EVALUATION OF INTEGRATED EXPLORATION PROGRAMS FOR REVITALIZATION OF OLD MINING DISTRICTS

by

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A Dissertation Submitted to the Faculty of the

DEPARTMENT OF GEOSCIENCES

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

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THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

I hereby recommend that this dissertation prepared under my direction

by Mauricio Fernando Francisco de la Fuente Duch

entitled Evaluation of Integrated Exploration Programs for Revitalization of Old Mining Districts

be accepted as fulfilling the dissertation requirement for the Degree

of Doctor of Philosophy.

John S. Sumner
Dissertation Director

Oct 24, 1979
Date

As members of the Final Examination Committee, we certify that we have read this dissertation and agree that it may be presented for final defense.

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Date

Charles E. Glass — 24 oct 1979
Date

Date

Final approval and acceptance of this dissertation is contingent on the candidate's adequate performance and defense thereof at the final oral examination.

11/78

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ACKNOWLEDGMENTS

Special acknowledgment is given to Ing. Guillermo P. Salas, General Director of the Consejo de Recursos Minerales. Without his support and help this study would not have been finished. For his help and encouragement demonstrated in many ways the memory of the late Ing. Juan José Martínez Bermúdez is honored.

I am most grateful to Dr. John S. Sumner, my advisor and dissertation director, for his sound advice, encouragement, and patience in deciphering the original manuscript. His assistance and guidance provided the necessary stimulation for the development of this work. Dr. Sumner also arranged the support for the computer analysis of the aeromagnetic survey carried out at the University of Arizona Computer Center. I especially appreciate the help and useful comments and suggestions given by my dissertation committee, Drs. Kenneth L. Zonge, William C. Peters, Charles E. Glass, and Randall M. Richardson.

The encouragement given by Drs. Dean Kleinkopf, Gary Raines, and Bruce Smith of the U.S. Geological Survey in the initial stages of this work and the opportunity to use the computer facilities of the U.S. Geological Survey in Denver, Colorado, for the linear feature analysis are especially appreciated.

The Consejo Nacional de Ciencia y Tecnología partially supported the development of this study, primarily during the course-work years.

Several of my fellow co-workers in the Gerecia de Exploración Geofísica, especially Ing. Guillermo Monroy Ochoa, helped me during different stages of this study. They went beyond their duties to cover my absences and they did a very good job. A special mention is given to Ing. José Francisco Hernández Martínez, who was the crew chief in the latest stages of the Concepción del Oro survey, for the many hours of discussions and his useful comments.

I am very grateful to the Misses Gabriela Parlange and Edíth Zubirán and Mrs. Helen Hauck for the typing of this dissertation and to my friends Gary and Cinda Young, who took care of my emotional health during the many weeks alone in Tucson.

The patience of my daughters Laura and Laiza, who faced the problems of a visiting father for almost a year, gave me the encouragement to finish this work and go back to being a normal father.

The encouragement, patience, and understanding that can be translated into the love of my wife Marcia cannot be compensated. My eternal love to her.

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ABSTRACT

Many economic and social problems are involved in closing an old mining district. It is proposed that one effective approach may be an integrated exploration program designed to revitalize mining in the district. The Concepción del Oro district, located in the northern portion of the State of Zacatecas, Mexico, is now facing exhaustion of its known ore reserves after over 400 years of almost uninterrupted mining. This district is used as a model for evaluating the effectiveness of integrated exploration programs.

The Concepción del Oro district covers an area of approximately 9,000 square kilometers. Geomorphically, the area is located between the Sierra Madre Oriental and Mesa Central provinces and shows the deformation of the Mexican geosyncline produced by Laramide orogeny.

The geology of the area was analyzed to obtain the basis for a regional exploration program. The most important conclusions from this analysis were that (1) almost all of the intrusive bodies found in the area contain associated mineralization, (2) the mineralization and the intrusive bodies are of relatively the same age, and (3) the contacts between the stocks and the sedimentary rocks were the most important control of the mineralization.

The regional exploration of the area also included a statistical analysis of more than 20,000 kilometers of linear features obtained from Landsat imagery. This analysis did not provide indications of the known mineral deposits or the location of the intrusive bodies, probably due to

the overwhelming number of linear features associated with the anticlinal structures of the area.

A regional geochemical survey of the area included analysis of more than 1,300 stream sediment samples for copper, lead, and zinc. All geochemical anomalies were found downstream from sills, dikes, and stocks, which confirmed the relationship between the intrusive bodies and the mineralization found in the geologic study. Results of the geochemical survey were affected by contamination from mines and prospect pits.

The regional exploration was completed with an aeromagnetic survey. Data from the total intensity aeromagnetic map obtained with this survey were digitized, and the International Reference Field removed to obtain a residual magnetic map of the area. Different filtering techniques were applied to the data. Continuation, both upward and downward, second-derivative, and pseudo-gravity gradient maps were obtained from the residual magnetic map. These analyses of the magnetic data failed to locate concealed intrusive bodies in the study area but did provide useful information about the characteristics of the known intrusive bodies. Based on these characteristics, the selection of target areas for detail exploration was made.

A detail exploration of all of the target areas has not been completed. The results obtained for the target areas located around the Concepción del Oro stock illustrate the types of surveys used. Detail exploration of the target areas included gravity, ground magnetics, induced-polarization (IP), and resistivity surveys as well as detail geologic and geochemical surveys. The usefulness of the gravity survey was affected by the large terrain corrections required due to the sharp relief, which made interpretation difficult. The ground magnetic surveys were useful in delineating intrusive bodies concealed by alluvial cover and in the study of the Sol y Luna iron body. More satisfying results were obtained from the IP and resistivity surveys.

Examination of this Concepción del Oro model for the use of an integrated exploration program in a worked-out district demonstrates the synergism inherent in this approach. Such programs should be effective in other regions throughout the world that have a similar need to revitalize their minerals industry.

INTRODUCTION

Many old mining districts in Mexico have been considered worked out because their known ore reserves are depleted or because their ore grades are uneconomic if mined with current mining methods. Many other districts are reaching these conditions; this is bringing great concern not only to the people in the district living off the mines but also to the government. The Mexican government has been implementing different solutions to the economic problem represented by the closing of a mining district, ranging from diversification of the local economy to a different source of income to the implementation of development programs for the mines.

If the problem of the district is related to ore grade, it is sometimes solved by using new mining procedures or better methods for processing the ore minerals. Both solutions were successfully applied by the Mexican government in the Santa Rosalía district, Baja California Sur, Mexico. If the problem is the depletion of known ore reserves, the solution could be implementation of exploration programs. Such programs range from direct underground exploration to the use of indirect techniques. What is considered a more effective approach to the revitalization of old mining districts is the implementation of an integrated exploration program that extends the boundaries of the district by using not only all available techniques but also the most appropriate methods for interpreting the results. The exploration program designed for the Concepción del Oro district, located in the State of Zacatecas, Mexico, will be used as a model to evaluate the effectiveness of integrated exploration programs for old mining districts.

The mining history of the Concepción del Oro area dates to the pre-Columbian years. The Indians living in the vicinity of the district presumably knew of the existence of minerals in the area and showed them to Francisco de Urdiñola, one of Cortés's captains, when he arrived in 1530. Around 1548 mining activities were flourishing in the Sierra de la Caja area, and the Spanish Crown established the Real de Minas of Mazapil and gave Urdiñola the title of Marquis of Aguayo as a reward.

By the end of the 18th century many of the earlier gold and silver bonanzas were depleted. This and the War of Independence (1810) reduced the mining activities. In 1889, the Mazapil Copper Company Limited was formed with British capital. This company reopened some of the old mines and opened new ones. This time the operations were oriented toward the exploitation of copper. The construction of the Saltillo-Concepción del Oro railroad and the establishment of a copper smelter in Concepción del Oro permitted an increase in mining activities. In 1910 the monthly production was 7,000 metric tons with an average grade of 5% copper. A decay in the mining accompanied the Mexican Revolution (1910), after which several companies were formed, although none of them had any important production. It was not until the second World War that the district was reopened to full capacity to supply the demand for copper. By this time almost all the oxide ore had been mined and workings continued in the sulfide zone.

A new recession occurred in the late sixties, and many mines had to close due to depletion of ore or due to increased mining costs and reduction in copper prices. The mining activities were reduced to the lead-zinc ores located in the Noche Buena and Salaverna areas. The closing of the mines brought many problems to the people of Concepción del Oro. At their request, the Mexican government decided to form Macocozac, a mixed capital company. This company, formed originally with the assets of the Mazapil Company, acquired most of the claims and mines in the vicinity of Concepción del Oro. Several mines were reopened, but the company faced the problem of very low ore reserves. In 1973, the Consejo de Recursos Naturales No Renovables (now the Consejo de Recursos Minerales) was called upon to implement a massive exploration project intended to increase the ore reserves.

Location of the Study Area

The study area is located in the northern part of the State of Zacatecas and in small portions of the States of Coahuila and San Luis Potosí. The area of approximately 9,000 square kilometers (Fig. 1) is bounded by lat 24°20' N. and 24°55' N. and long 100°45' W., and 102°15' W. The area is well connected by transportation routes with the rest of the country by the Guadalajara-Monterrey highway, which connects Concepción del Oro with Saltillo to the north and Zacatecas to the south. No other paved roads are found in the area, but many dirt roads connect the principal communities. During the rainy season some of these roads may be closed. The railroad from Concepción del Oro to Saltillo and several local air strips complement the access.

The climate, in the Koppen classification, is basically semidesert with cool winers. The average temperature is 18°C, ranging in summer from 35°C during the day to perhaps 0°C at night and in the winter from

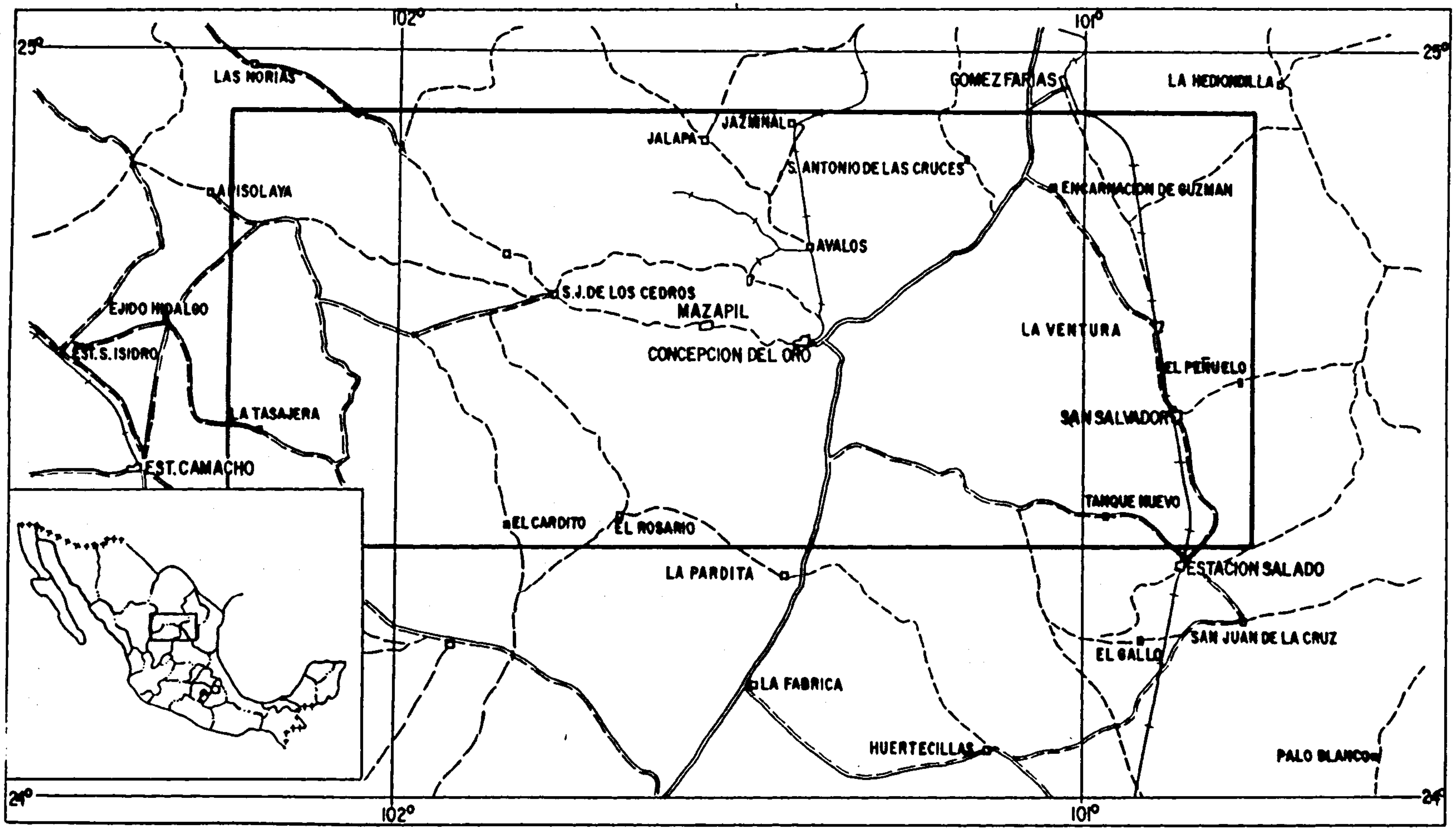

Fig. 1. Location of the study area

15°C in the day to below 0°C at night. The rainy season occurs during the summer with an average precipitation of 400 mm per year. The vegetation is scarce and typical of a semiarid region.

The economy of the area is based on mining or mining-related activities in the vicinity of Concepción del Oro and the other operating mines in the district. The small communities located far from the mines base their income on small-scale farming and on the collection of wild plants such as guayule, lechuguilla, and candelilla, which are used in the production of rubber, rope, and wax, respectively.

Geomorphology

The study area is located in two very distinct geomorphologic provinces: The Sierra Madre Oriental and the Mesa Central. To obtain a wider view of the geomorphology of the area, it is useful to make a brief review of the other provinces located in the region. The influence of the early paleogeographic elements during the Laramide orogenesis is considered to be determinant in the geomorphology. A brief description of the geomorphic provinces, which are located on Figure 2, follows. Figure 2 also shows the relationship between the geomorphic provinces and the early Late Jurassic paleogeography.

The Sierra Madre Oriental is characterized by rugged, high-relief anticlinal mountain ridges and deep synclinal valleys forming the eastern and northern borders of the Mesa Central. The relief above the plains and low hills to the north and east is of the order of 800 to 1,300 meters, and the width across the strike of the orographic units is normally less than 50 kilometers. The ranges trend northwest-southwest from west of Ciudad Victoria to south of Monterrey, and there the belt curves westward

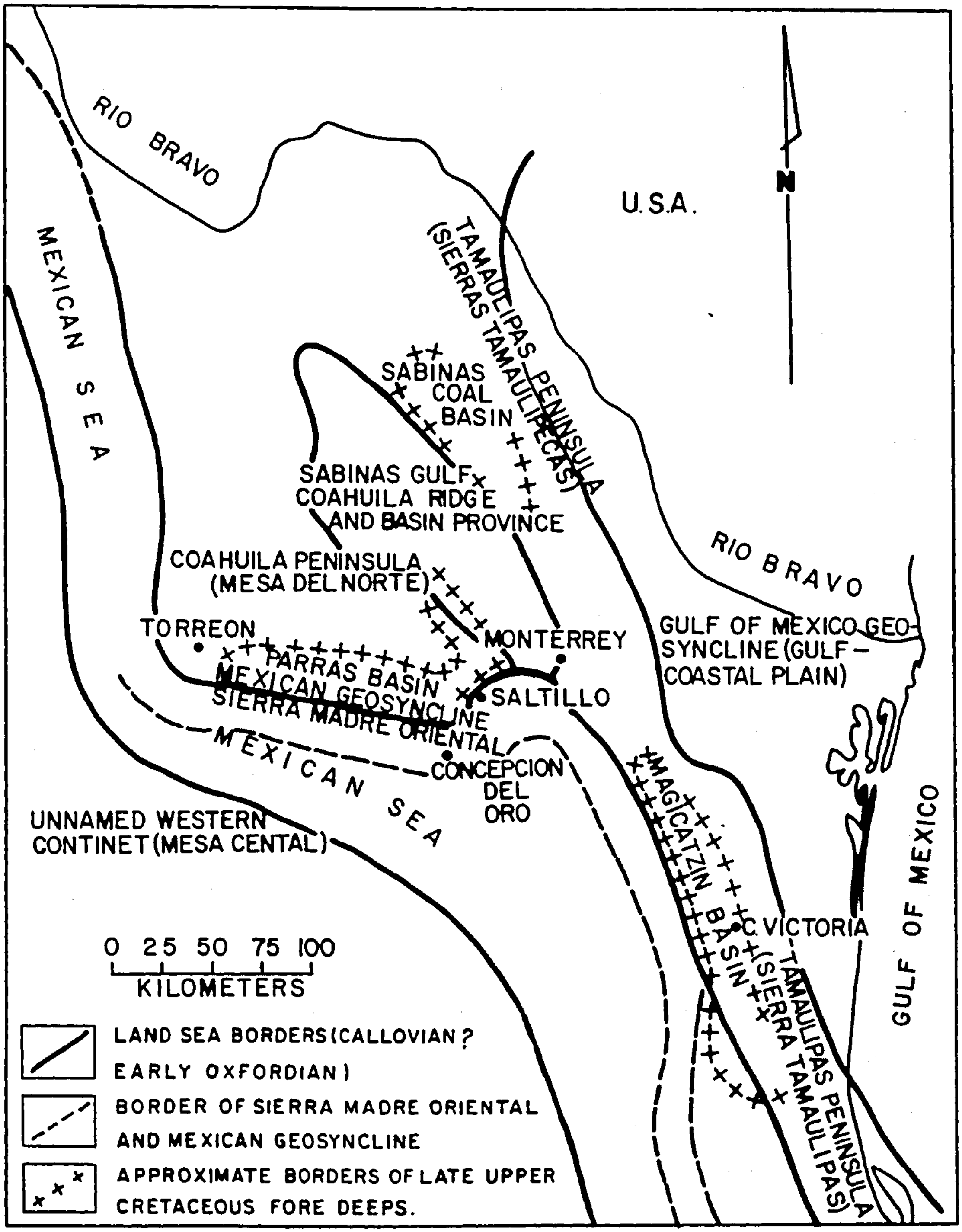

Fig. 2. Location of the geomorphological provinces and early Late Jurassic paleogeography. -- Modified from Mapes V., Zamora M., and Godoy (1964)

to the vicinity of Saltillo where the ranges trend almost due southwest to swing westward again near Buñuelos. The trend continues in this direction until west of Torreón where it is to the northwest, similar to that of the southernmost part of the Sierra Madre Oriental. This province coincides with the areas of greatest sedimentary thicknesses in the Mexican geosyncline.

The Mesa Central is a large area of central Mexico located to the west and south of the Sierra Madre Oriental. The surface expression of the inherent structure is reflected by igneous and anticlinal mountain masses. These mountains are separated by extensive plains and basins. The relief of the Mesa Central is generally in excess of 1,500 meters with the land surface rising gently toward the south. The landforms in this province are complicated by the effects of intrusive and extrusive igneous activity. This province and its northwestward continuation into the States of Chihuahua, Durango, and Sonora occupy the site of an unnamed Mesozoic positive tectonic element.

The Sierras Tamaulipecas province is formed by relatively low relief mountain ranges bounded to the east by the Gulf Coastal Plain. They occupy the site of the early Oxfordian Tamaulipas Peninsula.

The Gulf Coastal Plain is a direct continuation of the Gulf Coastal Plain of southern United States. Its limit to the west is formed by the Sierras Tamaulipecas. Its low topographic relief is formed by relatively undeformed Upper Cretaceous and Tertiary sedimentary rocks, which strike north and northwest and dip east to northeast but always toward the Gulf of Mexico. Recent Quaternary sands and gravels are found in the form of low mesas and terraces on top of the older sedimentary rocks.

The Mesa del Norte is applied here to the province located west of the northern extension of the Sierra Madre Oriental, east of the Coahuila Ridge and Basin province, and north of the Parras Basin. It corresponds rather closely with the Mesozoic Coahuila Peninsula. The ridges have relatively low relief and show no relation to the underlying structure and stratigraphy.

The Coahuila Ridge and Basin province is located between the Mesa del Norte and the Sierras Tamaulipecas provinces, north of the Sierra Madre. It is formed by elongate mountain ridges and wide, flat valleys that reflect the character of the strata and their structural deformation. This province corresponds closely with the Mesozoic Sabinas Gulf. The major difference between the mountain ridges of this province and the ridges of the Sierra Madre is that the ridges in the Sierra Madre are elongate and can be traced for several kilometers, whereas the ridges in the Coahuila Ridge and Basin province are short, wide, and intermittent. The relative relief of the mountain ridges is greater than that of the Mesa del Norte.

The Parras Basin was developed in late Late Cretaceous time at the border of earlier Mesozoic land masses, the Coahuila Peninsula. It is located between the westward-trending section of the Sierra Madre and the Mesa del Norte. The Magicatzin and Sabinas coal basins were formed similarly to the Parras Basin.

Tectonics

In general, the study area shows the deformation of the Mexican geosyncline and adjacent areas produced as a result of Laramide orogeny. The position and orientation of the geosyncline belt in this part of Mexico and its departure from the northwestward trend could be explained by the presence of the Coahuila and Tamaulipas Peninsulas. These peninsulas were extensions of the North American Mesozoic continent. They were covered by shallow seas in late Early and Late Cretaceous time but continued to form stable masses that served as buttressing elements during the orogeny.

The forces of the Laramide orogeny acted in a direction more or less perpendicular to the Coahuila and Tamaulipas Peninsulas, that is, from west to east in the eastern part of the area and from north to south in the northern part. These forces compressed the sedimentary rocks into a series of narrow elongate folds lying parallel to the old land masses and were overturned toward the north and east. This deformation also produced many fan structures and some overturning toward the south and west.

De Cserna (1956) gave a very detailed description of the tectonics of the area. For him, the deformation of the sedimentary rocks was produced by the continuous rising of the basement of the Mesa Central province and the gravity sliding of the Mesozoic sedimentary cover. The sliding of the sedimentary rocks was favored by the gypsum located at the base of the Jurassic sediments. In the Sierra Madre Oriental the sedimentary cover has an average thickness of 3,000 to 4,000 meters, with maximum thickness values greater than 6,000 meters in the central sections of the geosyncline. Humphrey (1956), quoting an earlier study by C. L. Baker, reported that the folds in the Sierra Madre Oriental represent a crustal shortening of the order of 50 percent.

GEOLOGY

The regional geology of the area has been studied by many geologists. Among the best reports are those by Burckhardt (1906), Bergeat (1910), Imlay (1938), Rogers, Van Vloten, and others (1963), Mapes V., Zamora M., and Godoy (1964), and Priego de Wit (1973).

In general, the area contains outcrops of sedimentary, igneous, and metamorphic rocks ranging in age from late Paleozoic to late Quaternary. Figure 3 shows the sequence of the sedimentary rocks and their correlation with units in other localities of northern Mexico and Texas. Figure 4 (in pocket) is a simplified geologic map of the study area.

