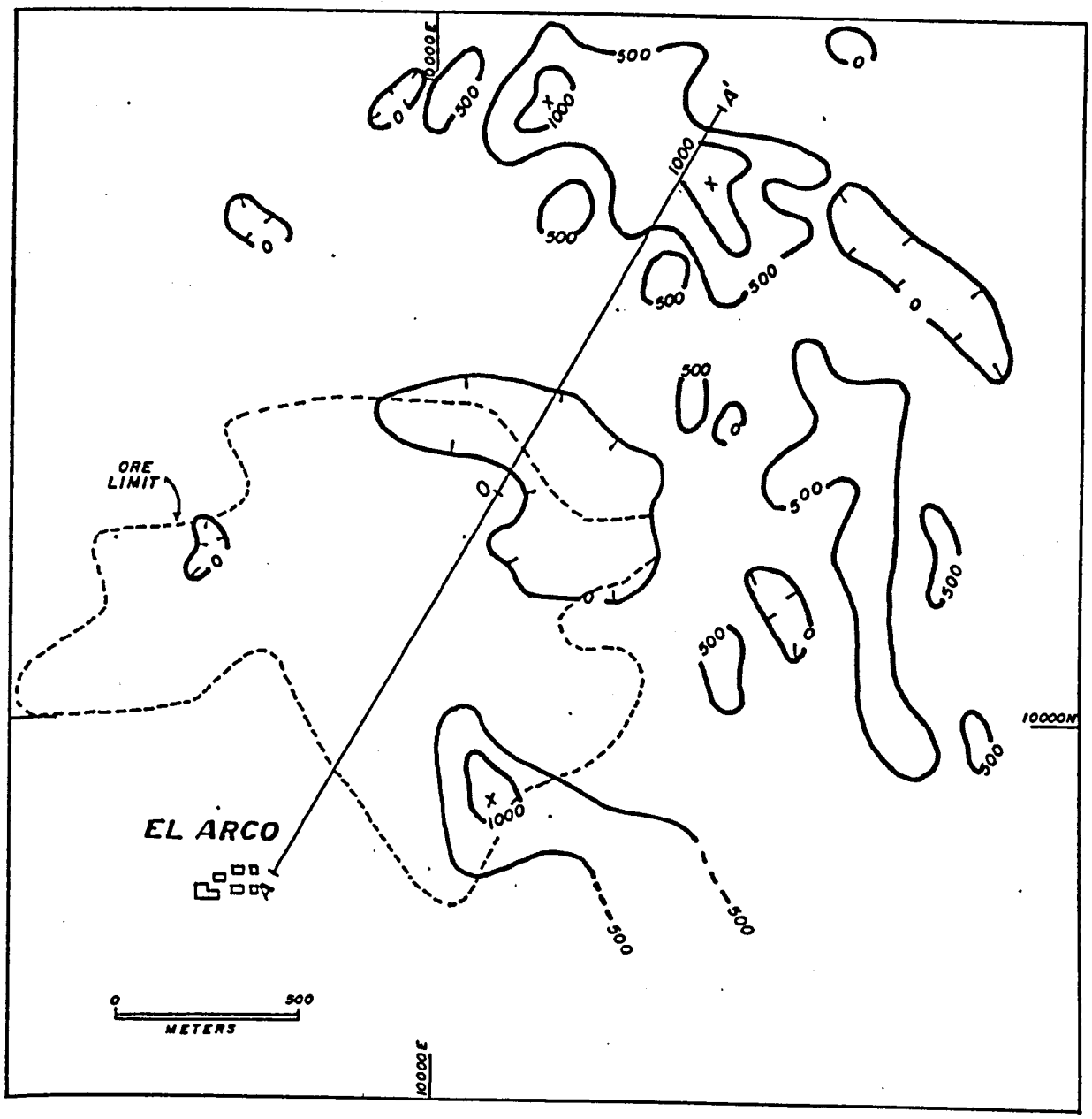


Figure 23. Ground magnetic contour map at the El Arco porphyry copper deposit

Gravity

A gravity profile along section A-A' (Fig. 20) is shown on Figure 21 together with the other geophysical profiles. The anomalous gravity low found at the center of the El Arco porphyry copper deposit is explained by the low density contrast between the granodiorite porphyry and the host rocks. It can be seen from Table 2 that the mineralization does not appreciably increase the density of the granodiorite, which is found to be 2.69 g/cm^3. The average density of the andesitic rocks is 2.72.

CONCLUSIONS

Geologic conditions in the El Arco-Calmalli mining district are best explained as a result of plate tectonic activity. The intrusion of middle Cretaceous granitic rocks is responsible for the mineralized areas. The tectonic environment of the district is not fully understood, but major structures and tectonic blocks are known.

The geophysical techniques applied to the El Arco-Calmalli district were useful in delineating the geophysical context of the region. The geophysical setting of the district is fairly well defined by the gravity map of Gastil et al. (1975), and aeromagnetic and ground magnetic anomalies differentiate the volcanic, intrusive, and ultramafic rocks that crop out within the surveyed area.

Regional resistivity and gravity methods were useful in determining the thicknesses of sedimentary formations and depth to buried topography in the El Arco area. These factors were very important in choosing areas for hydrologic studies.

Geophysical techniques helped to locate interesting areas to explore for economic mineral deposits. Mineralized structures in the district are clearly defined by induced-polarization and electromagnetic anomalies. Favorable structural controls of mineralization were also detected by interpreting regional geophysics. An interesting correlation between the mineralization at Calmalli, El Tambor, and Calizas and the IP anomalies and magnetic lows can be shown by superimposing the

regional IP contour map (Fig. 17) on the aeromagnetic contour map (Fig. 16).