Sedimentary Rocks

Basement Rocks

Outcrops of basement rocks are located in the northwestern part of the area. The exact age of these rocks has not been determined, although several authors seem to agree on a late Paleozoic (Permian) age. Córdoba (1965) reported that the oldest rocks may be of Precambrian age due to the intense metamorphism and stratigraphic correlations. A brief description of the different units from the oldest to the most recent follows:

Caopas Schist. Caopas schist crops out north of Caopas Ranch; it is formed by quartz schists (metavolcanics) and is the oldest unit in the area. In some places the Zuloaga limestone directly overlies the

SYSTEM	SERIES	STAGE	STUDY AREA: CONCEPCION DEL ORO	STUDY AREA: SIERRA SAN JULIAN	SIERRA DE PARRAS	NORTH-EASTERN MEXICO	GEOLOGIC TIME (MY)
CRETACEOUS	UPPER	MAASTRICHTIAN					65
		CAMPANIAN					
		SANTONIAN	PARRAS SHALE	PARRAS SHALE	PARRAS SHALE	SAN FELIPE FM.	
		CONIACIAN	CARACOL FM.	CARACOL FM.	CARACOL FM.		88
		TURONIAN	INDIDURA FM.	INDIDURA FM.	INDIDURA FM.	AGUA NUEVA FM.	
		CENOMANIAN	?	? C. DEL CURA FM.	? C. DEL CURA FM.	C. DEL CURA FM.	100
	LOWER	ALBIAN	CUESTA DEL CURA FM.	AURORA L.M.	AURORA LM.	AURORA L.M.	
		APTIAN	LA PEÑA FM.	LA PEÑA FM.	LA PEÑA FM.	LA PEÑA FM.	
		BARREMIAN	CUPIDO LM.	CUPIDO LM.	CUPIDO LM.	CUPIDO LM.	
		HAUTERIVIAN	?	?			118
		VALANGIAN	TARAISES FM.	TARAISES FM.	TARAISES FM.	TARAISES FM.	
		BERRIASIAN	? HIATUS	? HIATUS	? HIATUS	? HIATUS	141
JURASSIC	UPPER	TITHONIAN	LA CAJA FM.	LA CAJA FM.	LA CASITA FM.	LA CASITA FM.	
		PORTLANDIAN				?	
		KIMERIDGEAN				OLVIDO GVP. ?	
		OXFORDIAN	ZULOAGA LM.	ZULOAGA LM.	ZULOAGA LM.	ZULOAGA LM.	160
	MIDDLE	CALLOVIAN		HIATUS ?		?	
		BATHONIAN		NAZAS FM.		HUIZACHAL FM.	
		BAJOCIAN					
		AALENTIAN		?		?	176
	LOWER	TOARCIAN		HIATUS			
		PLIENSBACHIAN					
		SINEMURIAN					
		HETTANGIAN					195
TRIASSIC	UPPER						
	MIDDLE						
	LOWER						230
PERMIAN	UPPER			EL RODEO FM.			251
	LOWER			CAOPAS SCHIST			280

Fig. 3. Correlation of the sedimentary rocks of the area and adjacent areas of northern Mexico. -- Modified from Ortíz S. (1976)

Caopas schist, suggesting erosion of the upper basal formations before deposition of the limestone.

El Rodeo Formation. The El Rodeo formation, which crops out in the vicinity of El Rodeo Ranch, seems to be concordant with the Caopas schist. On the west side of the Sierra San Julián, the El Rodeo formation is overlain by the Zuloaga limestone. Chlorite schists and phyllites are found in this unit.

Nazas Formation. The Nazas formation is found on top of the schists and phyllites and under the Zuloaga limestone on the east side of the Sierra El Solitario de Teyra. It is formed of red beds of limonite, red sandstone, and conglomerate.The conglomerate comprises pieces of quartzite, red shale, and red sandstone, ranging from small particles to boulders more than 30 cm in diameter. This unit has been correlated with the Huizachal formation of Triassic-Jurassic age.

Jurassic System

Zuloaga Limestone. Imlay (1938) designated the Sierra Sombreretillo as the type locality of the Zuloaga limestone, which is considered the offshore equivalent of the La Gloria formation, distinguished from the latter by the absence of sandstone and shale. The thickness of the Zuloaga limestone ranges from 275 to more than 550 meters.

The Zuloaga limestone is mainly thick bedded, with bed thickness ranging from 0.3 to 4 meters. The lower and middle beds of the formation are thinner than the upper beds. The dominant color is dark gray, but medium- to light-gray colors are found in the middle and lower beds. Weathering sometimes changes these colors to reddish, yellowish or whitish gray.

The Zuloaga limestone is found forming the central and highest parts of the anticline structures. In the Concepción del Oro district most of the mineral deposits are found in this formation. The reason for the preference of the mineral deposits for this formation is not known, but the fact that the intrusions are located in the nucleus of the anticline structures, having contact primarily with the Zuloaga limestone, could be one of the answers.

The Zuloaga limestone is considered of Oxfordian age on the basis that the overlying beds contain late Oxfordian, Kimmeridgean, Portlandian, and Tithonian fossils.

One remarkable characteristic of this formation that clearly distinguishes it from other formations is the almost total absence of soil materials on top of it.

La Caja Formation. The Sierra de la Caja was designated (Burckhardt, 1930) as the type location of this formation. It consists of thin-bedded limestones, calcareous clays, and shales. It is considered by Imlay (1938) to be the offshore equivalent of the La Casita formation, distinguished from the latter because it contains more calcareous and less clastic beds. The thickness of this formation ranges from 40 to 150 meters.

The La Caja formation forms narrow strips around the Zuloaga limestone outcrops. Its contacts are sharply different from the thick limestone beds of the underlying Zuloaga limestone and the overlying Taraises formation. The La Caja formation weathers rapidly, forming saddles and elongate valleys parallel to the strikes of the beds. The fast rate of weathering produces very poor exposures. The formation is very rich in fossils. On the basis of these fossils it has been established (Burckhardt, 1930) that it is of Late Jurassic age, belonging in the Tithonian, Portlandian, Kimmeridgian, and perhaps late Oxfordian stages.

A middle unit of the La Caja formation, classified as early Portlandian age, contains, in the Sierra Santa Rosa, important values of phosphoritic material.

Cretaceous System

Taraises Formation. The Taraises formation was classified by Imlay (1938), who gave the Canón de Taraises as the type location. Its thickness ranges from 100 to 150 meters. There are two members in the Taraises formation. The lower member is a thick-bedded limestone, light to medium gray, and it does not contain fossils. The upper member is fossiliferous. It is formed of light-gray, thin-bedded limestone. Some beds in this unit are pinkish gray. The upper member contains pyrite concretions and some lenses and nodules of gray chert. The Taraises formation is of early Neocomian age and represents the Berriasian, Valaginian, and early Hauterivian stages. Rogers, De Cserna, and others (1957) implied that at least in the Concepción del Oro district the Berriasian stage is absent.

Cupido Limestone. Overlying the Taraises formation is the Cupido limestone. Because of its concordance it is very difficult to differenciate one from the other at the contact. The thickness of the Cupido limestone ranges from 250 to 150 meters. The Cupido limestone is the offshore equivalent of the Las Vigas and Parritas formations.

The Cupido limestone contains three members. Burckhardt (1906) gave the following description of these members. The lower member is formed by medium- to thick-bedded, dark-gray limestone that weathers to yellowish-gray due to the presence of pyrite concretions, similar to the upper member of the La Caja formation. This member contains many lenses and nodules of black chert. The central member is formed by medium- to thick-bedded , medium gray in color. The upper member is formed by light-gray, thick-bedded limestone that contains nodules of reddish-gray chert.

No fossils in identifiable condition have been collected from the Cupido limestone, but it is probably of late Neocomian age and appears to represent the late Hauterivian and Barremian stages. In the study area the younger beds may be of early Aptian age.

La Peña Formation. The northern side of Sierra Taraises near La Peña Ranch was designated by Imlay (1938) as the type location of the La Peña formation. The thickness of this formation ranges from 80 to more than 600 meters.

The thick-bedded sequence found in the upper member of the Cupido limestone seems to continue into the lower members of the La Peña formation. The upper part of the La Peña formation is formed by thin-bedded limestone, which contains more clay toward the top of the formation. Thin beds of black chert are interbedded with the limestone beds. The color is dark gray to black, but the formation weathers to a very distinct yellow to brownish yellow. This coloration permits an easy identification of the formation even from a distance.

The fossils found in the upper part of the La Peña formation indicate that it is of late Aptian or early Albian age (Burckhardt, 1906).

Cuesta del Cura Limestone. The Cuesta del Cura limestone was originally described by Imlay (1938) on the western side of the Sierra de Parras. The thickness of this formation ranges between 270 and 350 meters. The contact between the Cuesta del Cura limestone and the underlying La Peña formation is transitional. This situation makes the determination of the exact location of the contact very difficult.

In the study area the Cuesta del Cura limestone consists of two members. The upper member consists of thin-bedded limestones, dark gray to brownish black in color, that are wavy bedded and have abundant ripple marks and contain many bands of black chert. The lower member is formed by medium- to thick-bedded limestone units that become thicker bedded toward the base of the formation and contain nodules and lenses of black chert. These units alternate with units of thin-bedded limestone and chert similar to those in the upper member, but with fewer ripple marks. The ripple marks suggest that this formation was deposited in a shallow water environment with continuous agitation. The Cuesta del Cura limestone is considered by many authors as a facies of the Aurora limestone (Böse and Cavins, 1927; Burckhardt, 1930).

Fossils are scarce in the Cuesta del Cura limestone except for in the upper units. Based on these fossils and the observation that it lies on top of the La Peña formation, the age of the Cuesta del Cura limestone is basically Albian, although the upper units may belong to early Cenomanian age.

Indidura Formation. The Indidura formation was originally defined by Kelly (1936) in the vicinity of Delicias, Chihuahua. Imlay (1938) gave the same name to the formation located between the Cuesta del Cura limestone and the Caracol formation, located on the western side of the Sierra de Parras. The deposition of the Indidura formation shows many facies, depending on location, and Imlay suggested a review of the nomenclature.

The Indidura formation, as defined by Mapes V., Zamora M., and Godoy (1964), consists of two members. The lower member is formed by thin-bedded, platy and shaly limestones, which are gray to brownish-gray. The upper member consists of dark-gray shales containing a few beds of yellowish-gray limestone. The second member weathers easily, and sometimes small depressions are formed at the surface of the ground. The thickness of the Indidura formation averages 180 meters.

The Indidura formation has abundant fossils of Cenomanian and Turonian age. The Indidura formation was deposited in a shallow sea receiving sediments from the rising land masses in central Mexico after the deposition of the Cuesta del Cura limestone.

Caracol Formation. The Caracol formation was also classified by Imlay (1938), who gave the middle part of the Sierra de Parras as the type locality. The contact between the Indidura formation and the Caracol formation is placed at the base of the tuff-like material that characterizes the Caracol formation. The thickness of the Caracol formation averages 805 meters.

The Caracol formation was originally described by Imlay (1938) as a series of dark-gray to black shales with interbedded tuff. Mapes V.

and others (1964) reported that a new petrographic analysis of the tuffs showed no volcanic material and that the units must be considered an arkosic calcareous sandstone similar in composition to a graywacke.

The Caracol formation was correlated with the upper part of the Indidura formation by Imlay (1938) and is probably of Coniacian age.

Parras Shale. The Parras shale is the youngest of the Cretaceous system with an average thickness of more than 1,300 meters. The Parras shale was also defined by Imlay (1938), who gave the southern part of the Parras Basin as the type locality.

The Parras shale contact with the Caracol formation is transitional and hence very difficult to determine. The limit is drawn where the sandstone beds become relatively scarce. The Parras shale consists of black calcareous shales with some thin beds of sandstone, especially in the lower part. The Parras shale was deposited during the Santonian.

Quaternary System

Mayrán Formation. The Mayrán formation was also classified by Imlay (1938), who gave the Sierra de Parras as the type locality. The thickness of the formation is over 200 meters, and it consists of sandstone and limestone conglomerates. The average size of the pebbles is 2 to 5 cm, but some are as large as boulders. The lower part of the Mayran formation is classified as the Mazapil conglomerate of Tertiary age (Mapes V. and others, 1964).

Poorly cemented materials are found in the lower horizons of the mountains of the area. The cementing matrix is generally caliche. In the lower levels of the valleys the alluvial cover is generally less than 50 meters thick.

Igneous Rocks

The igneous rocks, ranging from basalts to rhyolites, are relatively abundant in the area. The most abundant igneous rocks are of intermediate to acidic composition. These rocks can be found in the form of small to moderately large plutons (stocks), pipelike apophyses, dikes, sills, and irregular bodies. The locations of the major stocks are sketched in Figure 5.

On the western side of the area plutonic rocks are relatively scarce, restricted primarily to the vicinity of Pico de Teyra. The composition of the rocks is mostly quartz monzonite with local monzonitic and granodioritic facies, although there is also some albitic pegmatite and aplite. There is also an albite pluton of many kilometers in diameter. A latite body is located in the Sierra de San Rafael. Imlay (1938) reported several small masses of monzonite and granite dikes farther north.

In the eastern part of the area the stocks are primarily monzonite and syenite. The dikes and sills range from trachyte to latite and andesite. The biggest pluton in this area is the Guadalupe Garcerón stock. It is largely monzonitic in composition but heterogeneous in appearance. It is characterized by abrupt changes in grain size and color and is cut by numerous dikes that range in composition from monzonitic to syenitic. Rogers, Van Vloten, and others (1963) suggested that the stock was formed by successive surges of magma that were increasingly syenitic. The Matehuapil stock is similar to the Guadalupe Garcerón stock. The Cerro Pedregoso stock is a relatively homogeneous porphyritic syenite.

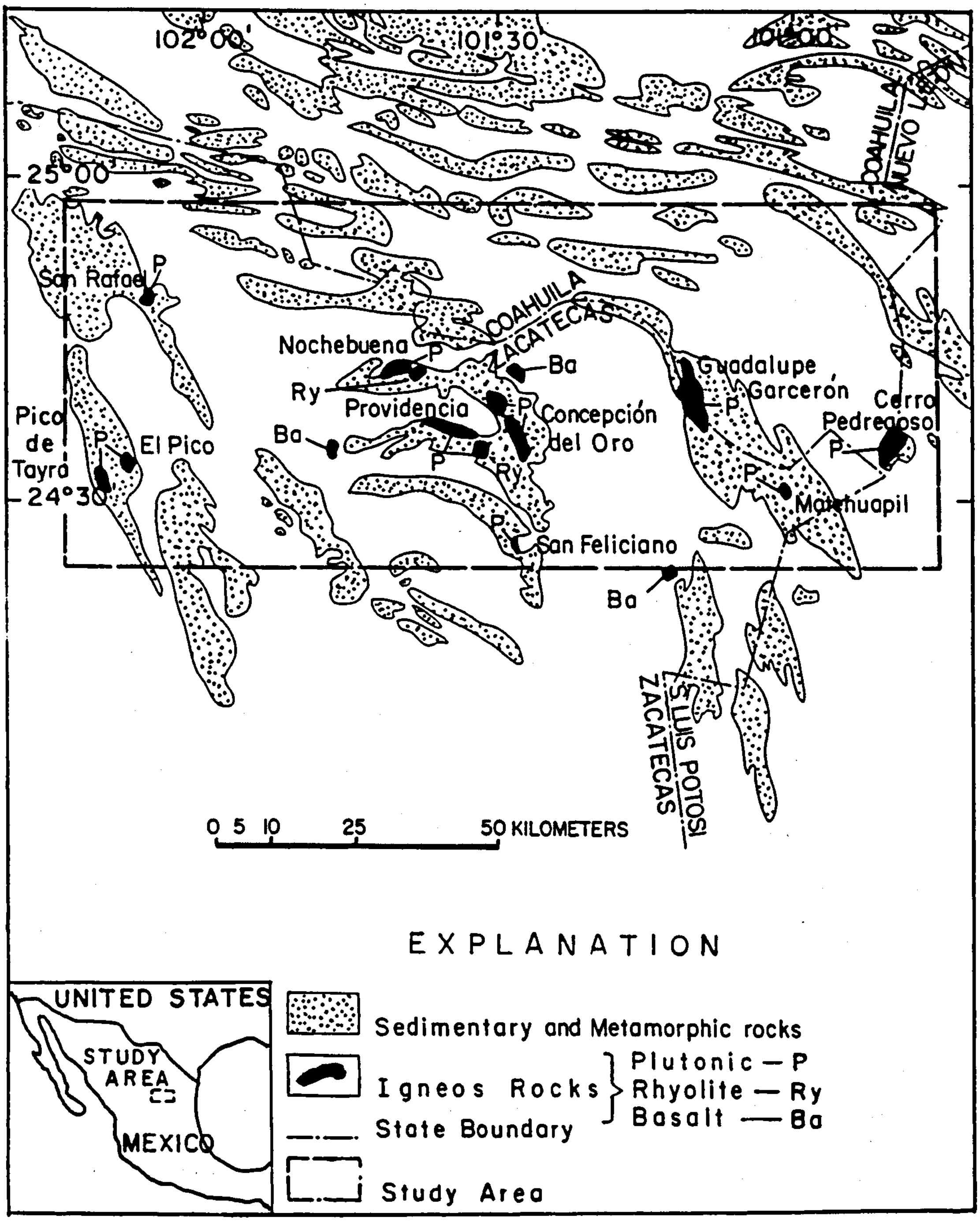

Fig. 5. Sketch map of the area showing the distribution of igneous rocks

The central part of the study area, in the vicinity of Concepción del Oro, shows the greatest concentration of intrusive rocks. The rocks of the stocks in this area contain more quartz and plagioclase than the rocks on the western side, which range from granodiorite to diorite.

The principal stocks in the central part of the study area are the Noche Buena, the Providencia, and the Concepción. The last two stocks are separated by less than 150 meters of Zuloaga limestone and seem to be connected at depth to form a single stock. Several small stocks are found in the area, as well as pipelike apophyses of the main stocks. Dikes and sills are abundant in the area; sometimes the contacts with the larger plutons are visible, but often the contact is not clear. The composition of the hypabyssal rocks is generally similar to that of the stocks, ranging from dacite to andesite.

All the intrusive bodies described are believed to be of the same age and to have been emplaced at relatively shallow depths after the folding of the sediments. The Concepción del Oro stock has been dated by the K-Ar method at about 40 m.y., which would place the intrusions at the end of the Eocene (Mapes V. and others, 1964).

The stocks are discordant with the sedimentary rocks they intruded, and some have exerted an upward thrust that domed and in places faulted the country rocks. Figure 6 shows a schematic section through the Concepción del Oro stock showing the doming and faulting of the roof by upward magma pressure.

Several rhyolitic bodies are found in the central part of the study area. The rhyolites are relatively small and were deposited over old erosion surfaces. Small bodies of basalt are found on the eastern side of

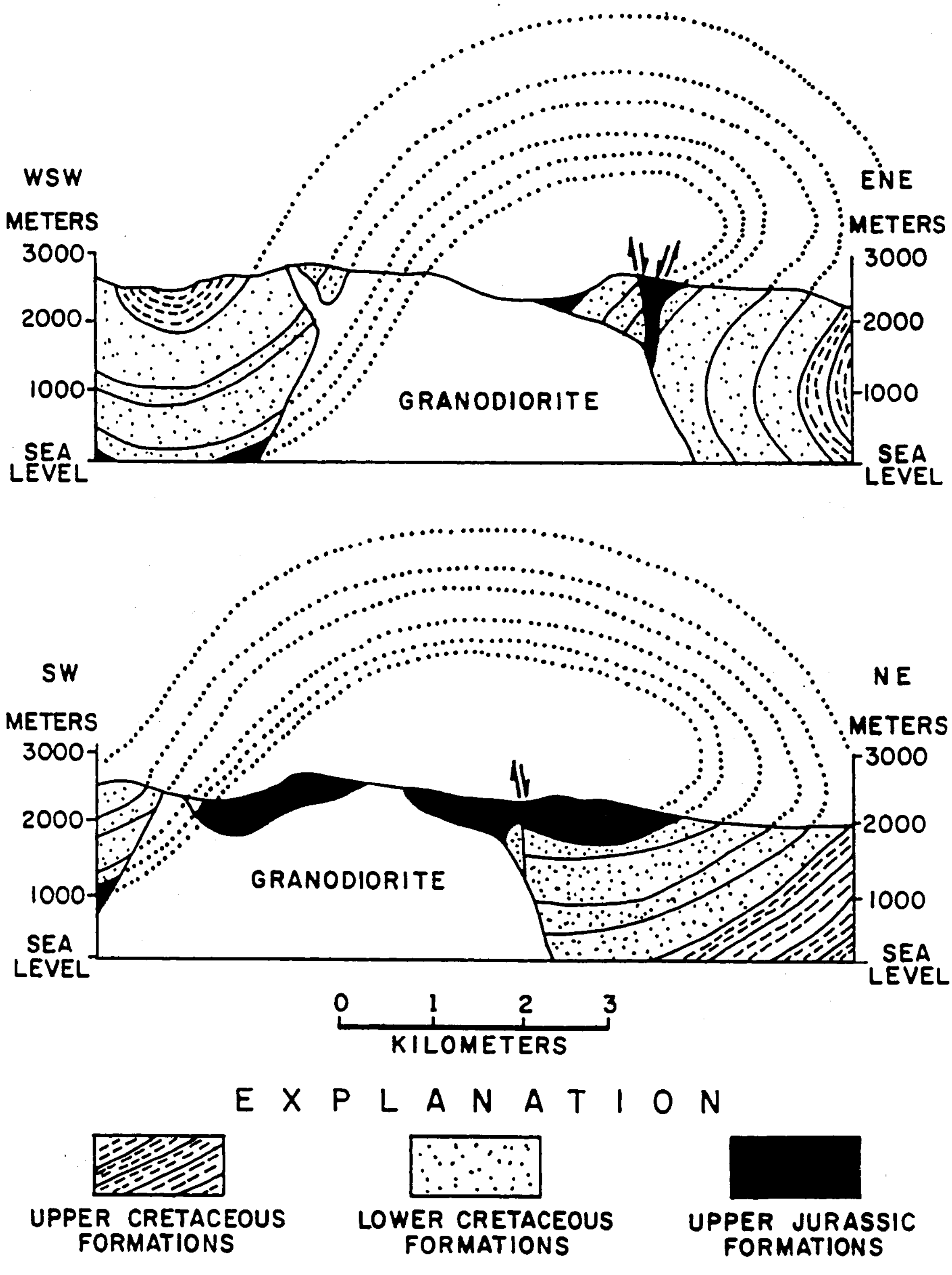

Fig. 6. Schematic sections through the Concepción del Oro stock showing doming and faulting due to intrusion. -- Modified from Rogers, Van Vloten, and others (1963)

the Sierra de Concepción del Oro and western side of Sierra Santa Rosa. Both the rhyolites and the basalt bodies are the result of the volcanic activity started in the Miocene (Basin and Range).

Metamorphic Rocks

The metamorphic rocks in the area are found mainly in and around the stocks, although they are also found in and around the small intrusive bodies. Endomorphism and contact metamorphism were produced by the heat and fluids of the intrusions. The alteration of the sedimentary rocks depends on several factors, including the amount of sediments that were in contact with the intrusion and the position of the strata in relation to the intrusion. The last is due to the preference of the metasomatic fluids for the bedding planes as conduits for their circulation.

The endomorphism of the granodiorite stocks is characterized by a a transformation to garnet and some diopside. Wollastonite, vesuvianite, magnetite, calcite, and chalcopyrite are also found in joints and fractures of poorly metamorphosed granodiorite.

As was mentioned before, the alteration of the sediments depends on the extent of the contact with the intrusion. The resulting metamorphic rocks depend on the original composition of the sedimentary rocks. If they are basically limestone (Zuloaga and Cupido limestones), marble is formed by recrystallization. Small particles of garnet and vesuvianite are found as a result of impurities in the limestone. If the sediments contained limestone as well as siliceous materials (Taraises formation and Cuesta del Cura limestone), the chert beds and lenses transformed into garnet and vesuvianite and the limestone recrystallized. Finally, if the sediments contained small amounts of limestone and were rich in clay minerals (La Caja, La Peńa, and Indidura formations) hornfels were formed. The hornfels consist of garnet and wollastonite.

An aureole of a few meters to several hundred meters is found outside the tactite and hornfels formed by contact metamorphism. This aureole is characterized by decoloration of the sedimentary rocks and, in some places, by the recrystallization of the limestones.

Structural Geology

The different fold and fault characteristics and the distribution of the igneous rocks were used by De Cserna (1956) to divide the area located at the boundary between the Mesa Central and Sierra Madre Oriental into three geologic provinces.

These provinces, shown on Figure 7, are designated, from south to north, as the intrusion belt, the plain and range belt, and the valley and ridge belt. The study area is located mainly in the intrusion belt and in the southern part of the plain and range belt. The intrusion belt was renamed by Rogers, De Cserna, and others (1962) as the mineral belt due to the relationship between the mineral deposits and the intrusions.

Valley and Ridge Belt

The valley and ridge belt, located outside of the study area, is the east-west-trending section of the Sierra Madre Oriental. A series of long narrow ridges, arcuate toward the east, is the principal characteristic of this belt. The ridges form a nearly unbroken mountain barrier with very few transverse canyons. The ridges are the expressions of deeply eroded anticlines, and the narrow valleys are the topographic expressions of eroded synclines. Faulting is rare and generally of small

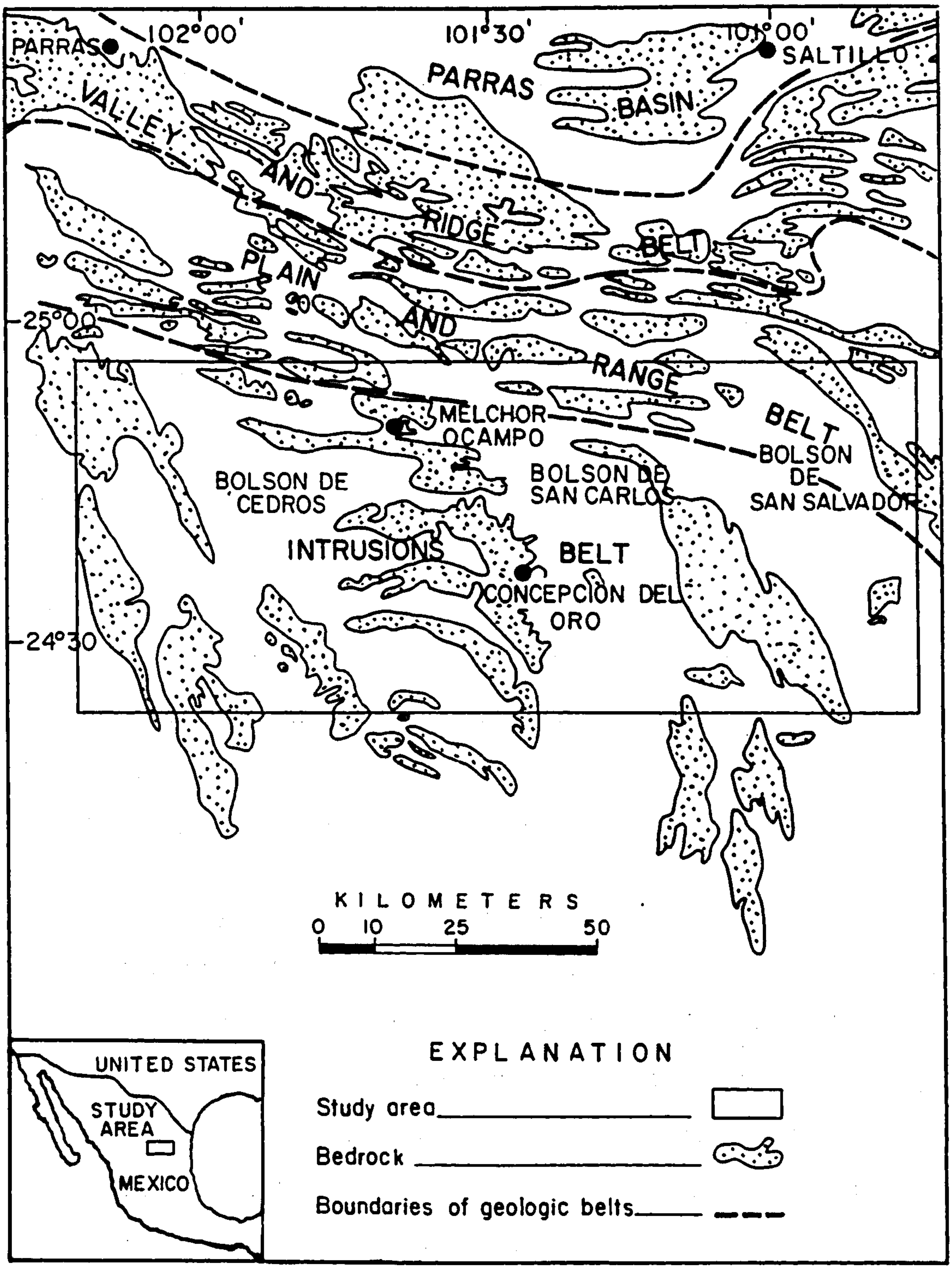

Fig. 7. Sketch map showing the division of the area according to its principal structural features. -- Modified from Rogers, De Cserna, and others (1962)

magnitude. Some low-angle overthrusts are found in the eastern front of the Sierra Madre Oriental. The relationship between the width of the ridges and the valleys is 1:1 in this belt. This close spacing could be the result of crowding of the folds in the vicinity of the foreland mass.

Plain and Range Belt

The plain and range belt lies along the boundary between the Mesa Central and the Sierra Madre Oriental. The ridges are more widely spaced than in the valley and ridge belt, with the relationship between the width of valleys and ridges being 2:1. The relatively broad valleys not only reflect the presence of more open syncline structures but have formed by faulting at the expense of the anticline. Normal faults are common, and thrust faults have not been found. Figure 8 is an index map showing the principal structural features located in the study area. A brief description of only the structural units of the plain and range belt found inside the study area is given.

Sabanilla Anticline. The Sabanilla anticline is represented in the study area by the Sierra de Gómez Garcías and the Sierra La Carbonera forming a continuous ridge of approximately 60 kilometers. The anticline can be traced farther northwest, outside the study area, for many kilometers. Near the town of Gómez Garcías the structural trend of east-southeast changes to S. 25° E. A normal fault located in the northeast side of the structure brings the Zuloaga limestone nucleus of the anticline in contact with the alluvium of the valley.

San Francisco Anticline. The San Francisco Anticline is represented by the Sierra de la Taravilla and the Sierra del Jazminal. Its

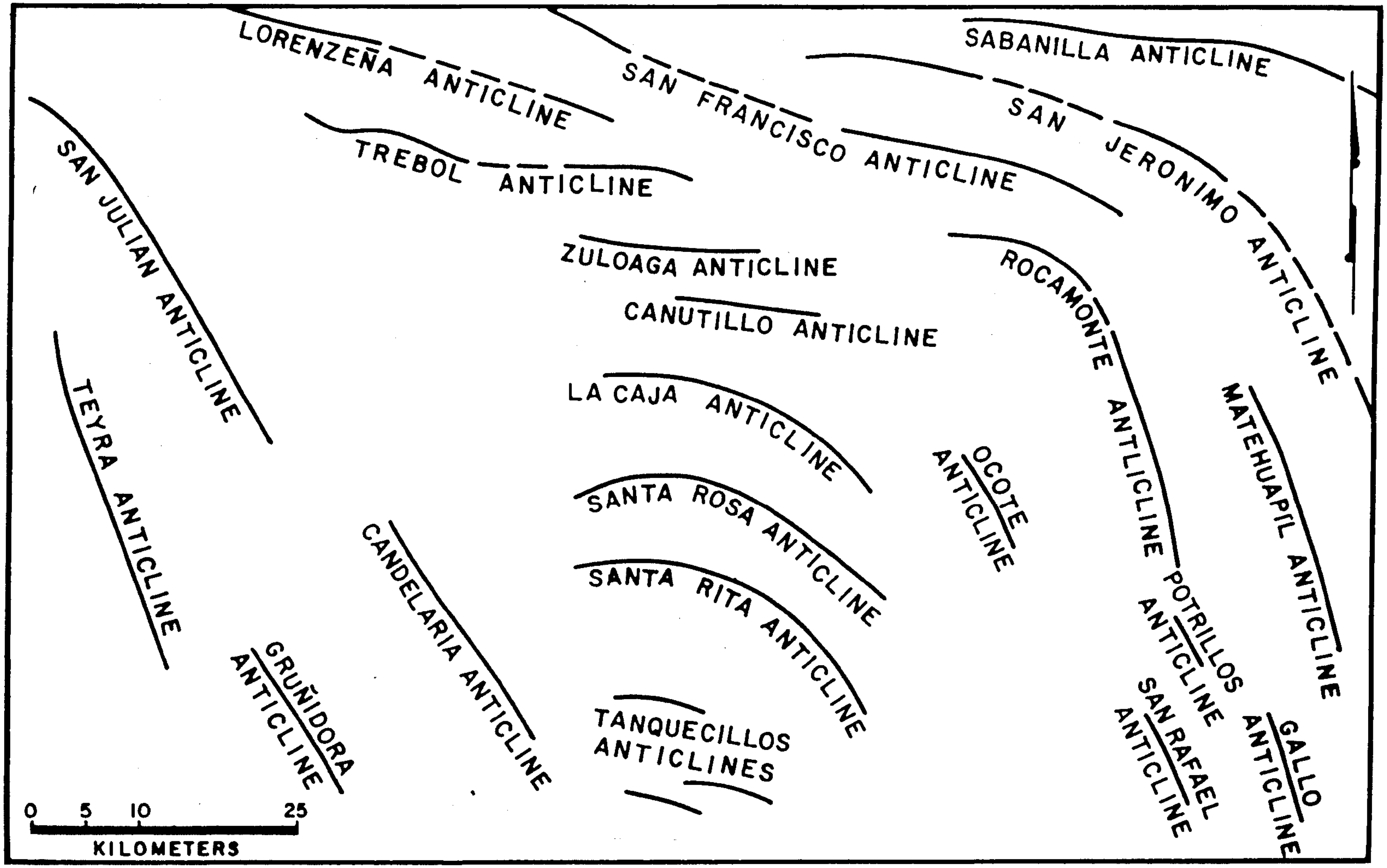

Fig. 8. Index map showing the location of the principal anticlinal structures of the study area

mountainous continuations outside the area are the Sierra del Guaje and the Sierra San Francisco. The anticline of the Sierra de la Taravilla plunges southeast, going under the Bolsón of San Carlos, and is overturned toward the north. East of the Bolsón of San Carlos the anticline structure seems to continue, forming the Sierra Jazminal, with its nucleus formed by Cuesta del Cura limestone. A normal fault on the north side of the structure brings the Cuesta del Cura limestone in contact with the Caracol formation and the Parras shale. A change in the trend similar to that of the Sabanillas anticline is assumed, and its continuation is established at the east of the Sierra Rocamonte.

San Jerónimo Anticline. The San Jerónimo anticline is represented by the Sierra San Jerónimo and seems to be en echelon with the Taravillas structures. The San Jerónimo anticline plunges west, and it is a symmetrical structure. The east side of the structure is covered by alluvium for almost 14 kilometers before coming to the surface forming the low relief Sierra de los Muchachos. A normal fault in the north side of Sierra de los Muchachos shows a throw of more than 1,000 meters bringing together units of La Caja formation and Parras shale.

Lorenzeña Anticline. The Lorenzeña anticline is represented by the Sierra de Lorenzeña just outside the area, the Sierra del Socavón in the west, and the Sierra del Gabán to the east. The Sierra del Gabán anticline is overturned toward the north as are the Lorenzeña and Socavón structures.

Intrusion Belt

The intrusion belt lies within the Mesa Central province, which resembles the Basin and Range province in the United States. The principal characteristic of this province is the relatively prominent development of bolsons and the smaller area occupied by the mountain ranges. Block faulting is very important, and in addition the belt is characterized by fairly common reverse faults and by a wide distribution of igneous rocks, both intrusive and extrusive. The distribution of the volcanic rocks seems to be related, at least in part, to the block faults, which probably served as conduits for basaltic magma. A brief description of the principal structural elements found in the intrusion belt follows.

Trébol Anticline. The Sierra del Trébol and the Sierra de Sombreretillo form the Trébol anticline, although it is also possible that both sierras represent an en echelon structure. This anticline in the portion of the Sierra del Trébol is a symmetrical anticline, except for local overturns. The portion known as the Sierra Sombreretillo shows a strong overturn toward the south. The south limb of the Trébol anticline was buried by a south-dipping fault. There is also a transverse fault near the central portion of the Sierra del Trébol.

Zuloaga Anticline. The Zuloaga anticline is represented by the Sierra de Zuloaga and its west continuation is known locally as the Sierra del Carpintero. The anticline is more than 50 kilometers long and slightly overturned toward the south. In its northern limb there is a thrust fault that can be traced for more than 12 kilometers. This fault dips south and shows a structural displacement of more than 1,100 meters, which brings the Zuloaga limestone to rest on top of the Caracol formation.

Canutillo Anticline. The Sierra de Canutillos is the topographic expression of the Canutillo anticline, which trends almost east-west and is moderately overturned toward the south. The Zuloaga limestone found on the nucleus of the anticline shows fan folding. Faults are present in the form of thrust and normal faults. The most important fault, located in the south limb, is a normal fault approximately 14 kilometers long, dipping south. The throw of the fault has been estimated at more than 1,100 meters, bringing the Zuloaga limestone in contact with the Caracol formation. Also, some transverse faults can be found in the structure.

La Caja Anticline. The La Caja anticline is represented by the Sierra de Concepción del Oro and the Sierra de la Caja. In the Sierra de la Caja the trend of the anticline is almost east-west, although it curves toward the southeast ending with a S. 45° E. trend at Sierra de Concepción del Oro. The last portion of the anticline became more complex due to the intrusion of granodiorite stocks. Here, the fold is overturned toward the northeast, and near Concepción del Oro it is almost recumbent. From the bend of the structure to the west (the Sierra de la Caja) the structure is a symmetrical anticline but in its nucleus there is some evidence of fan folding.

On the northern side of the Sierra de la Caja, the La Caja thrust fault dips south, starting near the Noche Buena stock, and extends east almost to the Providencia stock. Displacement on the fault moved the Zuloaga limestone on top of the Caracol formation, which represents a stratigraphic throw of at least 1,100 meters. Another thrust fault, located on the south side of the Sierra de La Caja, dips north and apparently was produced by the intrusion of the Providencia stock. Many normal faults are found in the vicinity of the Concepción del Oro stock. This stock was emplaced mainly in the nucleus of the La Caja anticline producing an upward lifting of the sedimentary rocks and fracturing and faulting. The most important fault is the Concepción del Oro fault, which goes around the stock almost parallel to the contact between the intrusion and the sedimentary rocks. The fault plane is almost vertical, and maximum throw is almost 900 meters. The south side of the Concepción del Oro stock intruded the syncline located south of the La Caja anticline, producing a topographical connection between the La Caja anticline and the Santa Rosa anticline located to the south.

Santa Rosa Anticline. The Santa Rosa anticline is represented by the Sierra de Santa Rosa and its western extension is known locally as the Sierra de San José. The anticline is also curved, starting with a N. 40° W. trend and changing toward the west, ending with an almost east-west trend. The complete anticline is moderately overturned toward the north, although in the Sierra de San José portion the Zuloaga limestone forming its nucleus is fan folded.

Santa Rita Anticline. The Sierra de Santa Rita is the topographic representation of the Santa Rita anticline, which is parallel to the Santa Rosa anticline. The trend of the Santa Rita anticline goes from N. 20° W. in the south end to almost east-west in the west side. The anticline is slightly overturned toward the north and its western end plunges into the Bolsón de Cedros. There is a thrust fault located in the central part of the anticline, which runs for almost 20 kilometers. This fault dips south and the structural displacements seem to be very small.

Tanquecillos Anticlines. Tanquecillos anticlines is the name applied to the folds located south of the Santa Rita anticline. They are four small anticlinal structures trending northwest and west-northwest and are cut by several faults. The structures are symmetrical and seem to be almost parallel to the Santa Rita anticline, although the curving is not very well defined.

Candelaria Anticline. The Sierra de Candelaria is located northwest of the Sierra de Tanquecillos. Its orientation is N. 40° W., and it has been severely eroded. This is the topographic expression of the northwest-trending Candelaria anticline. Its nucleus shows basement rocks below the Zuloaga limestone. On the east side of the Sierra de Candelaria there are two anticline structures trending N. 60° W., almost perpendicular to the major trend, that seem to be the continuation of the Santa Rosa and Santa Rita anticlines. These folds are the result of two different stages of folding (De Cserna (1956), the oldest represented by the northeast-trending folds that are similar in age to all of the folds previously described and the northwest-trending folds that were formed as a result of basement folding that occurred after the folding of the sediments. This explanation has been extended to the San Julián, Teyra, and Gruñidora anticlines.

San Julián Anticline. The San Julián anticline is located east of the Trébol anticline in the northwest corner of the area. The Sierra de San Julián is the topographic expression of the structure that has been severely eroded and its nucleus is formed by basement rocks. The southwest side is not well represented, but the northeast side suggests that the anticline is not symmetrical. There are several faults both longitudinal and transverse.

Teyra Anticline. The Sierra de Teyra is the topographic representation of this structure. There are three intrusive bodies, probably connected at depth, that are responsible for great deformation of the sedimentary rocks. The evidence of the anticline structure is somehow occult by the doming produced by the intrusions. The trend of the Sierra de Teyra is northwest, and the sedimentary rocks dip away from the stocks. The major stock is known as the Pico de Teyra and forms the highest mountain in the area.

Gruñidora Anticline. Located in the southwest corner of the area, the Sierra de Gruñidora is the topographic expression of the Gruñidora anticline. Similar to the Sierra de Candelaria, two different trends of anticline structures are found in the Sierra de Gruñidora. The northeast section shows an anticline structure trending northwest, and the southeast section contains anticline structures trending N. 60° E. with nuclei formed by dome-type outcrops of Zuloaga limestone.

Ocote Anticline. The Ocote anticline is represented by the low north-northwest-trending Sierra del Ocote located southwest of Concepción del Oro. A thrust fault is located on the eastern side of the fold. The fault produced the displacement of the Zuloaga limestone, which is the nucleus of the structure, to rest on top of the Caracol formation. The dip of the fault is approximately 15° W. The Ocote anticline is considered by some authors (Rogers, De Cserna, and others, 1957) as the continuation of the Canutillo anticline.

Rocamonte Anticline. The Rocamonte anticline is represented by the Sierra de Rocamonte and its northern continuation is the Sierra de Colorada. The anticline is almost symmetrical in all its extension. At the Sierra de Colorada it has an east-west trend changing toward the south and is northwest-southeast trending at the Sierra de Rocamonte. The Guadalupe Garcerón stock intruded the anticline structure producing great deformation of the sedimentary rocks, although there are no important faults resulting from the intrusion.

Matehuapil Anticline. The Matehuapil anticline is located east of the Rocamonte anticline. The structure is overturend toward the east; it has a northwest-southeast trend and plunges south. In the eastern side of the structure there is a normal fault that can be followed for more than 10 kilometers. The Matehuapil stock intruded the anticline, producing deformation to the sedimentary rocks, but there is no major faulting associated with the intrusion.

Potrerillos Anticline. The Sierra de Potrerillos is the topographic expression of the northeast limb of the northwest-trending Potrerillos anticline and is located south of the Sierra Rocamonte. The anticline is overturned toward the northeast and is severely faulted.

San Rafael Anticline. The San Rafael anticline is located south of the Potrerillos anticline almost at the south end of the study area. Its topographic expression is the Sierra de San Rafael, a mountain range more than 35 kilometers long. The anticline trends toward the north-northwest, and many faults are located in the area. The most important fault is located in the southeast limb of the anticline. The throw of the fault put the Zuloaga limestone in contact with the Caracol formation. South of the study area, the Sierra de San Rafael shows evidence of at least three north-northeast-trending anticlines.

Gallo Anticline. The Sierra del Gallo and the Sierra de Coyotitos located to the west of it are the topographic representations of the Gallo anticline. The Gallo anticline is formed by two anticlinal folds trending to the northwest and overturned toward the northeast. The structure is located east of the San Rafael anticline. The anticline located at the Sierra del Gallo has its west limb faulted by a normal fault.

Mineral Deposits

The mineral deposits in the area were known, as mentioned before, since pre-Columbian times. Both metallic and nonmetallic mineral occurrences are found in the area. The metallic minerals seem to be, in all cases, related to the intrusive bodies. The nonmetallic minerals such as phosphate rock, talc, and gypsum are related to sedimentary strata. Due to the objectives of the project, attention is given to only the metallic mineral deposits. The nonmetallic mineral deposits, especially phosphate rock, are well documented by Rogers, De Cserna, and others (1957) and Rogers, DeCserna, and others (1961) and in other reports.

Almost all intrusive bodies found in the area contain associated mineralization. Only the mineral deposits located in the vicinity of Concepción del Oro have been mined economically and are therefore well known and documented in the literature. The other occurrences are only reported or, in many cases, only small diggings and test pits mark their location. The different types of deposits in the Concepción del Oro district offer a good basis to generalize on the types of mineralization most likely to be found in the area.

Mineralogy

The ore and associated metallic minerals are gold, magnetite, pyrite, chalcopyrite, galena, sphalerite, and small amounts of arsenopyrite, tetrahedrite, and bournonite. The gangue minerals are calcite, quartz, and calc-silicates such as garnet, vesuvianite, and wollastonite.

The oxidation zone varies in depth in different mineralized bodies extending to 50 to more than 500 meters below the surface. The oxidation affected the ore minerals in different ways. The gold remained in the oxidation zone as an enrichment product. The zinc and iron sulfides became soluble and were removed. The lead tends to be less mobile and remains in the oxidation zone. The silver, depending on its association with the galena, could remain or be washed away. This is illustrated in Figure 9, which shows the variation in silver, lead, and zinc content with the depth of the ore.

The age of mineralization was deteremined by Buseck using the K-Ar method (cited by Mapes V. and others, 1964). Two samples were used. The first one was adularia, which under x-ray diffraction proved to be a potassium feldspar without sodium, measured 38 m.y; the second one, a sample of biotite gave 40 m.y. Because the feldspars, using the K-Ar method, produce lower measurements, both determinations can be considered as equal. These estimations confirm that the mineralization and the intrusion are more or less of the same age.

Zoning, in its classical sense, is not found in the mineral deposits. But the mineral deposits themselves provide the zoning. The

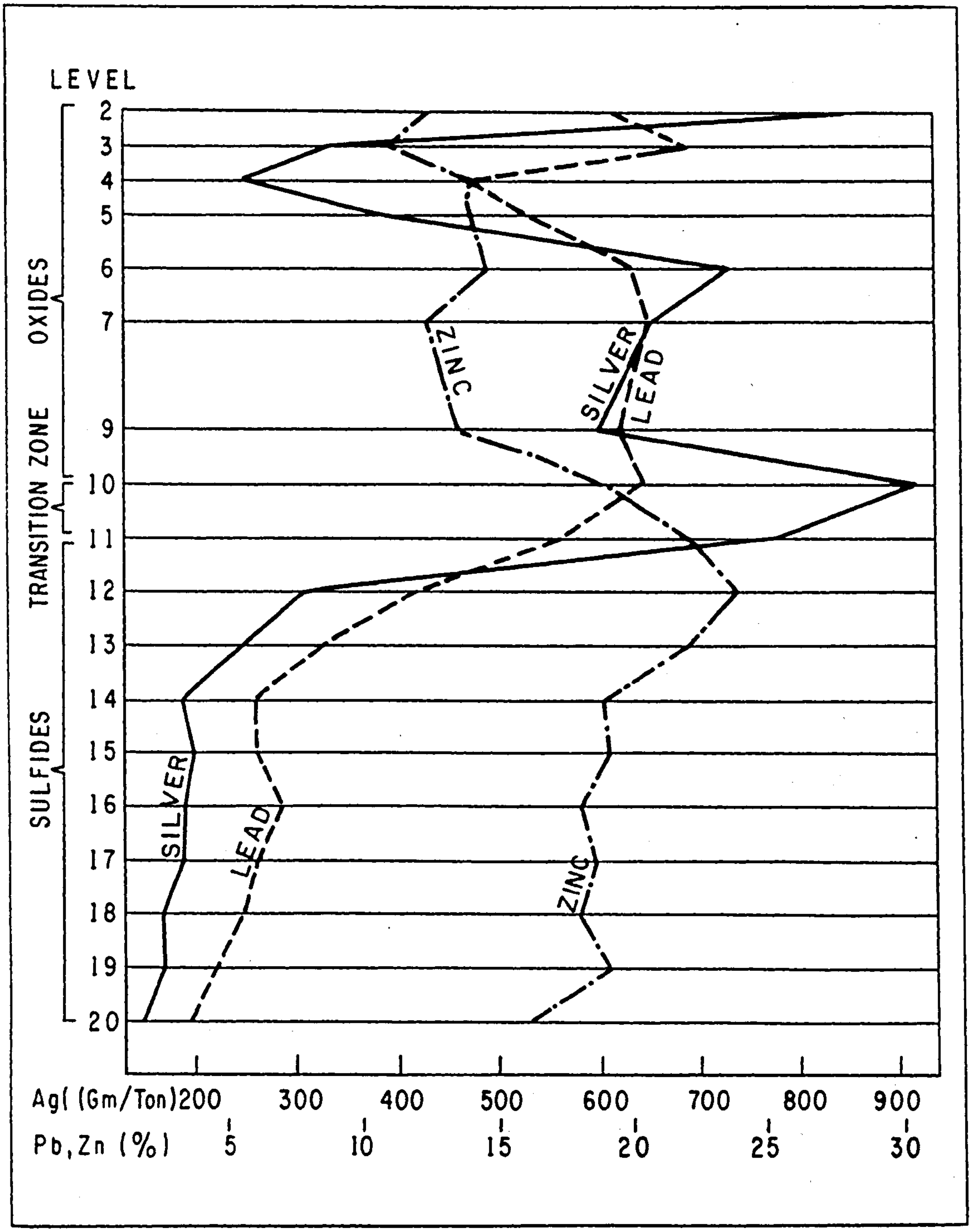

Fig. 9. Variations of silver, lead, and zinc grade with depth at the Zinc West body. -- After Mapes V, and others (1964)

deposits in the Concepción del Oro vicinity are rich in copper, magnetite, and gold, with minor amounts of zinc and lead. The deposits in the Aranzazu area contain copper and zinc but no magnetite. Finally, the deposits of Salaverna and Noche Buena areas contain mostly lead, zinc, and silver.