The geophysical work carried out over the area recommended by geology at the El Arco porphyry copper deposit was useful in delineating the mineralization and locating the first holes drilled. It can be said that the discovery of the El Arco deposit is the result of a comprehensive program of geologic mapping and geophysical surveys.

Based on the above conclusions, an exploration drilling program has been recommended to evaluate the geophysical anomalies found northeast of the El Arco porphyry copper deposit. Surveys using the new geophysical techniques such as complex resistivity (Zonge and Wynn, 1974) are planned for the near future to interpret subsurface alteration and to obtain sulfide discrimination in areas of interest.

Additional exploration has been recommended outside the El Arco-Calmalli district in areas with similar geologic conditions. Among these are the Bonett area located 60 km northwest of El Arco and several areas close to the City of El Rosarito.

REFERENCES

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geol. Soc. America Bull., v. 81, p. 3513-3536.

Barthelmy, D. A., 1974, Geologic and K-Ar age relationships of copper mineralization and Mesozoic plutonic rocks in the El Arco area, Baja California (abs.): Geol. Soc. America Abstracts with Programs, v. 6, no. 3, p. 142.

Beal, C. H., 1948, Reconnaissance of the geology and oil possibilities of Baja California, Mexico: Geol. Soc. America Mem. 31.

Campa, M. F., and Oviedo, A., 1976, La cabalgadura laramidica del dominio volcánico sedimentario (Arco de Alisitos-Teloloapan) sobre el miogeosindinal mexicano en los límites de los Estados de Guerrero y México (abs.): III Congreso Latinoamericano de Geologia UNAM.

Damon, P. E., and Montesinos, E., 1975, Late Cenozoic volcanism and metallogenesis over an active Benioff zone in Chiapas, Mexico: Department of Geosciences, University of Arizona.

Echavarri, A., 1975, Estudio petrográfico de alteración y mineralización hidrotermal en el depósito de El Arco, B.C.: unpublished report Hermosillo, Mexico, Industrial Minera Mexico, S.A.

Ernest, W. G., 1965, Mineral paragenesis in Franciscan metamorphic rocks, Panoche Pass, California: Geol. Soc. America Bull., v. 76, p. 879-914.

Gastil, G. R., Phillips, P. R., and Allison, C. E., 1975, Reconnaissance geology of the State of Baja California: Geol. Soc. America Mem. 140, 170 p.

Hamilton, W., 1969, Mesozoic California and the underflow of Pacific mantle: Geol. Soc. America Bull., v. 80, p. 2409-2430.

Henry, C. D., 1975, Geology and geochronology of the granitic batholith complex, Sinaloa, Mexico: unpublished Ph.D. dissertation, University of Texas, Austin, Texas.

Hubbert, M. K., 1948, A line-integral method of computing the gravitational effects of two-dimensional masses: Geophysics, v. 13, p. 215-225.

Ifex International, 1971, Total intensity aeromagnetic survey, Calmalli mineral prospect, Baja California, Mexico: unpublished map, Hermosillo, Sonora.

Instituto del Petroleo, 1974, Private report: Hermosillo, Mexico, Industrial Minera Mexico, S.A.

Isacks, B., Oliver, J., and Sykes, L. R., 1968, Seismology and the new global tectonics: Jour. Geophys. Res., v. 73, p. 5855-5900.

Krause, D. C., 1965, Tectonics, bathymetry, and geomagnetism of the southern continental borderland west of Baja California, Mexico: Geol. Soc. America Bull., v. 76, p. 617-650.

Larson, R. L., and Chase, C. G., 1972, Late Mesozoic evolution of the western Pacific Ocean: Geol. Soc. America Bull., v. 83, p. 3627-3644.

Larson, R. L., and Pitman, W. C., 1972, World-wide correlation of Mesozoic magnetic anomalies, and its implications: Geol. Soc. America Bull., v. 83, p. 3645-3662.

Lowell, J. D., and Guilbert, J. M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry ore deposits: Econ. Geology, v. 65, p. 373-408.

Minch, J. A., 1975, Transpeninsular faulting and the continental borderland (abs.): Geol. Soc. America, v. 7, p. 350.

Normark, W. R., 1971, Transfer of lower Baja California, Mexico, from North American to Pacific lithospheric plates (abs.): Geol. Soc. America, Cordillerean Section, Riverside, California.

Osoria, A., 1971, Geología del Distrito Cuproaurifero de Calmallí Municipio de Ensenada Baja California: Asoc. Ing. Minas, Met. Geol. de Mexico, Memoria IX Convencion, p. 449-455.

Santillan, M., and Barrera, T., 1930, Las posibilidades petrolíferas de la costa Occidental de Baja California, entre los paralelos 30 y 32 de latitud norte: Mexico Inst. Geologia Anales, v. 5, p. 1-37.

Shafiqullah, M., 1974, Letter report: Hermosillo, Mexico, Asarco Mexicana, S.A.

Sillitoe, R. H., 1972, A plate tectonic model for the origin of porphyry copper deposits: Econ. Geology, v. 67, p. 184-197.

Silver, L. T., Allen, C. R., and Stehli, F. G., 1969, Geological and geochronological observations on a portion of the Peninsular range batholith of northwestern Baja California, Mexico (abs.): Geol. Soc. America Spec. Paper 121, p. 279.

Smith, D. L., 1972, The vertical distribution of heat flow in northwestern Mexico: unpublished Ph.D. thesis, University of Minnesota.

Sumner, J. S., 1972, Geophysical exploration for porphyry copper deposits: Mining Met. Inst. Japan Jour., v. 88, no. 1016, p. 730.

Zonge, K. L., and Wynn, J. C., 1974, Recent advances and applications in complex resistivity measurements: Geophysics, v. 40, p. 851-864.