These differences in mineralogy suggest a different formation temperature going from mesothermal to hypothermal deposits. This also corroborates the idea given by Mapes V. and others (1964) that the hydrothermal solutions, formed in a deep magmatic chamber during the crystallization of the stocks, flowed through channels produced by the contact of the intrusion with the sedimentary rocks and the openings produced during the shrinking of the stocks.

Mineralization Controls

The most important control of the mineralization is given by the contact between the stocks and the sedimentary rocks. Where the contact is parallel to the bedding plane it gives place to tabular bodies. On the other hand, where the intrusion is discordant the contact is irregular and produces irregular pipelike bodies known locally as *chimeneas*. These deposits are the largest and most productive deposits of the area. As an example, the Zinc West body (a *chimenea*) is known to extend more than a thousand meters vertically.

Fractures formed both during the folding of the sedimentary rocks and during the intrusions of the stocks are another control of the mineralization. Many of these fractures are mineralized, but generally they are not economic to mine. Only one vein-type deposit is known. The vein El Placer starts in the granodiorite and cuts the sedimentary rocks going out almost perpendicular to the bedding planes. In general, the importance of the fractures is that they were, in many cases, the conduits for the hydrothermal solutions.

Very important controls of the mineralization are provided by some favorable strata and some horizons in the sedimentary rocks. These controls result from the physical and chemical properties of the sediments and their ability to be deformed, broken, or replaced. In the study area the horizons most likely to be mineralized are some beds of the Zuloaga limestone, the contacts between the Zuloaga limestone and the La Caja formation, the La Caja and Taraises formations, the Taraises and Cupido formations, and the Cupido and La Peña formations. Many other types of controls could be found in the area, but they are less important than those previously mentioned.

REGIONAL EXPLORATION

Two basically different exploration techniques were planned to estimate the mineral potential of the entire study area: a geochemical survey of stream sediments and an aeromagnetic survey. Both studies were carried out during the first field season of the project. A third technique, the analysis of Landsat imagery of the area, was later incorporated during the development of this project.

Landsat Image Analysis

The first study of the Landsat images of the area was done by Salas G. (1975). In that work, the images were used mainly to attempt to define the characteristic lineaments of the different metallogenetic provinces of Mexico and the possible correlation of the lineaments with the mineral deposits. Correlation of lineaments with mineral deposits has been controversial for amny years. Different investigators (Salas G., 1975; Raines, 1978) recognize this relationship, while others (Gilluly, 1976) deny it.

The study of the Lansat-1 image of the Concepción del Oro area was done using bands 5 and 7 of the image whose center is located at lat 24±34' N., long 101°21' W. and was taken on July 22, 1973. This image shows excellent quality and has less than 0.1% cloud cover. The scales were 1:1,000,000 and 1:250,000. The selected image covers not only the study area but extends outside to the east. Because of the lack of vegetation, this area is well suited for the analysis.

Inspection of the image permits recognition of many of the structural elements described previously, and some photogeologic analysis is possible, particularly the linear feature analysis, which was done using all the curvilinear and rectilinear features of natural origin that were identified in the image. Many roads in the area appear to be linear features on the image, and where recognized these were eliminated from the linear feature map (Fig. 10).

The procedure for the linear feature analysis applied to the data was described by Sawaltzky and Raines (1978). The analysis was carried out at the computer facilities of the U.S. Geological Survey in Denver, Colorado.

The first step of the analysis was the digitization of the linear features map, reducing the linear features to two-dimensional coordinates of endpoints of straight-line segments. The curvilinear features were reduced to a sequence of connected line segments.

The second step, the trend analysis, consisted of the determination of the most significant trends based on the strike-frequency histogram, which shows the absolute frequency of occurrences of line segments belonging in 180 one-degree zones of direction. To obtain the significant value of a frequency value the probability that the frequency value will occur if the data set is drawn from a uniformly distributed population of directions is first calculated. The distribution of possible frequencies is a binomial distribution, and its mean is the central value between the greatest and least frequencies. A frequency value at or near the uniform frequency mean will have a low significant value, while a frequency value with a large deviation from the mean value will be considered of high

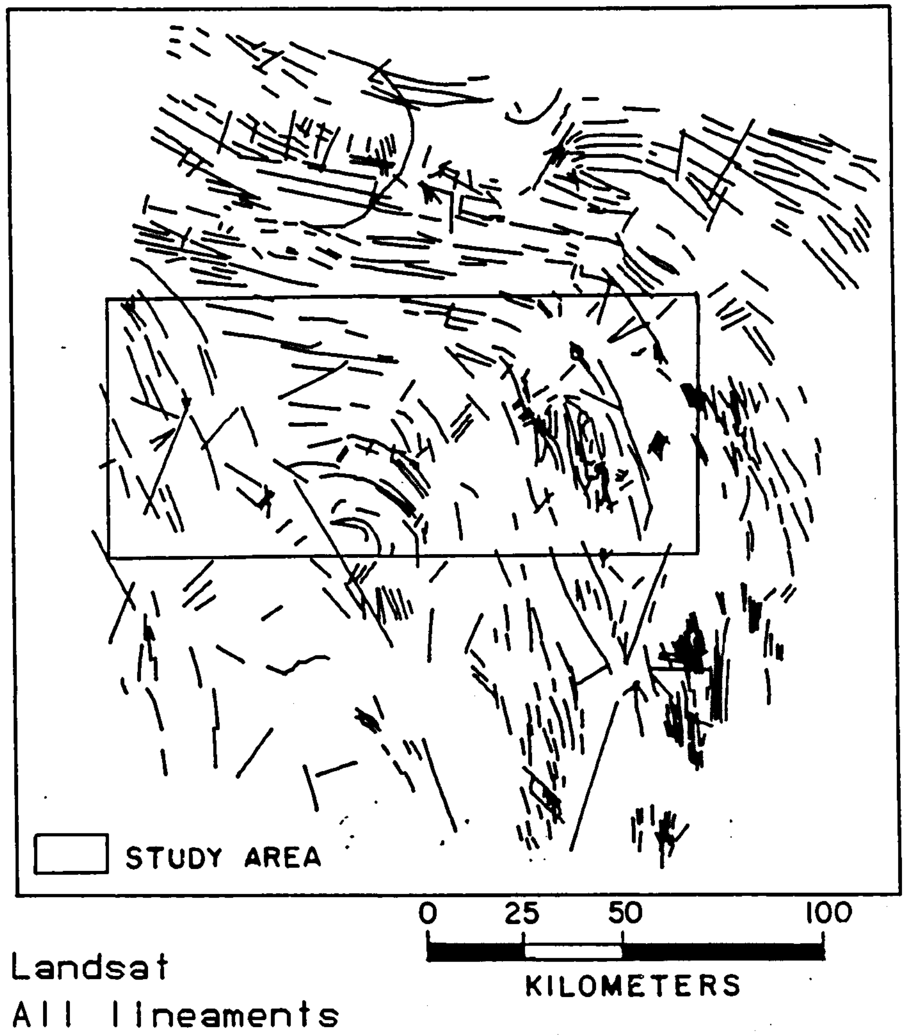

Fig. 10. Map of linear features of the Concepción del Oro area obtained from a Lansat I image

significance if the value is greater than 90 percent. The same model applies to the trend analysis of length-weighted linear features. Each linear feature that contributed an increment of one to the strike-frequency histogram now contributes an increment proportional to its length. In general, the significant trends determined by the non-length-weighted data are eliminated by the length-weighted analysis. Very often new trends consisting of a few long linear features are revealed. Finally, a running average was applied to smooth both the strike-frequency and length-weighted data. Smoothing enhances trends of several zone interval widths that are otherwise concealed.

Figure 11 shows the strike-frequency histograms of the unweighted and length-weighted linear features of the area. The number of line segments recorded in the studied image was 984, and the total length was 20,115 km. The same figure shows the statistically significant intervals obtained both with the unweighted (upper part, horizontally shaded) and the length-weighted (lower part, diagonally shaded) data.

The interval between N. 64° W. and N. 85° W. represents 19 percent of the linear features in the area and 25 percent of the total length. The linear features found in this interval are shown in Figure 12. As can be seen in the figure, these linear features are mostly located in the northern portion of the image and can be correlated with the similarly trending anticlinal structures found in the area and are interpreted as the result of those structural units.

Figure 13 shows the linear features found in the interval N. 6° W. to N. 28° W. This interval represents 25 percent of the linear features, both in number and in length. This interval and the previously

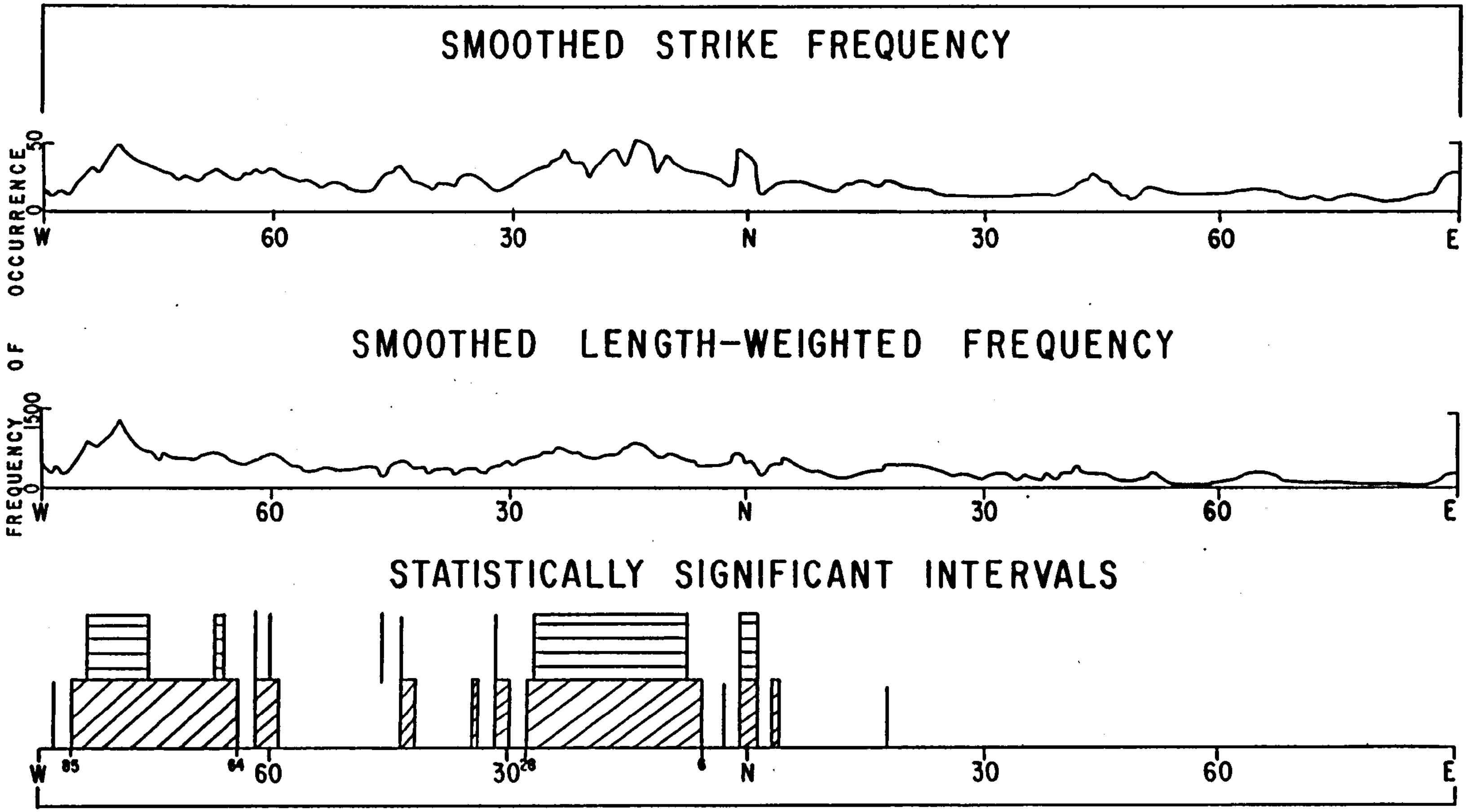

Fig. 11. Strike-frequency histogram and trend analysis of the linear features of the Concepción del Oro area

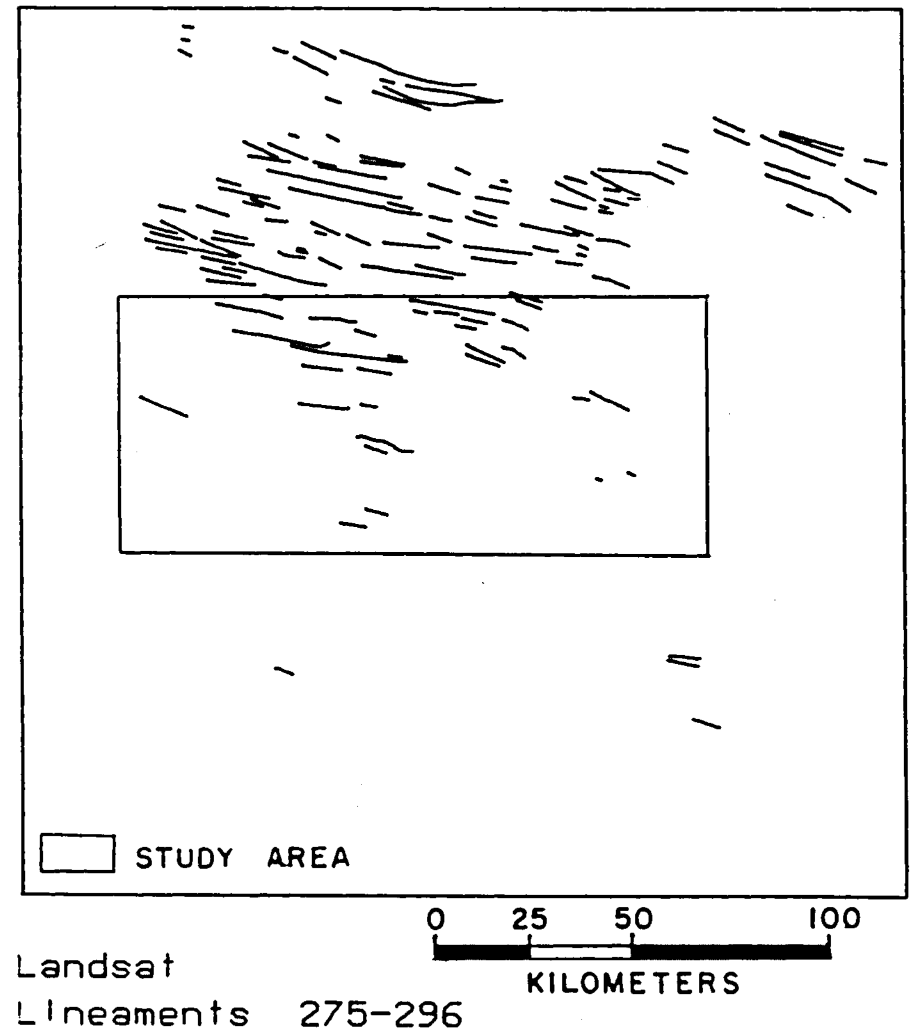

Fig. 12. Linear features found in the N. 64° W.-N. 85° W. interval

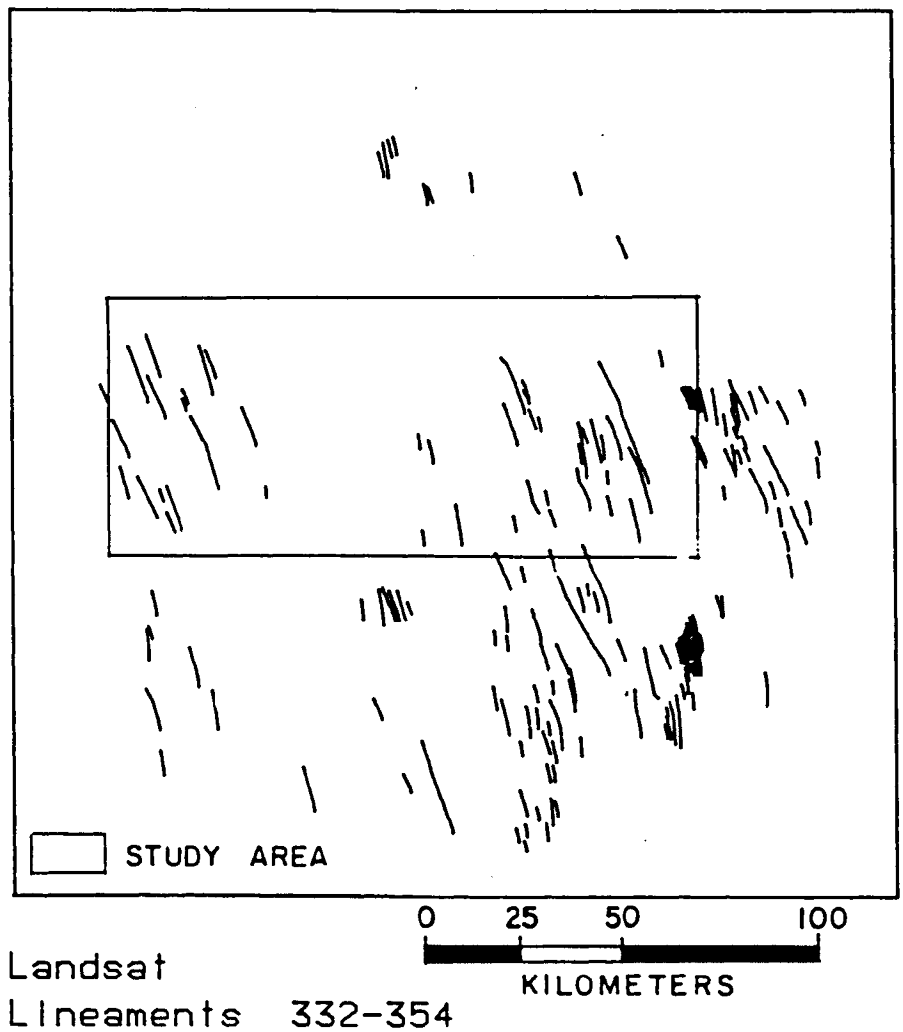

Fig. 13. Linear features found in the N. 6° W.- N. 28° W. interval

described interval are the most statistically significant intervals. The linear features in this interval located in the east and southeast part of the study area show a larger concentration than those located in the west and southwest part of the study area. Once again, the linear features in this interval can be interpreted as a result of the anticlinal structures trending in the same interval. The difference in the number of linear features is interpreted as partly the result of the degree of erosion of the surface structures. Structures located in the west and southwest part of the study area have been deeply eroded, and many of the structural elements producing the linear features found in those with less degree of erosion have vanished.

Apart from these two intervals there are a few other intervals in the northwest quadrant that are considered departures from the major intervals having the same origin. There are no statistically significant intervals in the northeast quadrant. Figure 14 shows the linear features located outside the two principal intervals.

The metallic mineral deposits in the area are located, as previously noted, in the vicinity of the intrusive bodies. The linear feature analysis did not show any definite correlation between the linear features and the location of the intrusive bodies. This may be due to the overwhelming number of linear features related to the anticlinal structures, leaving those not related to folding of the sedimentary rocks as not statistically significant.

It can be concluded that the linear feature analysis as carried out did not provide any indication of the known mineral deposits in the area

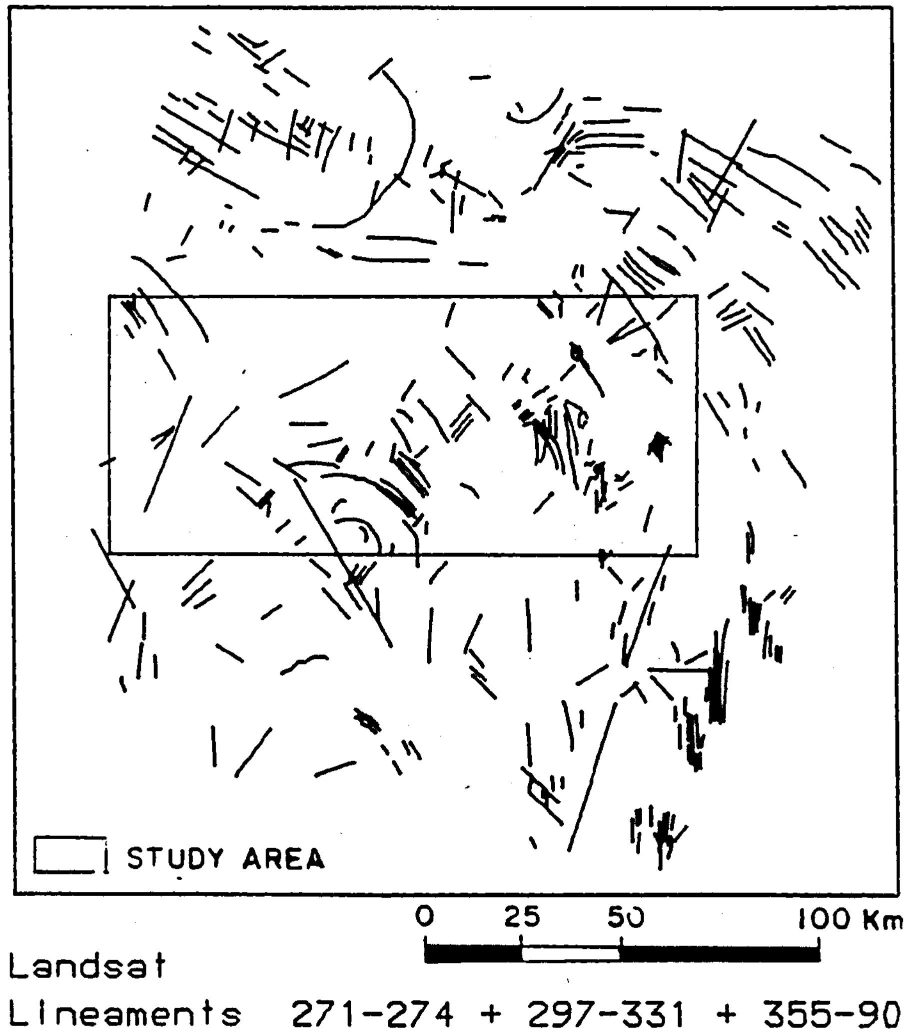

Fig. 14. Linear features located outside the two principal intervals

or the location of the intrusive bodies. At least in this area, this type of analysis does not appear to provide any exploration advantages.

Regional Geochemistry

The first regional survey carried out in the Concepción del Oro project, done at the beginning of the first field season, was the stream sediment geochemical analysis. The survey was planned to cover all the principal streams, keeping the separation between sampling points generally less than one kilometer. From July to November 1973 more than 1,300 samples were collected. From each sample about 100 grams of minus 80 mesh material were sent to the geochemical laboratory in Mexico City. Each sample was analyzed by colorimetric techniques for copper, lead, and zinc. Once the results were available they were treated with the standard procedures to determine background and anomalous values for each element. Values of 50 ppm were considered background and values over 200 ppm were considered anomalous for both copper and zinc. The background value for lead was established at 25 ppm and values over 75 ppm were considered anomalous.

To obtain faster coverage, the area was divided into three parts and each part surveyed by a different individual. The results obtained for the western area were reported by Arriaga M. (1973), for the central area by Morín M. (1973), and for eastern area by Martínez V. (1973).

Figures 15 and 16 show the locations of the anomalies in the western and eastern portions of the study area, respectively. Many anomalous values were related to contamination produced by mines and prospect pits. This was particularly true around the town of Concepción del Oro, where values of over 2,000 ppm were traced to old dumps.

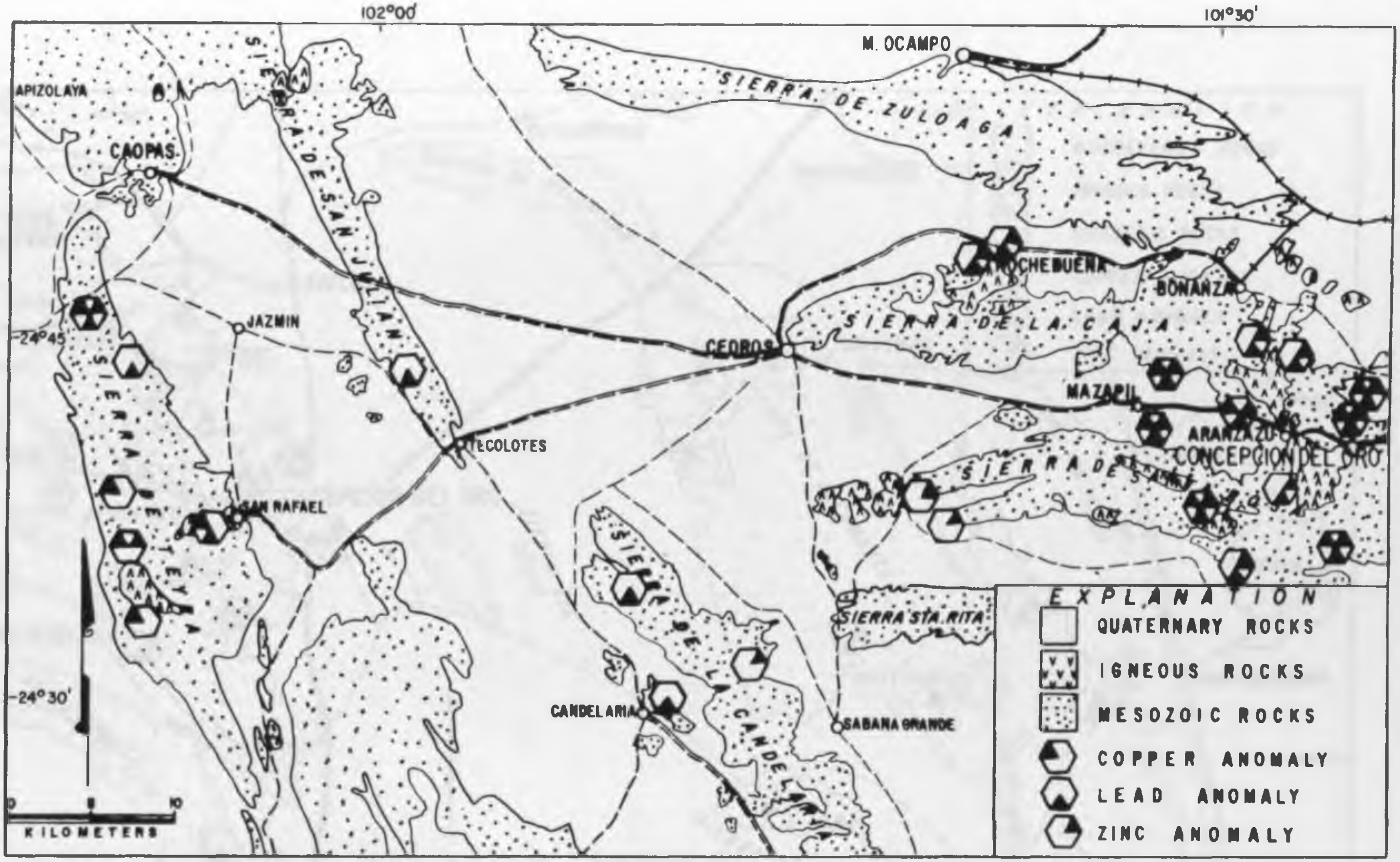

Fig. 15. Location of the geochemical anomalies found in the western portion of the study area

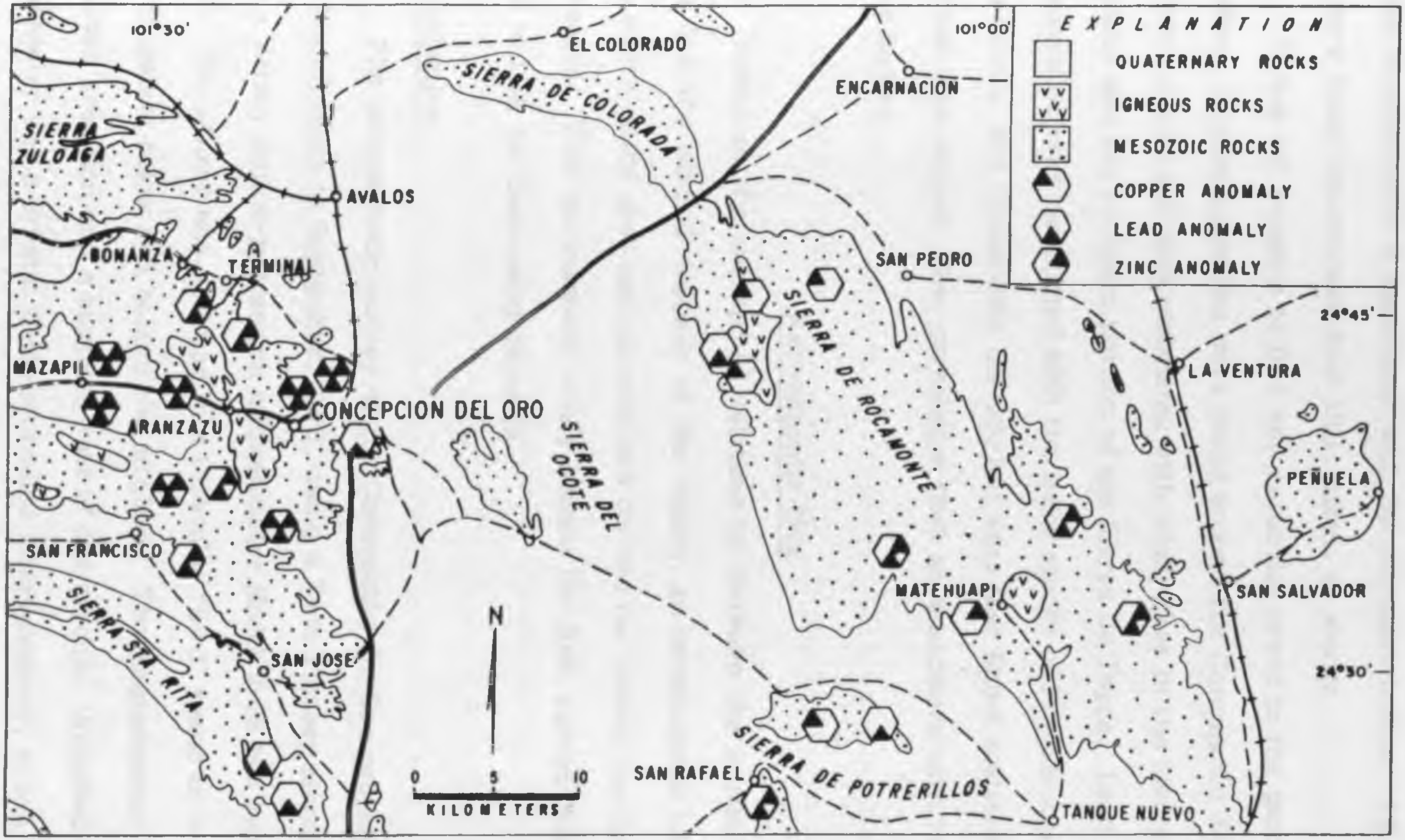

Fig. 16. Location of the geochemical anomalies found in the eastern portion of the study area

The main result of the geochemical survey was the confirmation that the mineralization is associated with the intrusive bodies. All anomalies were found downstream from sills, dikes, or stocks.

It was not possible to find any particular trend in the geochemical anomalies. Copper anomalies were found around the Concepción del Oro and Teyra stocks and also associated with small dikes in the Sierra de Potrerillos and the northern portion of the Sierra de Teyra. Lead and zinc anomalies were associated with the major stocks of Providencia, Noche Buena, and Concepción del Oro but were also found scattered over the whole area without other correlation than an association with the intrusive bodies.

Aeromagnetic Map

Based on the anticipated relationship between the intrusive bodies and the mineral deposits of the region, an aeromagnetic survey of the entire study area was planned and carried out during the first field season. This aeromagnetic study became the first survey done in Mexico to look for base-metal deposits.

Data Collection

The aeromagnetic survey of the Concepción del Oro project was flown from August to September, 1973, using a Twin Pioneer aircraft in which a Varian proton-precession magnetometer Model V-85 has been installed. The sensor was enclosed in a Fiberglas "bird" towed on a coaxial cable 30 meters below and behind the airplane. The magnetometer had a one-gamma precision and a sampling rate of one second. Attached to the magnetometer was a crystal clock-controlled intervalometer, which provided a timing signal to both the location camera and the analog recorder. The analog output was displayed on a double-pen Hewlett-Packard recorder Model HP 7100B. The camera, a 35 mm Aeropath Model NU, was shock mounted on the floor of the aircraft.

The survey was made with a flight-line spacing of two kilometers over alluvial valleys and one kilometer over rock outcrops. All lines were flown at a constant barometric elevation of 10,000 feet (3,048 meters) above mean sea level. The average elevation of the valleys is 6,500 feet (1,981 meters) and the average elevation of the mountain ranges is approximately 8,000 feet (2,438 meters).

Navigation was accomplished from 1:25,000 photomosaics having marked flight paths. Flight lines were drawn in a magnetic north-south direction; the magnetic declination in the area is 8°40' E. Two lines perpendicular to the grid were flown to provide additional tie-line control, bringing all flight lines to the same level to facilitate contouring.

The diurnal variation of the magnetic field was recorded with a ground-based Varian proton-precession magnetometer Model M-50 coupled to a Hewlett-Packard Model 680 recorder. The magntometer had a sensitivity of one gamma and a sampling rate of one minute. The base station was installed at the La Pardita airstrip, and there is a record taken for every day of the aerial survey.

Data Processing

Because there was no digital recording unit on the plane, all data processing was done using the analog records. The data processing started in the field. After each flight the film of the tracking camera was developed and the location of the airplane during the survey marked on the 1:25,000-scale photomosaic. Wherever the deviation of the flight line exceeded the line spacing a new flight over that portion of the line was done. A package containing the analog magnetic records (airborne and base station), the 1:25,000-scale photomosaics with the position of the fiducials of the flight marked on them, and the position film was regularly sent to the central office in Mexico City.

When the data were received in the Analog Processing Office, the first step was to transfer the fiducial points to a photomosaic at the same scale as the final map, in this survey, a 1:50,000 scale. Additional fiducial points were sometimes picked out from the positioning film to obtain a better control of the line. Once the fiducial points on the flight line were properly marked on the photomosaic, a "working-strip" showing the exact location of the fiducials along the line was obtained and the fiducial locations were transferred to the maps. These maps contained the basic planimetric features of the area and had been previously made from the photomosaics.

Simulataneously the diurnal correction was obtained from the base-station record and was put on the airborne records as a variable datum line. With a transcriptor table manufactured by Aeroservice, the values of the magnetic record were placed on the working-strip at the proper contouring interval of 20 gammas. Finally, the magnetic values were transcribed from the working-strip to the map and the map was hand contoured.

A summarized flow chart (Fig. 17) shows the various steps taken in making the final aeromagnetic map. The total intensity aeromagnetic map of the Concepción del Oro area, reduced to a scale of 1:250,000, is shown on Figure 18 (in pocket).

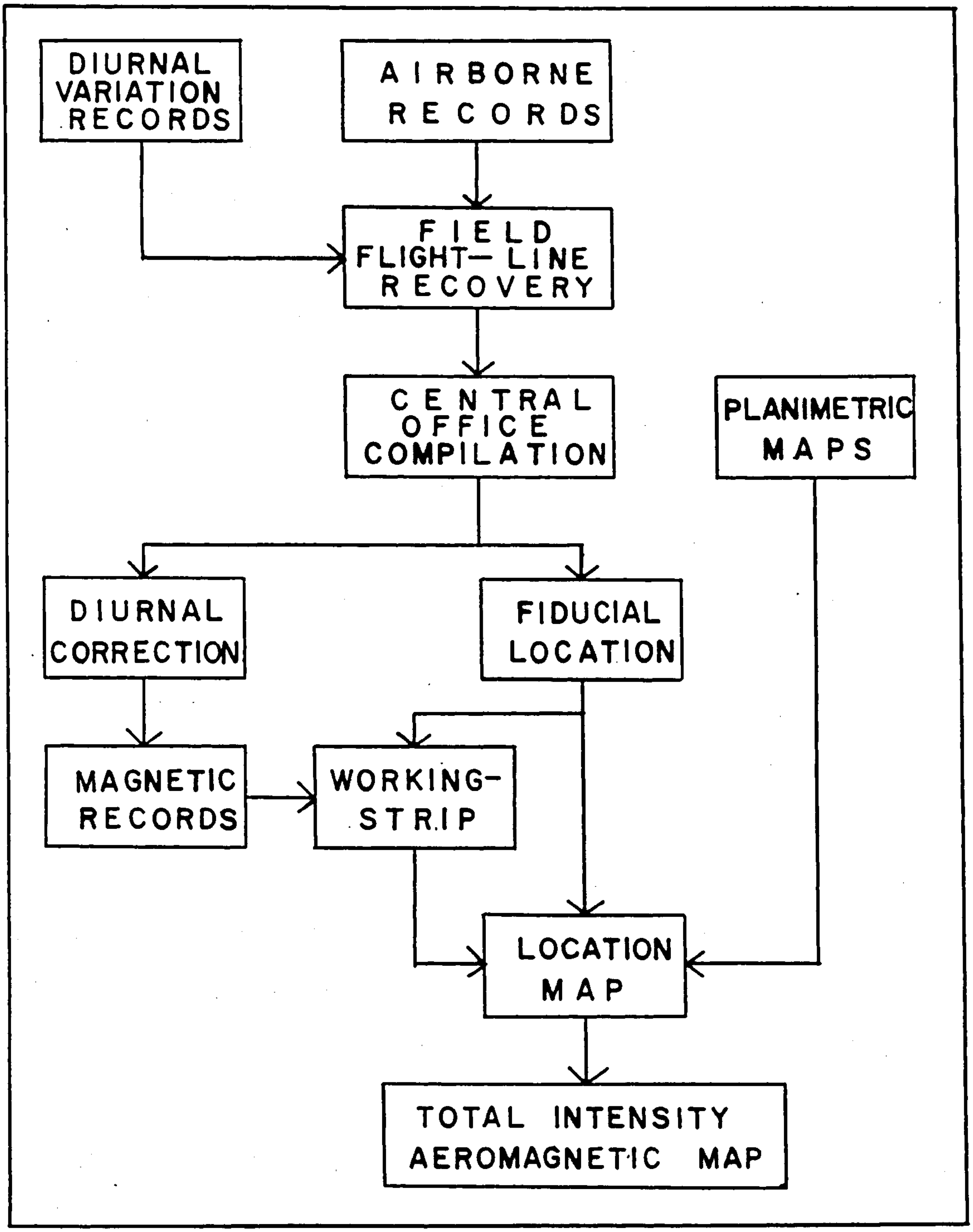

Fig. 17. Flow chart of procedure followed in constructing the the total intensity aeromagnetic map of the study area

<u>Data Analysis</u>

The inspection of the total intensity map shows the presence of several anomalies, mostly of the dipole type, on east-west-trending regional magnetic contours. By looking at the geologic map it is clear that all the stronger local anomalies correlated with the already known intrusive bodies.

An initial overview of the aeromagnetic map gives no indication of any concealed intrusive bodies in the study area. This is a discouraging result because it denies the possibilities of mineralization in new areas, assuming correlation between intrusive bodies and mineral deposits.

In general, the dipole magnetic anomalies have a close correlation with the outcrops of intrusive bodies with the exception of the anomaly located near the town of MelchorOcampo (lat 20°50' N., long 101°38' W.) where the magnetic anomaly apparently indicates that the outcrops of intrusive rocks are only an apophysis of a major intrusive body.

To obtain a better understanding of the magnetic anomalies the total intensity map was digitized and filtering techniques were applied to the data. The digitization was made on a one-kilometer grid. A total of 9,900 grid points were obtained.

The first step in this analysis was the construction of the residual magnetic map of the area. This was done by subtracting the International Geomagnetic Reference Field obtained from the grid values of total magnetic intensity IGRF-1965 (Fabiano and Peddie, 1969) shown in Figure 19 and adding 1,000 gammas to avoid negative values. The east-west-trending regional contours present in the original map disappear in the residual map leaving the dipole anomalies virtually unchanged.

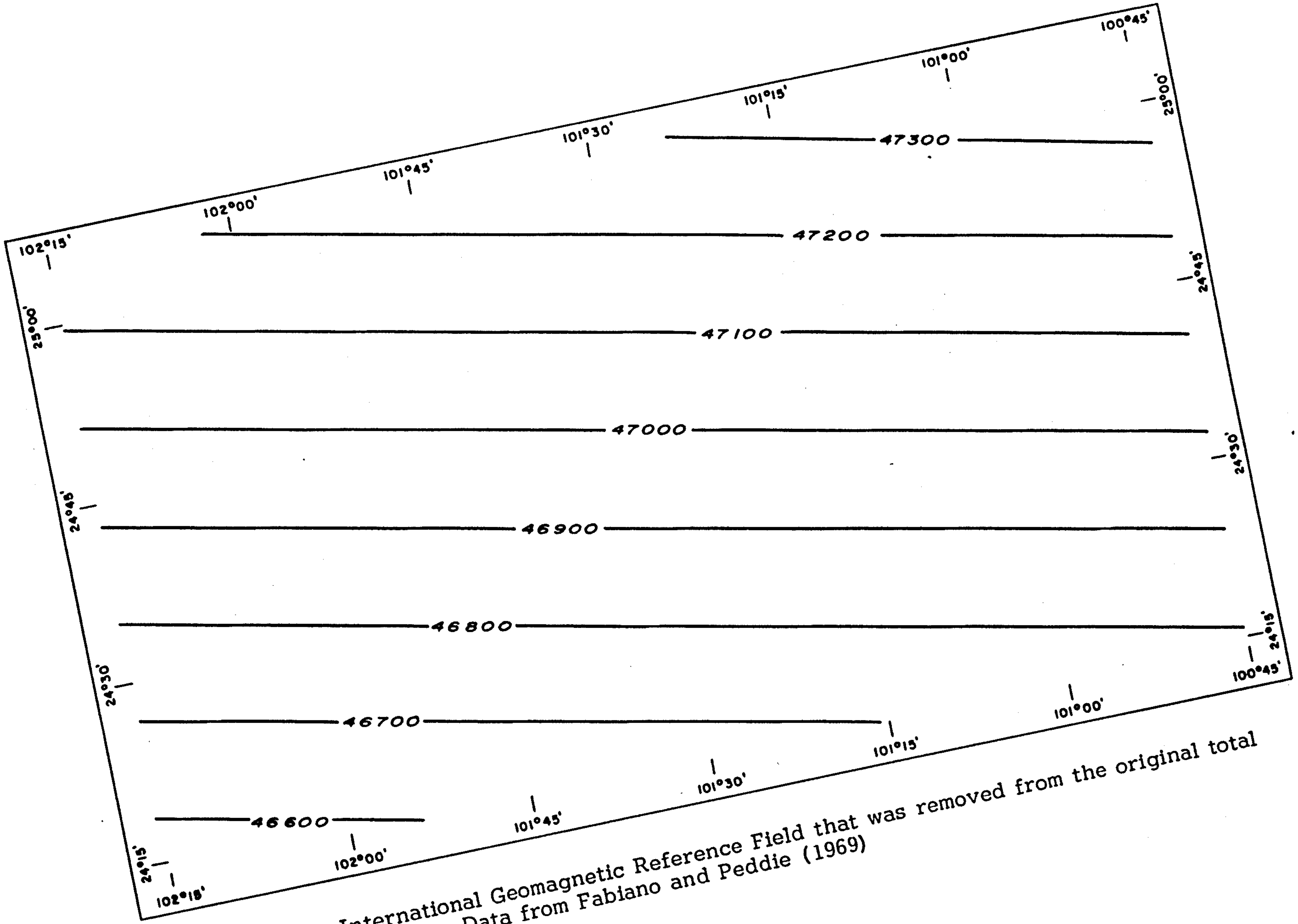

Fig. 19. International Geomagnetic Reference Field that was removed from the original total magnetic intensity data. -- Data from Fabiano and Peddie (1969)

The theory behind the upward and downward continuation of potential fields can be found in several references, for example, Grant and West (1965), but the first practical application of the continuation analysis to potential field data was given by Henderson (1960) and Oldham (1967). The method described by Oldham is based on the work done by Tomoda and Aki (1955) for the downward continuation of two-dimensional potential fields. Later on, Tsuboi, Oldham, and Waithman (1958) expanded it to include the three-dimensional cases.

Basically, the method is based on the approximation of a potential field by the sum of surfaces, each expressible in the form

$$Z = g_{ij}(\sin x)/x \cdot (\sin y)/x) \qquad (1)$$

where g_{ij} is a constant.

The center point of each of the surfaces given by equation (1) is located at points (x_i, y_j) on a uniform grid. The grid interval is scaled so as to be equivalent to π. Under these conditions

$$Z = g_{ij} \qquad \text{when } x \to 0,\ y \to 0$$

$$Z = 0 \qquad \text{when } x = \pi \text{ or } y = \pi$$

therefore, the sum of all such surfaces gives the potential field values at all the grid points, and hence is an approximation to the actual potential field. The potential field due to a single surface defined by equation (1) at any point (x,y) on a horizontal plane at a depth D below the surfaces is given by

$$g_D = g_{ij}\int_0^1\int_0^1 \cos(px)\cos(qy)\exp\left(\pi(p^2+q^2)^{\frac{1}{2}}\frac{D}{s}\right)dp\,dq \qquad (2)$$

If the points at which g_D is to be evaluated are uniformly spaced and distances are measured in terms of the grid interval (s), relation (2) takes the form

$$g_d(m,n) = g_{ij}\int_0^1\int_0^1 \cos(m\pi p)\cos(n\pi q)\exp\left(\pi(p^2+q^2)^{\frac{1}{2}}d\right)dp\,dq \qquad (3)$$

where d is the ratio of depth to the grid interval and m and n take on only integral values, including zero. By calculating g_d for various values of m and n, the potential field at the new level due to the surface in question can be determined completely. Since the values of g_{ij}, can be obtained from the field data, the problem is to compute a set of coefficients given by

$$f(m,n) = \int_0^1\int_0^1 m\pi p\ \cos(n\pi q)\exp\left(\pi(p^2+q^2)^{\frac{1}{2}}d\right)dp\,dq \qquad (4)$$

The double integral (equation 4) does not appear to be integrable analytically, thus numerical methods have to be used for its evaluation. Oldham (1967) evaluates the coefficients using Weddle's rule for numerical integration. He gives operators for d = ± 0.5s and d = ± 1.0s, each of size 31 x 31. The principal problem in using these coefficients, apart from the number of multiplications needed (1,961) for the calculation of the continued field at each grid point, is that no information can be obtained over a distance of 15 grid intervals adjacent to the boundary of the field map. This problem was partially solved by Mufti (1972) with the design of small-sized operators. He gives sets of coefficients of size 9 x 9 for upward continuation and coefficients of size 11 x 11 for downward continuation. The Mufti coefficients were applied to the Concepción del Oro residual total intensity map.

Normally, the upward continuation is used to simplify the appearance of magnetic maps by suppressing local features and accentuating broad features generally associated with deep structures. The downward continuation is used for the exactly opposite purpose, that is, to increase the resolution of the weak anomalies.

Mufti coefficients were used for the continuation of the Concepción del Oro residual total intensity map. The values were upward continued for both the d=-0.5s and d=-1.0s levels (s = 1 km) and downward continued to level d = 0.5s using a computer program that convolves the data with the appropriate coefficients. The data were also downward continued to the d = 1.0s level but the output data were almost useless because of the oscillations and noise produced when the level of continuation is located inside the body responsible for the anomaly. In some parts of the study area, as in the location known as Noche Buena stock, even the downward continuation to the d = 0.5s level shows some degree of oscillation. Figure 20 shows a north-south traverse through the Noche Buena stock. The strong oscillations of the d = 1.0s downward continuation, and the not-too-strong oscillations of the d = 0.5s downward continuation are shown in this figure. These oscillations are sometimes used to estimate the depth to concentrations of magnetic material because the oscillations appear as the level of the magnetic material is reached.

Another way to amplify the short-period components and to attenuate the long-period components contained in the residual total intensity data is known as the second vertical derivative. This method, originally introduced by Peters (1949), was used in conjunction with prismatic models to estimate depths to the basement from total magnetic intensity anomalies by Vacquier and others (1951). The mathematical theory is as follows.

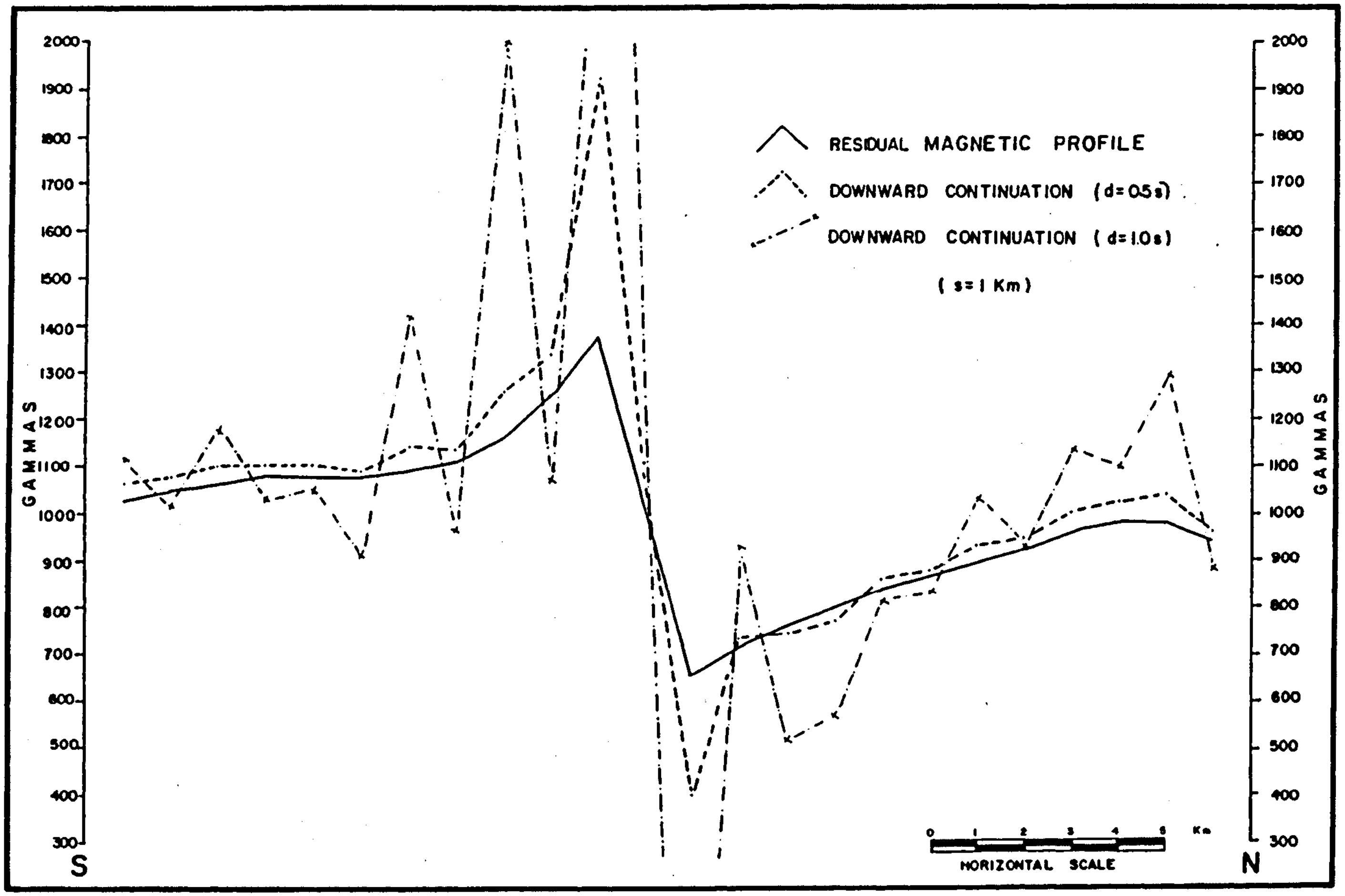

Fig. 20. Profile across the Noche Buena stock showing the oscillations of the downward continued data (d = 1.0s)

The anomaly in magnetic potential ΔV satisfies Laplace's equation at all points of free space, that is

$$\nabla^2(\Delta V) = 0 \tag{5}$$

The component of the total intensity anomaly ΔT in the direction of the earth's normal field is,

$$\Delta T = - \frac{\partial(\Delta V)}{\partial t} \tag{6}$$

where t is a unit vector in the direction of the earth's undisturbed field. Equation (6) is valid as long as $\Delta T \ll T_0$ is the magnitude of the total field. Combining both equations we have

$$\nabla^2(\Delta T) = \frac{\partial^2(\Delta T)}{\partial x^2} + \frac{\partial^2(\Delta T)}{\partial y^2} + \frac{\partial^2(\Delta T)}{\partial z^2} = 0 \tag{7}$$

Therefore ΔT satisfies Laplace's equation and admits to be analyzed by the methods of potential theory.

In practice the computation of second vertical derivatives is based on the average of the field at various radii from the station at which the second vertical derivative is evaluated. Henderson and Zietz (1967) used the formula

$$\frac{\partial^2 \Delta T}{\partial z^2} = \frac{2}{s^2}\left(3\overline{\Delta T_0} - 4\overline{\Delta T_1} + \overline{\Delta T_2}\right) \tag{8}$$

where ΔT_0 is the center value, ΔT_0 is the average value at a radius s, and ΔT_2 is the average value at a radius $(2s)^{\frac{1}{2}}$, while Elkins (1951) used a similar formula changing the radius of the outside average value to $(5s)^{\frac{1}{2}}$, and Rosenbach (1953) gave the formula

$$\frac{\partial^2 \Delta T}{\partial z^2} = \frac{1}{24s^2} (96\Delta T_0 - 18\overline{\Delta T_0} - \overline{\Delta T_0}) \qquad (9)$$

where the three ring averages, s, $(2s)^{\frac{1}{2}}$, and $(5s^{\frac{1}{2}}$, are used. In their paper Henderson and Zietz (1967) demonstrated that the second vertical derivative is similar to the residual obtained from a 9-point average, differing only in magnitude. Mesko (1966) compared the different second-derivative formulas on the basis that they are two-dimensional digital filtering operations equivalent to a fixed high-pass filter.

The second vertical derivative of the Concepción del Oro residual total intensity data were calculated using the Rosenbach (1953) coefficients convolved with the field data in a computer program. Figure 21 shows how the second vertical derivative method helped to separate the magnetic anomaly poruduced by the iron ore of the Sol y Luna mine from the anomaly produced by the Concención del Oro stock while Figure 22 shows how the upward continued data reflect basically the anomaly produced by the stock.

When the total intensity is measured in an area of medium magnetic inclination like Mexico (54° in the Concepción del Oro area) the center of the magnetic anomaly is not located right above the geometrical center of the causative body, and the anomalies change their pattern according to the strike even if the structure is the same. In the polar regions, however, for practical purposes the center of the positive anomaly can be assumed to be above the center of the magnetic body and the same magnetic body produces the same anomaly pattern irrespective of its strike. To make use of these advantages, a "pseudo-gravity" gradient map was calculated from the residual magnetic map.

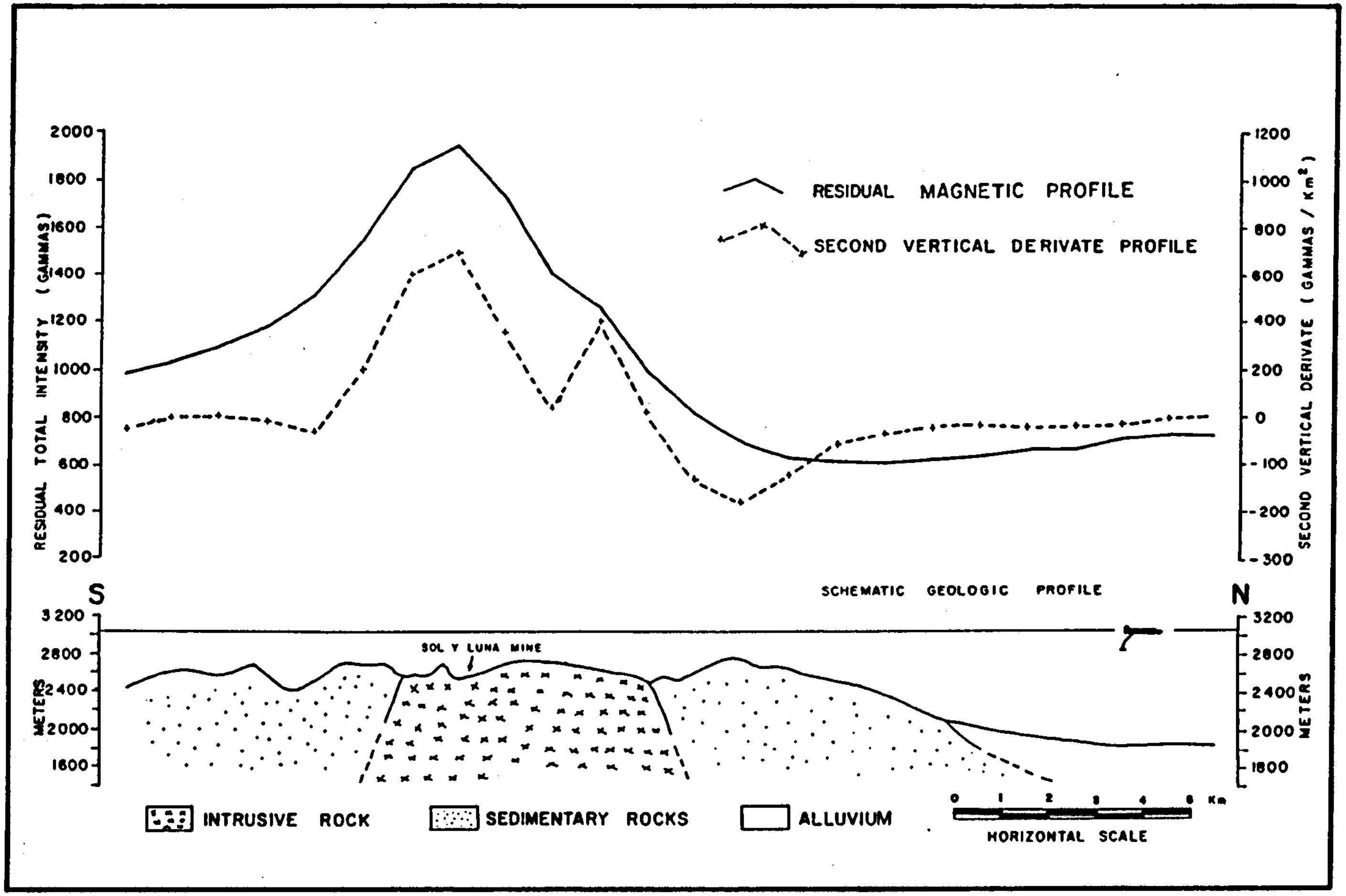

Fig. 21. Profile across the Sol y Luna mine and the Concepción del Oro stock showing the separation of the magnetic anomalies obtained from the second vertical derivatives

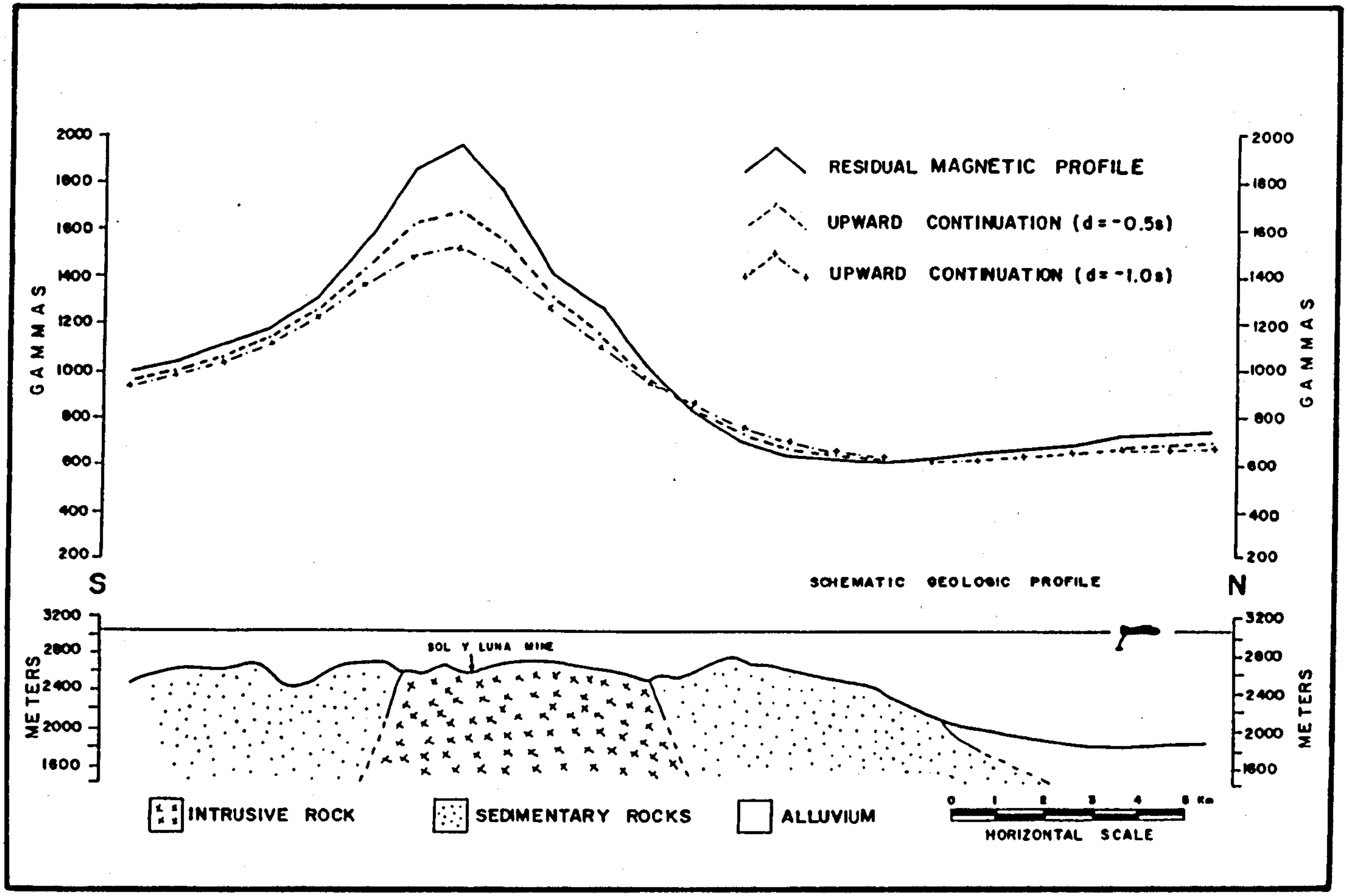

Fig. 22. Profile across the Sol y Luna mine and the Concepción del Oro stock showing the upward continued data obtained from the residual magnetic data

This method was developed by Baranov (1957) using the Poisson relation and defining a "pseudo-density" contrast. The mathematical basis can be found in Baranov's paper and in a simplified way in Grant and West (1965). Hasegawa (1967) designed a new method based on Baranov's work for the calculation of the pseudo-gravity gradient map. The hawegawa coefficients were used for the calculation of the pseudo-gravity gradient map of Concepción del Oro. The coefficients were convolved with the residual total intensity data using the same computer program used for the continuation and second vertical derivative analysis.

In general, the magnetic anomalies of the "pseudo-gravity" gradient map, compared with the residual magnetic map, moved toward the north and the gradients of the south flanks of the anomalies became as steep as those in the northern flanks. In Figure 23 the traverse across the Noche Buena stock is used to compare the residual magnetic profile with the "pseudo-gravity" gradient profile.

To illustrate the results obtained with the different types of filters applied to the data from the aeromagnetic survey of the Concepción del Oro area the following portions of each map are presented. Figure 24 is a sketch map of the geology around the Concepción del Oro stock. The stock is a granodiorite intrusion and the surrounding sedimentary rocks are limestones and shales corresponding to the Zuloaga limestone and La Caja formations of Jurassic age and to the Cretaceous sequence from the Taraises to the Caracol formations. At the Sol y Luna mine located 5 km soutwest of the town of Concepción del Oro there is a body of approximately 10 million tons of iron ore (Mapes V. and others, 1964) formed at the contct betwen the intrusions and the Cupido limestone. Section A-A'

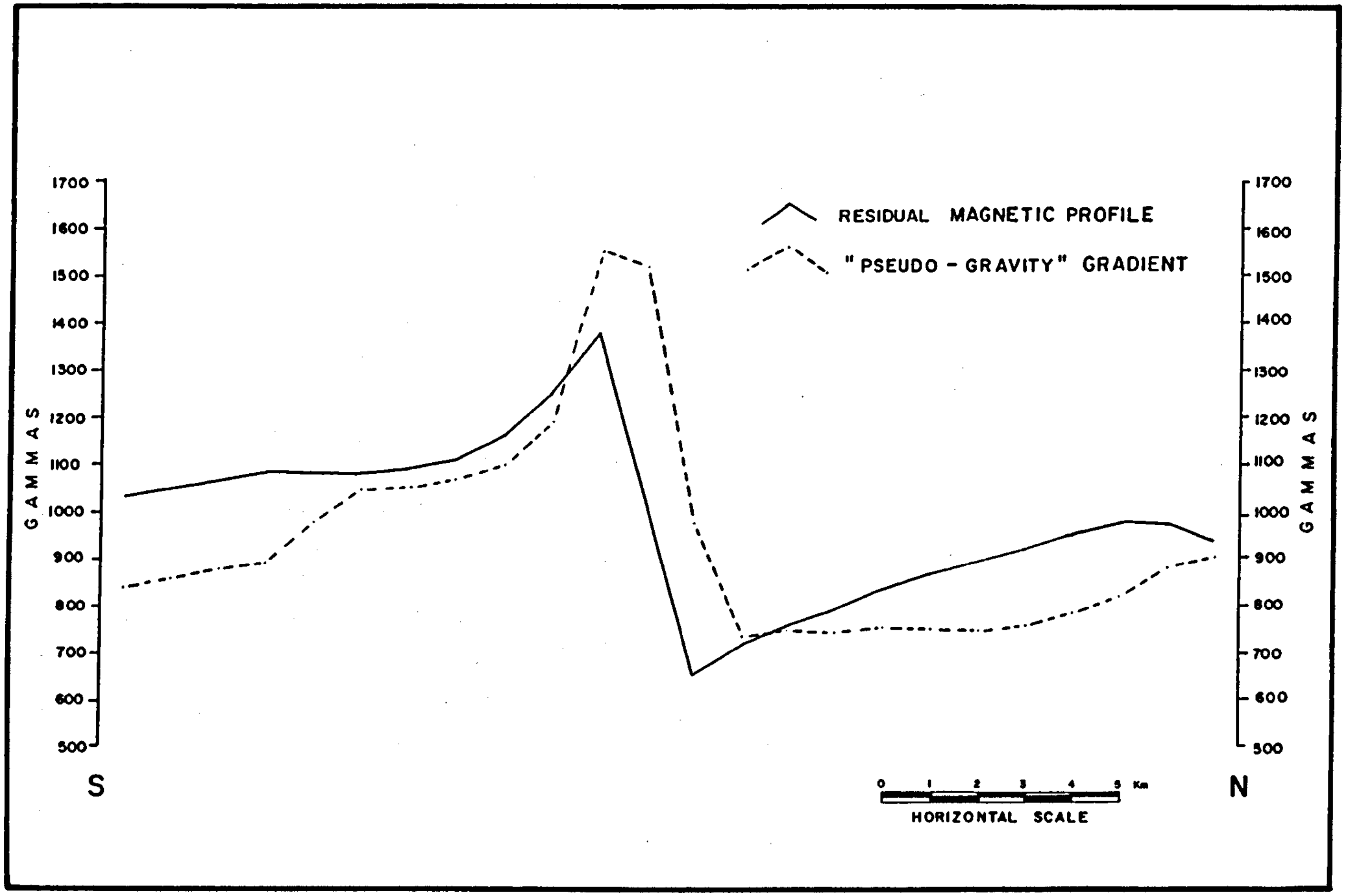

Fig. 23. Profile across the Noche Buena stock comparing the residual magnetic pseudo-gravity gradient profiles

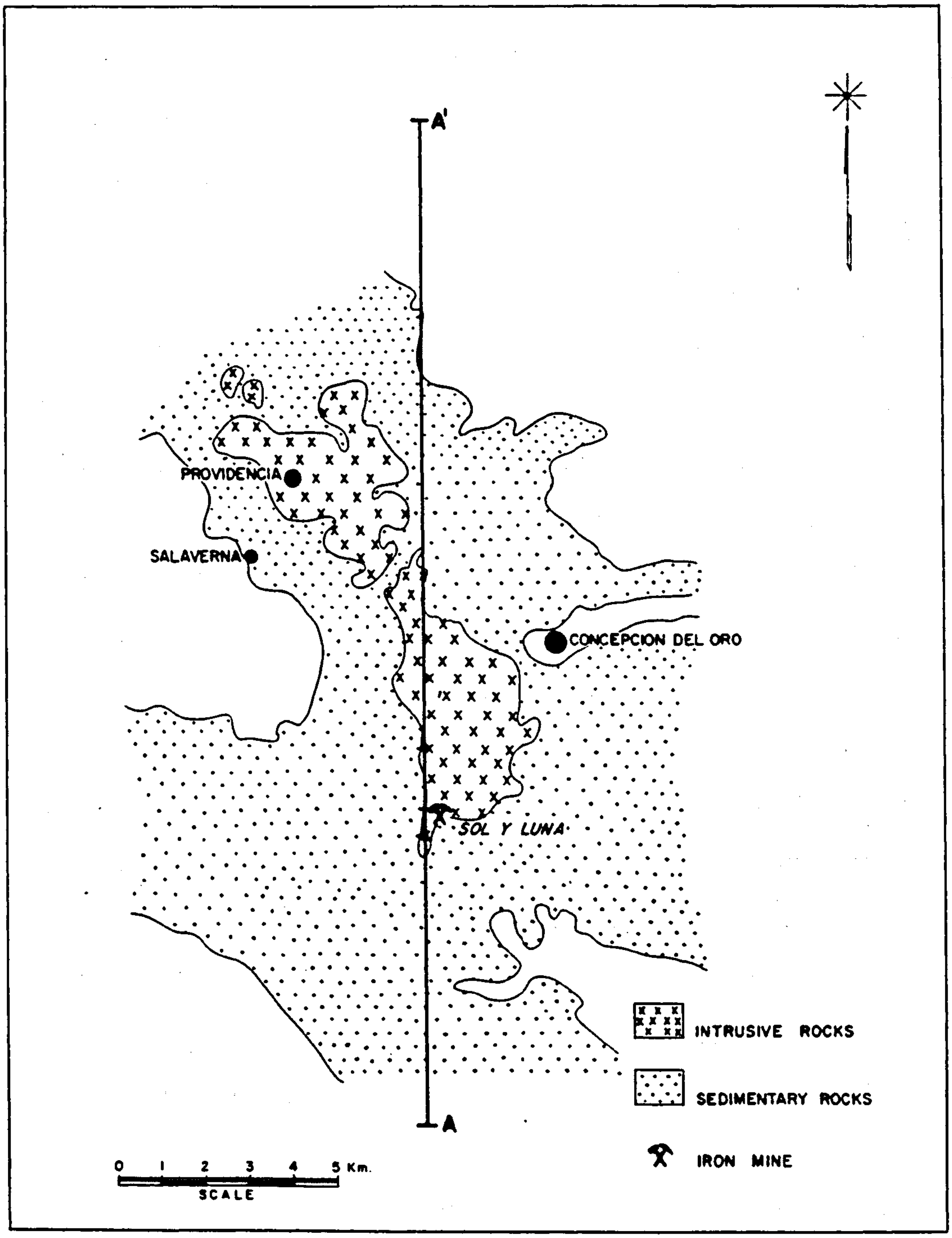

Fig. 24. Sketch map of the geology around the Concepción del Oro stock

was used to illustrate the profiles across the Concepción del Oro stock in Figures 21 and 22.

The residual magnetic map of the Concepción del Oro stock area is shown in Figure 25. A major dipole anomaly, with a high value of 1,946 gammas located almost over the Sol y Luna mine and with a low of 607 gammas located 7 km north of the high is the principal characteristic of the map. Near the town of Salverna another high of 1,293 gammas is found as an extension of the principal high giving the idea that both, the Concepción del Oro and the Providencia stocks are the same stock at depth. This idea is confirmed in the upward continuation maps Figures 26 and 27, in this last figure corresponding to the upward continuation level of d=-1.0s the amplitude of the dipole is only 900 gammas and the high near Salaverna is not as obvious. The opposite is present in Figure 28, which shows the downward continuation map. Here the major high shows values of more than 2,400 gammas with a low of less than 600 gammas. The high at Salaverna seems to be more independent with values of more than 1,600 gammas. Similar effect is shown in the second vertical derivative map, Figure 29; here the Salaverna high shows an elongate northwest trend that correlates with the general trend of the intrusions. The effect of the iron ore is present, and the anomaly of the Concepción del Oro stock is not clear. Figure 30 is the "pseudo-gravity" gradient map, and here the dipole anomaly almost disappears; two lows of less than 600 gammas appear both north and south of the high. The elongate high correlates pretty well with the outcrop of the intrusive body and the effect of the iron mineralization is not so noticeable.

Even when, as mentioned at the beginning of this section, the aeromagnetic survey fails to discover concealed intrusive bodies, the

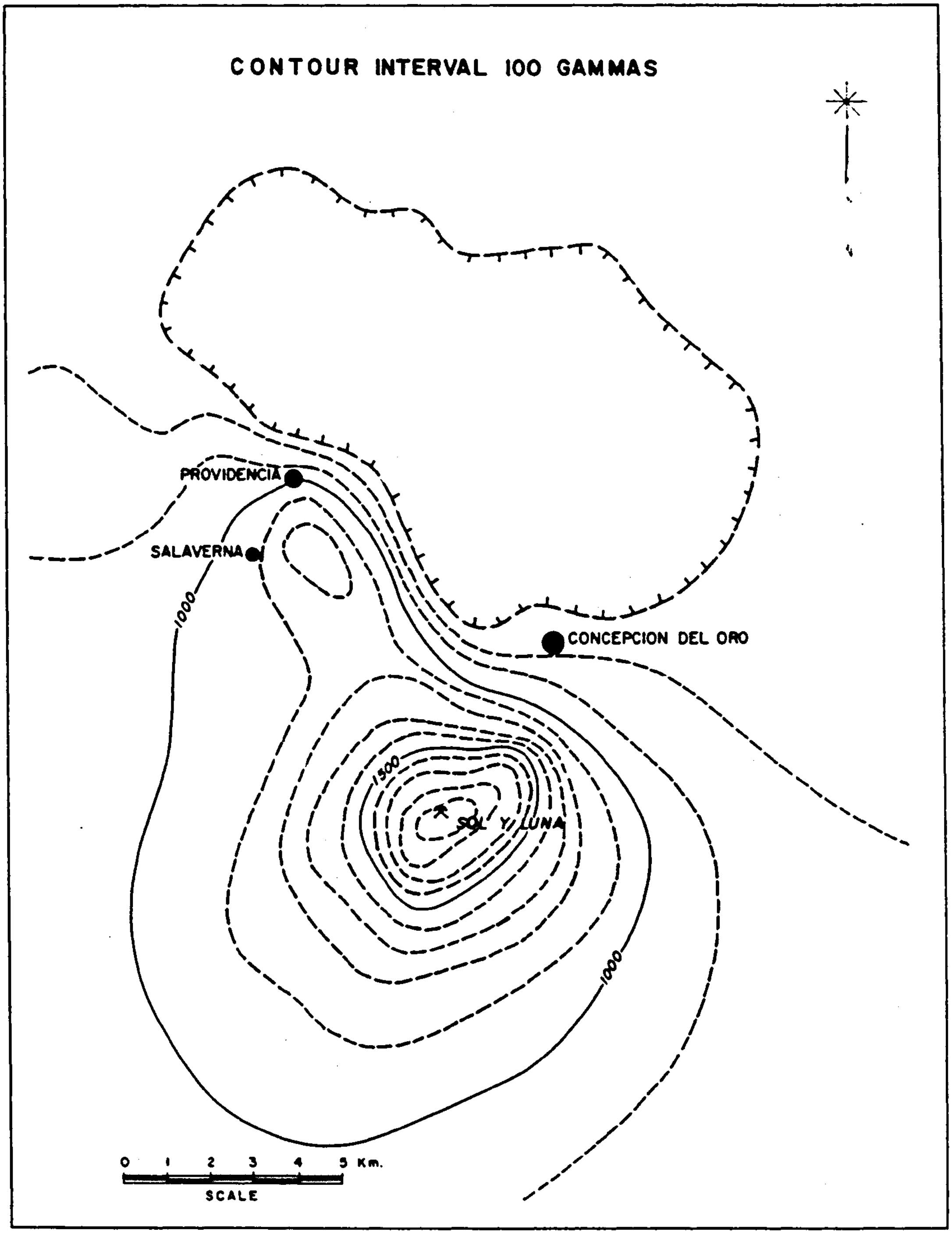

Fig. 25. Residual magnetic map of the Concepción del Oro stock area

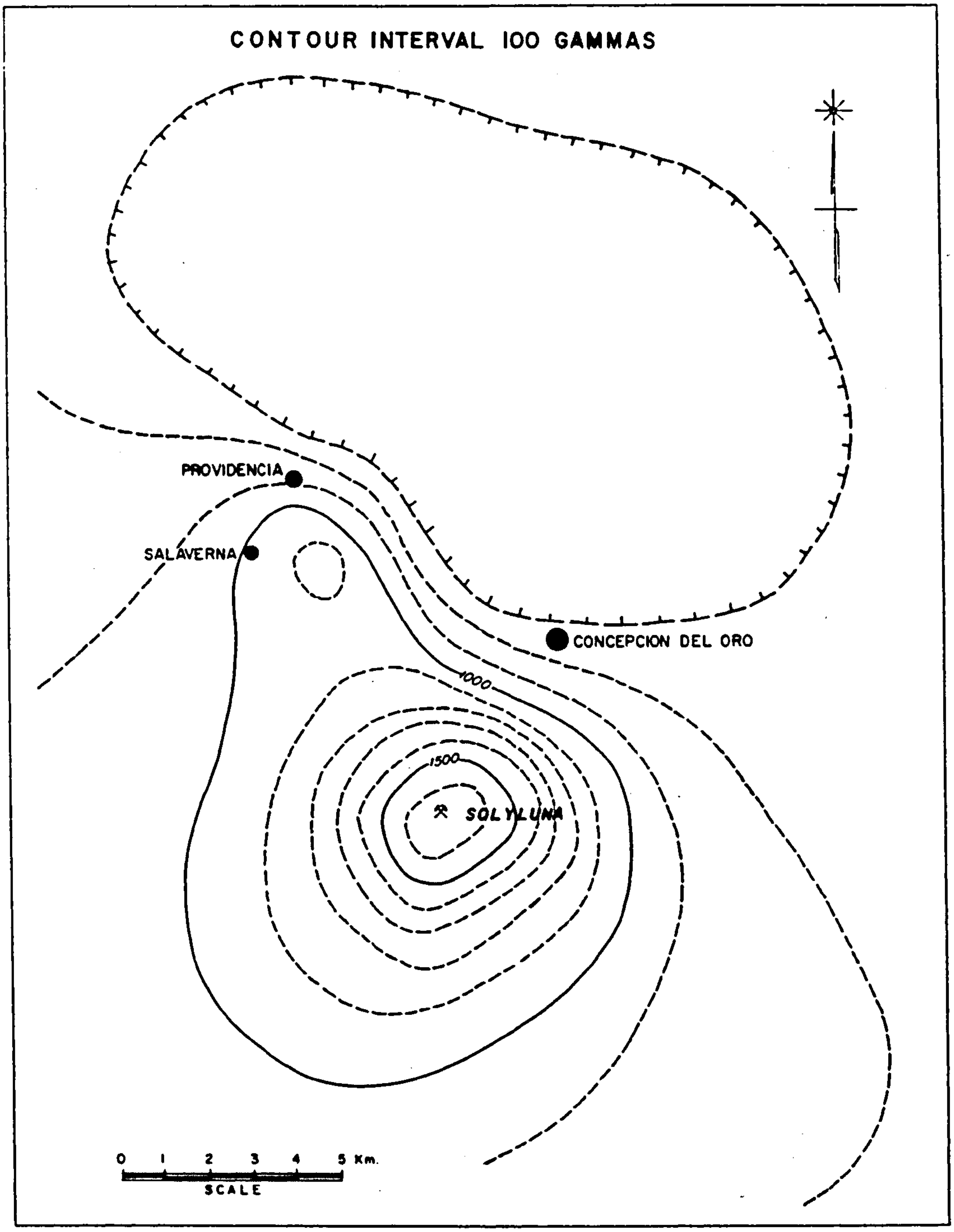

Fig. 26. Upward continuation map of the Concepción del Oro stock area obtained from the residual magnetic data, d = -0.5s

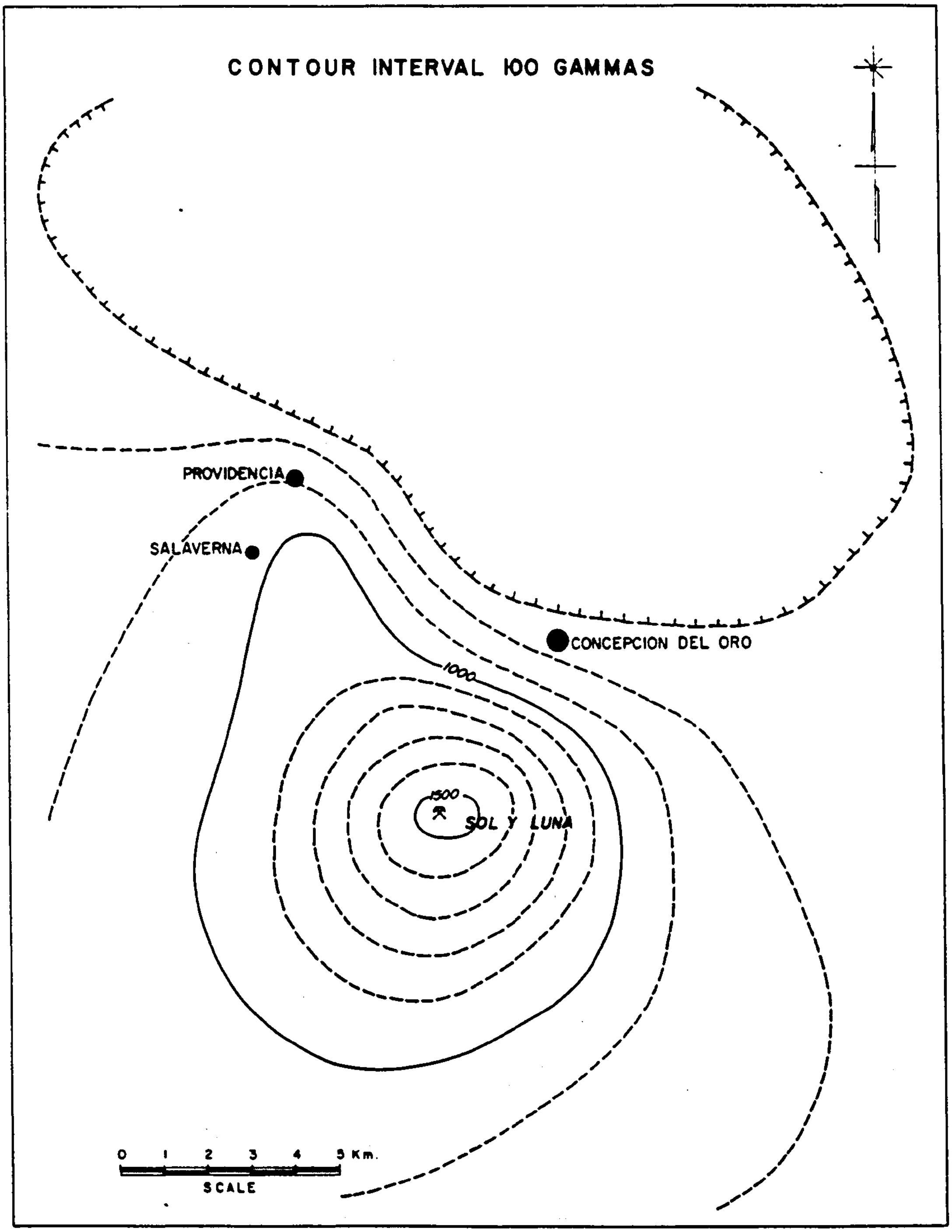

Fig. 27. Upward continuation map of the Concepción del Oro stock area obtained from the residual magnetic data, d = -1.0s

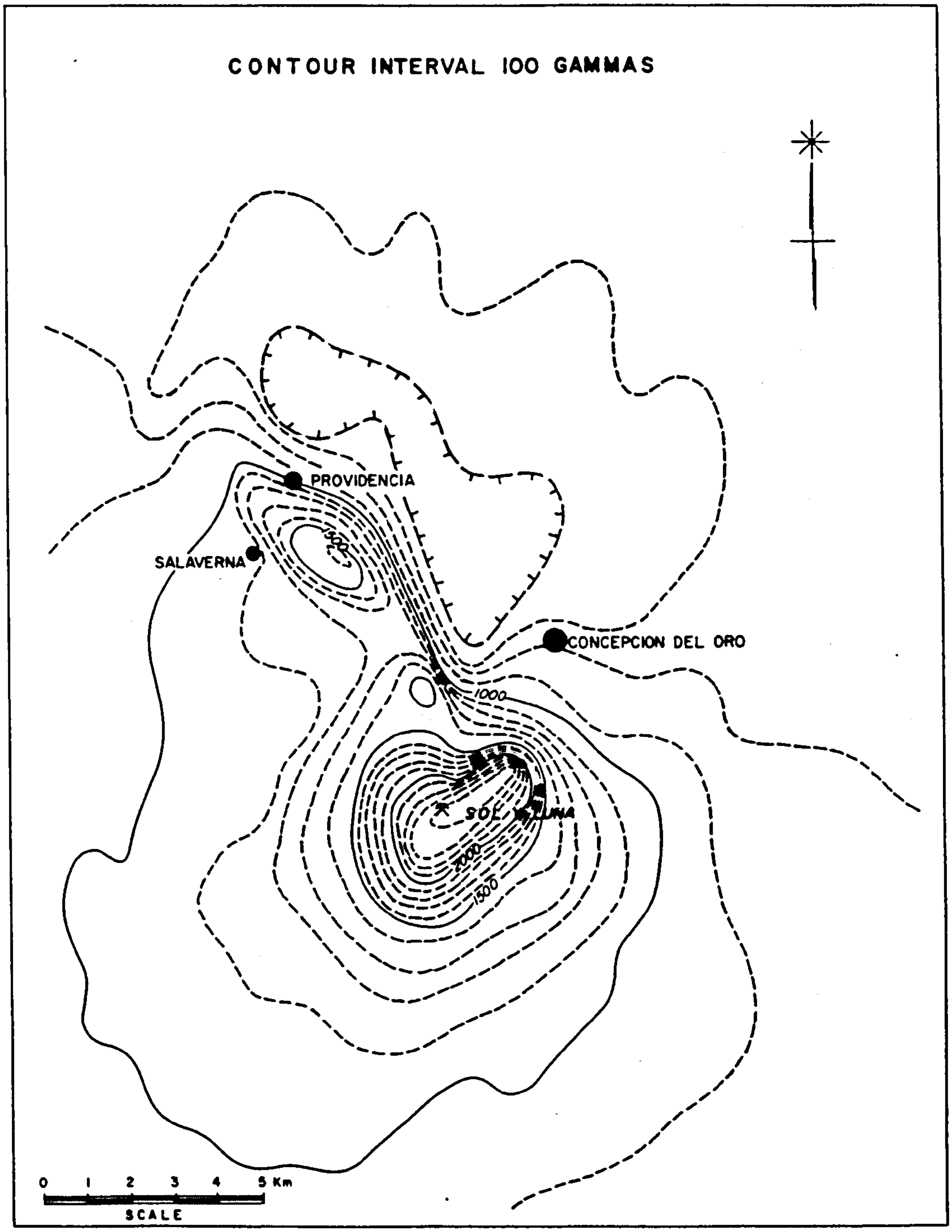

Fig. 28. Downward continuation map of the Concepción del Oro stock area obtained from the residual magnetic data, d = 0.5s

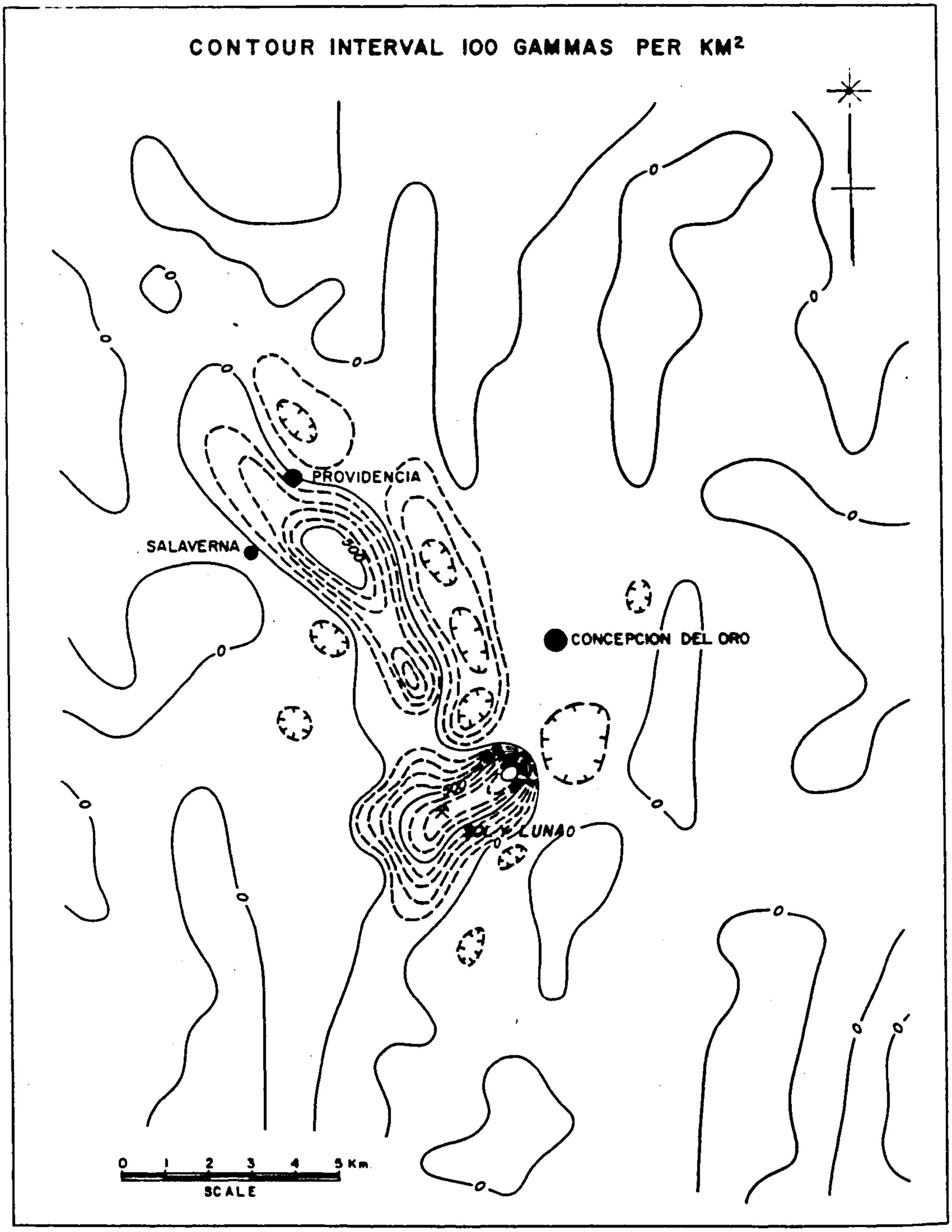

Fig. 29. Second vertical derivative map of the Concepción del Oro stock area obtained from the residual magnetic data

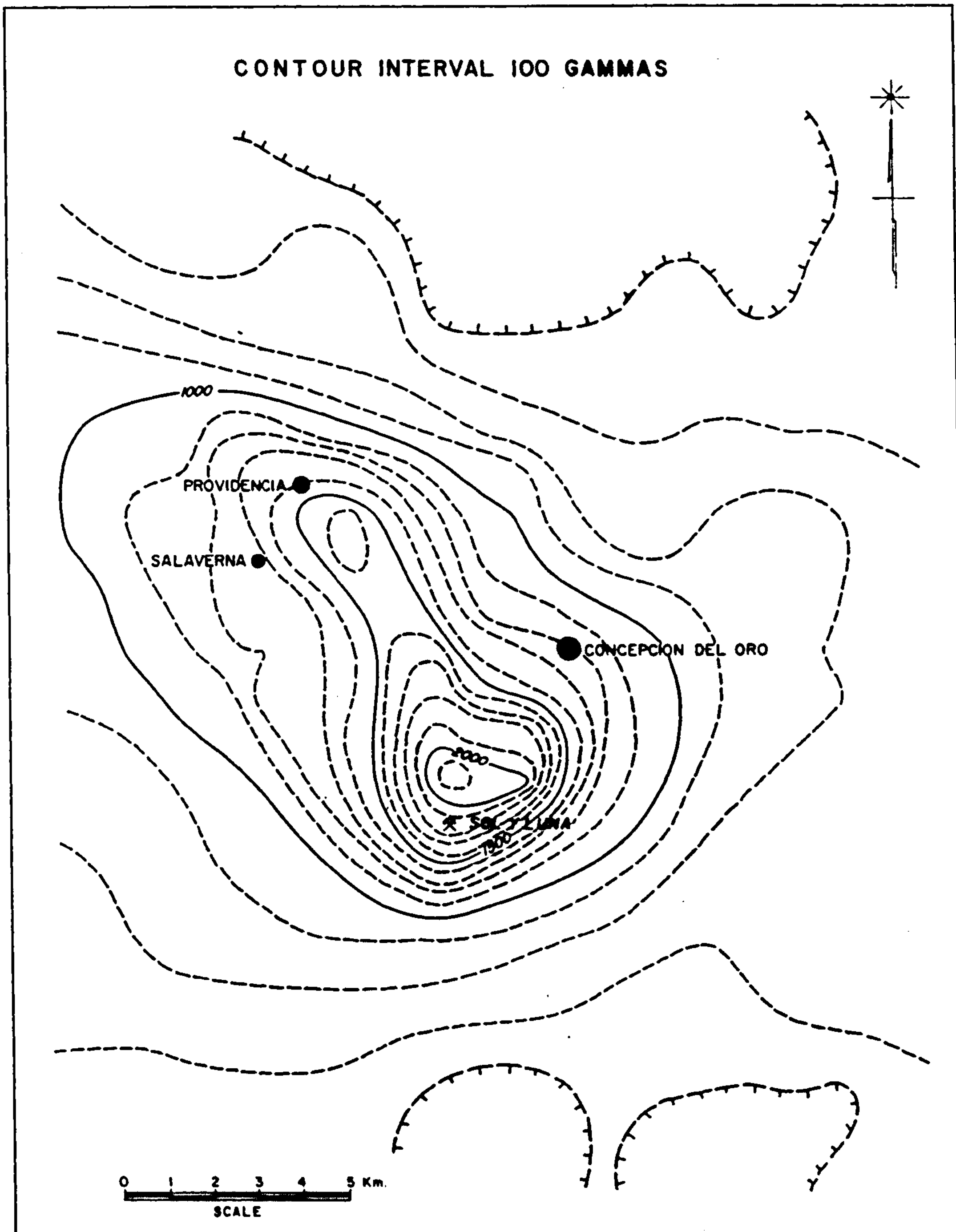

Fig. 30. Pseudo-gravity gradient map of the Concepción del Oro stock area obtained from the residual magnetic data

amount of information that can be extracted with a careful analysis of the six maps justifies the survey.

For the Concepción del Oro area, the aeromagnetic survey seems to be the only regional exploration technique that has produced the results needed to coordinate a detail exploration of many of the outcropping intrusive bodies found in the area.

DETAIL EXPLORATION

The detail exploration of the Concepción del Oro area was carried out not only based on the results obtained from the regional exploration but was also controlled by land ownership and, as mentioned in the introduction, by the necessity to increase the ore reserves in the immediate vicinity of the town of Concepción del Oro, where the mineral processing facilities are already installed.

Ten potential areas were chosen from the regional exploration as being suitable for detail exploration. From these areas, two were ruled out because the mineral rights were owned by different groups. Each of the remaining areas were ranked according to its potential possibilities and location. At present only the Concepción del Oro and San Rafael areas have had a complete detail exploration. All the other areas are under different stages of exploration.

The Concepción del Oro area was subdivided into eight target areas located around the Concepción del Oro stock and covering a total of 31.5 square kilometers. The results of the exploration of these areas can be found in the reports by Maldonado R. (1973) and Hernández M. (1975).

The San Rafael area is located northeast of the Pico de Teyra stock and covers an area of 10 square kilometers. The results of the exploration of this area can be found in the reports by Arriaga M. (1974), Ortíz S. (1976), and Hernández P. (1976).

Detail Geochemical Surveys

Although the regional geochemical samples were severely affected by contamination and therefore the results not as useful as expected, a detail geochemical survey was planned for all study areas. The detail surveys were carried out by collecting soil samples and rock chips where available, using the same stations as for the geophysical surveys. More than 5,000 samples were analyzed by atomic absorption methods for copper, lead, and zinc.

The analyses showed that most samples, especially the rock chip samples, were contamination free. The data for each area were normalized and statistically analyzed to define the anomalous areas. The data were also trend analyzed.

The highest anomalies of copper and zinc were found in oxidizing caps over either the intrusive bodies or at the contact zones between the intrusive and sedimentary rocks. It was also possible to identify a positive relationship between the geochemical anomalies and fracturing of the intrusive rocks. In particular, lead anomalies could be correlated with fractured areas in nonaltered intrusive rocks. More details can be found in the report by Arriaga M. (1974).

Detail Geophysical Surveys

The detail exploration with geophysical methods was planned on the basis of the geology of each area. In general, the areas were located to cover the contacts between the intrusive bodies and the sedimentary rocks. The traverses needed for the geophysical studies were perpendicular to the general strike of the sedimentary rocks. Generally, this strike is parallel to the strike of the contact between the intrusive and sedimentary rocks.

Magnetic Surveys

Ground magnetic surveys were planned to obtain a better definition of the contact zone between the intrusive and the sedimentary rocks. In the Concepción del Oro area 95 traverses totaling 130 kilometers were measured. The distance between the traverses was 200 meters, and observation stations were spaced 25 meters.

Askania vertical component magnetometers were used in the Concepción del Oro areas and McPhar proton-precession magnetometers (total field component) were used in the other areas. The diurnal variation was controlled by leaving one magnetometer fixed and recording the magnetic values each 5 minutes.

The results obtained from the magnetic survey were presented both as profiles along the traverses and as vertical component maps. The magnetic results were very useful for delineating the intrusive bodies wehre they were covered by alluvium.

Many areas showed small dipole anomalies over the intrusive rocks that can be correlated with a major content of disseminated magnetite in the intrusive rock or, more often, with the concentration of magnetite in fractures or along the contact between the intrusive body and the sedimentary rocks. The Sol y Luna iron body is perhaps the major example of a concentration of magnetite in a contact zone. This iron orebody contains almost 10 million tons with a grade of 47% iron (Mapes V. and others, 1964). A N. 30° W. profile across the Sol y Luna iron orebody showed a vertical magnetic anomaly of over 5,000 gammas (Figure 31).

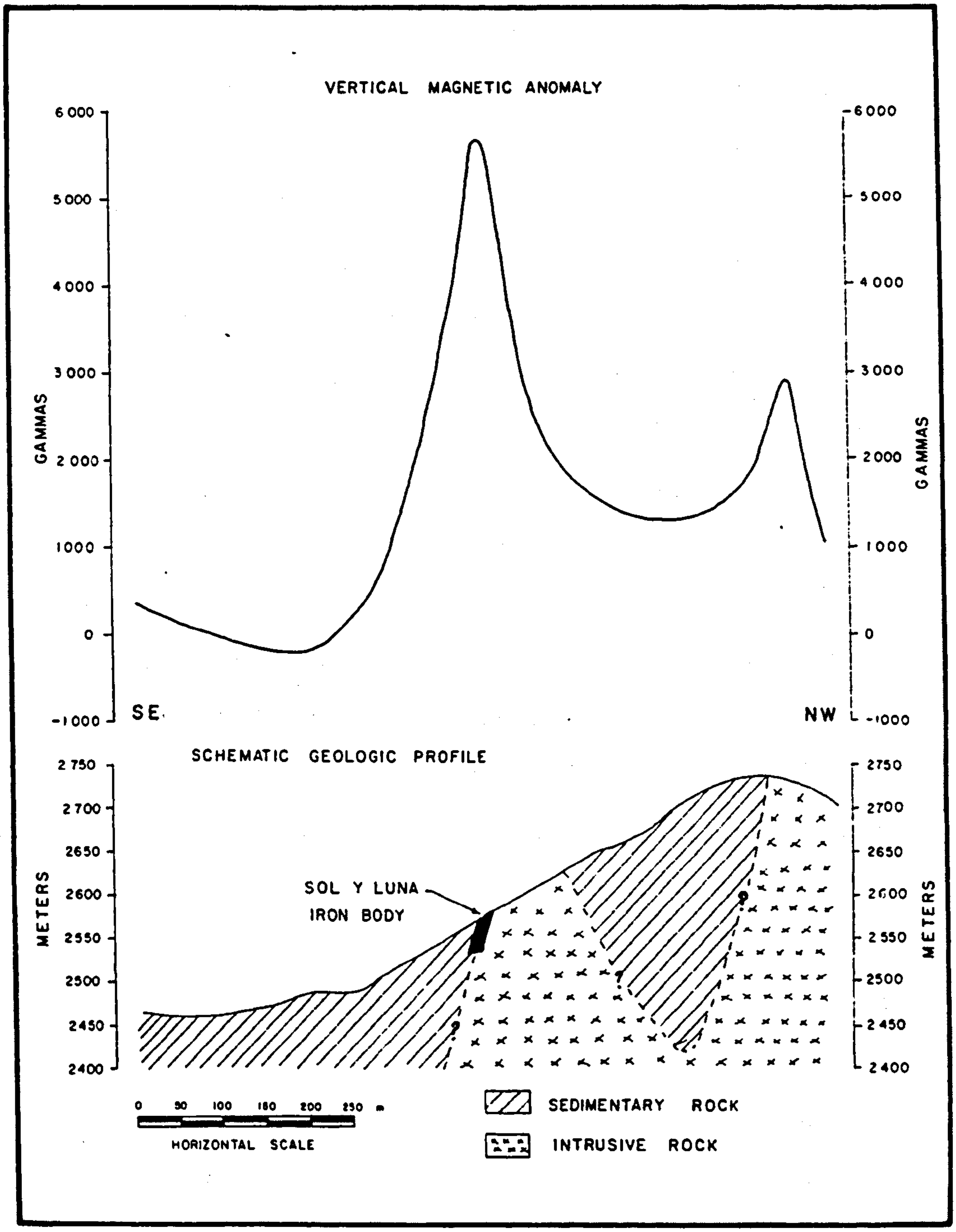

Fig. 31. Profile across the Sol y Luna mine showing the vertical magnetic anomaly produced by the iron body

Gravity Surveys

In an area like the Concepción del Oro area with sharp relief the application of gravity surveys for mining exploration can be rather limited. Large terrain corrections and relatively low density contrasts became significant factors.

A test survey was carried out using a Sharpe gravity meter with an estimated precision better than 0.05 milligals. The survey was located in Area II in which the Concepción del Oro stock is in contact with sedimentary rocks. A 10-meter grid was carefully located and leveled. A total of 201 stations were measured and the data were corrected following normal procedures. The density used for the calculations was 2.4 g/cm^2. The terrain correction was calculated using a template and the values given by Bible (1962).

The Bouguer gravity map of Area II shows a small anomaly (0.24 milligals) of semicircular shape over the sedimentary rocks. Even where this anomaly correlates with the induced-polarization anomaly obtained in the same area it is not possible to determine the origin of the anomaly because of the lack of precision of the terrain correction. The values of the terrain correction (around 1.60 milligals) were estimated to have a precision of approximately ± 0.15 milligals due to the topographic maps used in the estimation of the terrain correction.

The close spacing between the stations was used trying to avoid the terrain correction problem, but a positive conclusion will have to wait until the drill holes proposed in the area are completed.

Induced-polarization Surveys

A common characteristic of all the different types of mineral deposits found in the Concepción del Oro area is that there is some disseminated mineralization around them. This is particularly true where the mineralized bodies are found in the contact between the intrusive and the sedimentary rocks. Because of this and the mineralogical composition of the ore bodies, the induced-polarization surveys seem to be the most appropriate geophysical method to use in the detail exploration of the area.

Induced-polarization (IP) surveys were carried out in all the detail exploration area and totaled 223 kilometers of profiles. Two kinds of equipment were used: a Scintrex Mark V transmitter and receiver in the early stages of the exploration and a more powerful and modern Scintrex Mark VII transmitter and a Scintrex IPR-8 receiver for approximately 80 percent of all the measurements.

Both kinds of equipment work in the time domain. The Mark VII transmitter has a power of 15 kW and was powered by a four-cylinder Volkswagen engine. The IPR-8 receiver provides a reading of the decay curve using 1, 3, or 6 slices. The center slice of the mode 3 is reasonably close to the measurements made by any receiver of the "Newmont-type." The first and last slices measured on this mode are used for a rapid check of the curve shape.

In the Concepción del Oro surveys the transmitter and receiver timings were 2 seconds and the mode 3 readings were used.

Because the readings are made in time domain the effect of electromagnetic coupling is not as important as in the frequency domain

Orellana, 1974). The measurements were taken using a three array, a pole-dipole array in which the distance between the three electrodes is kept constant and the fourth electrode is located at a distance of more than five times the distance between the other electrodes. The use of this array was classified by Sumner (1976) as being a good reconnaissance array with a fairly good resolution, good signal-to-noise ratio, good electromagnetic coupling rejection, and fair survey speed. The disadvantages are that it is asymmetrical and it needs relatively more wire.

Each profile was measured using three different electrode spacings (a = 50, 100, and 200 meters) to permit three different levels of observation. The results were both in the form of contour maps (one for each electrode spacing) and as pseudo-sections, a not very conventional form for time-domain data (Figure 32). In general, the values obtained with both the resistivity and IP surveys can be correlated with the different geologic formations found in the exploration areas.

Resistivity values of more than 1,000 ohm-meters are related to the massive, thick-bedded limestones found in the Zuloaga and Cupido formations and also in areas where the thin-bedded limestones of the other sedimentary formations have been highly metamorphosed and the limestones are found as marble. Values of more than 30,000 ohm-meters were very common.

Resistivity values between 250 and 500 ohm-meters were found in areas where the thin-bedded limestones of the La Caja, Taraises, and Cupido formations are not metamorphosed. Similar values, but generally between 250 and 500 ohm-meters, were found in areas where the granodiorite intrusive bodies are not altered.

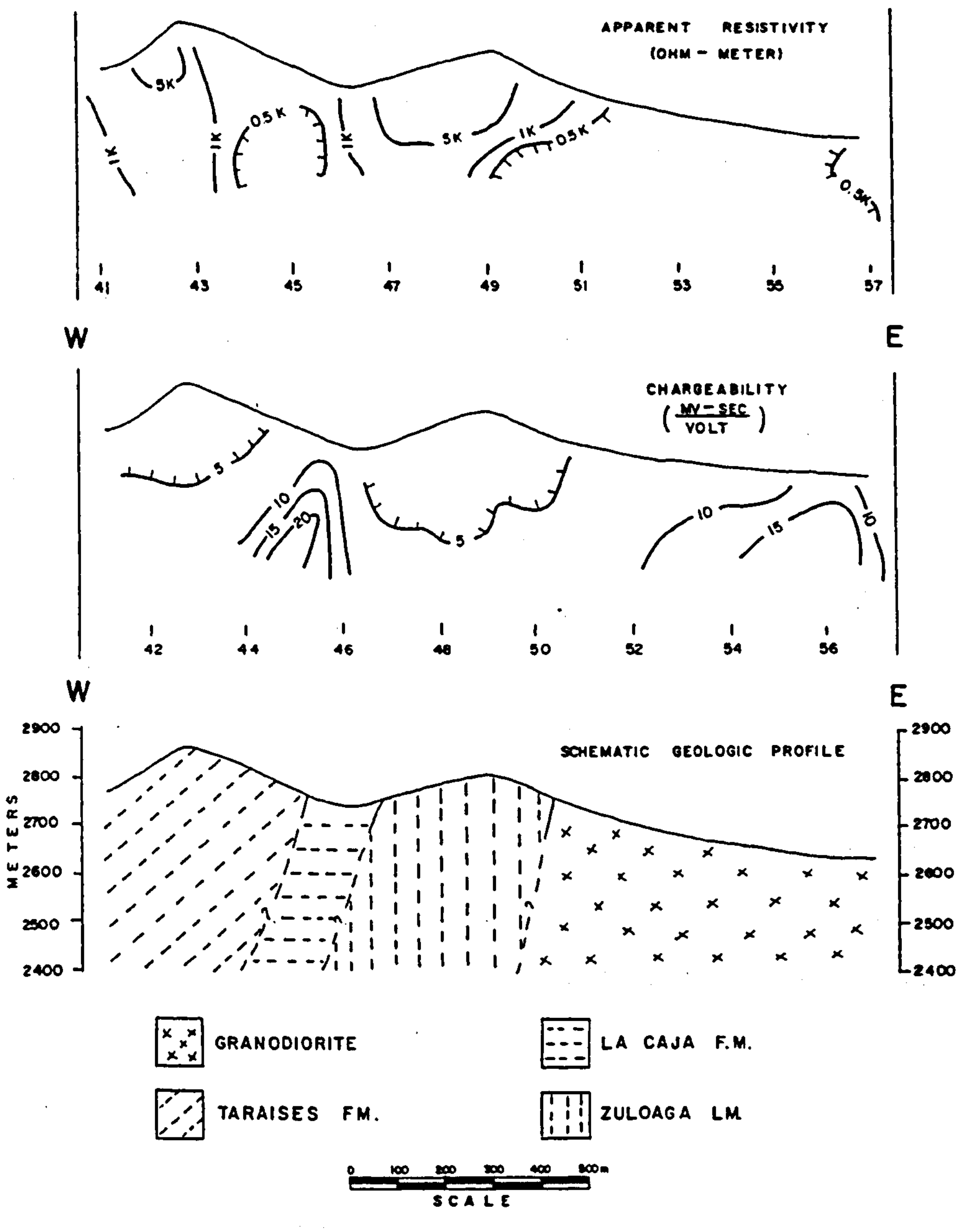

Fig. 32. Chargeability and resistivity pseudo-sections of line 30 N., Area II, Concepción del Oro project

between 250 and 500 ohm-meters were found in areas where the granodiorite intrusive rocks are not altered.

Resistivity values of less than 250 ohm-meters were considered as resistivity anomalies. These values were found in areas where the granodiorite showed fracturing and different degrees of alteration; and sometimes in areas of sedimentary rocks that did not show any indication of alteration. These areas are considered as the most attractive targets from the resistivity point of view.

Chargeability values of less than 5 mV-s/V were found that correlate with the granodiorite and with areas of metamorphosed Zuloaga limestones. Chargeability values between 5 and 20 mV-s/V were measured in areas where the sedimentary rocks of the La Caja, Taraises, and Cupido formations are present. The values of chargeability seem to decrease as the sedimentary rocks become more metamorphosed. Values in this range can also be found in the Zuloaga limestones if they are not metamorphosed.

Chargeability values of more than 20 mV-s/V were considered as chargeability anomalies. As with the resistivity anomalies, these anomalies were also found in areas where the granodiorite is highly fractured and altered and in areas of sedimentary rocks with sometimes no indication of alteration.

The prospect area known as Area II, located approximately 5 kilometers west of the town of Concepción del Oro near the town of Aranzazu, is used to illustrate the results obtained with the IP and resistivity surveys. Figure 33 is a simplified geologic map of Area II showing the distribtuion of the different rock units found in the area. It is

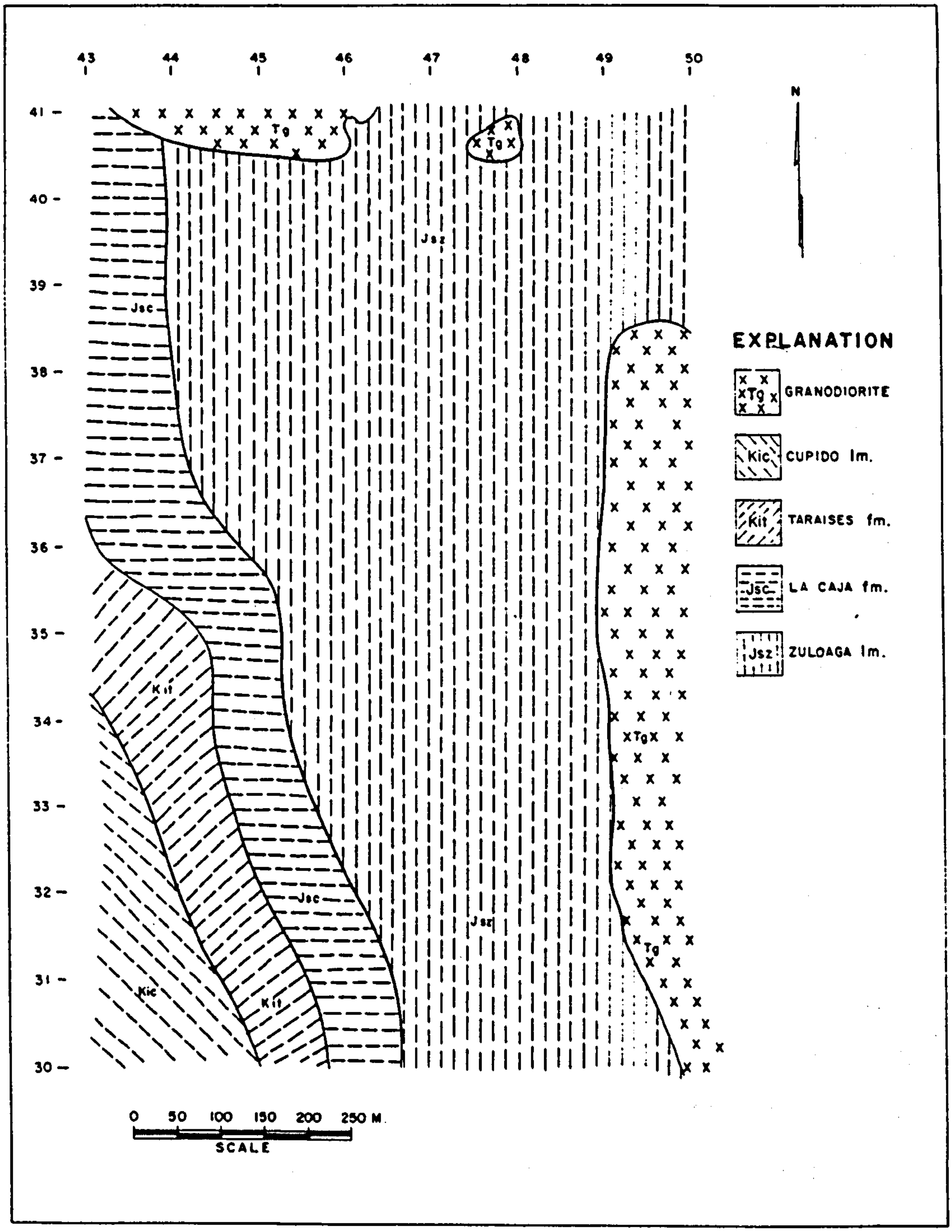

Fig. 33. Simplified geologic map of Area II, Concepción del Oro project

presented to illustrate the correlation between the geology and this geophysical data.

The resistivity values obtained with an electrode spacing of 50 meters are shown in Figure 34. Values of more than 1,000 ohm-meters were measured over the Zuoaga limestone, while values of less than 100 ohm-meters are located over the La Caja and Taraises formations. High resistivity values reaching more than 30,000 ohm-meters are located in the central portion of the Zuloaga limestone if a 100-meter electrode spacing is used (Figure 35). If the 200-meter electrode spacing is used, the high resistivity values are displaced toward the west, following the dip of the Zuloaga limestone, and a zone with values of less than 1,000 ohm-meters is found between lines 31 and 35. The values of less than 100 ohm-meters are found with the three electrode spacings correlating with a bend in the strike of the La Caja and Taraises formations. The resistivity values obtained with the 200-meter electrode spacing are shown in Figure 36.

The chargeability values obtained with the three electrode spacings are presented in Figures 37 to 39. Values of less than 5 mV-s/V are found correlating with the intrusive rocks and portions of the Zuloaga limestones that are metamorphosed, while values between 5 and 20 mV-s/V correlated with the La Caja formation increasing in size as the electrode spacing increases. The anomaly located between lines 31 and 33 (electrode spacing, a = 200 meters) shown in Figure 39 correlates with the resistivity anomaly found with the same electrode spacing. Because it is located relatively near the underground works of the Gorro Frigio and

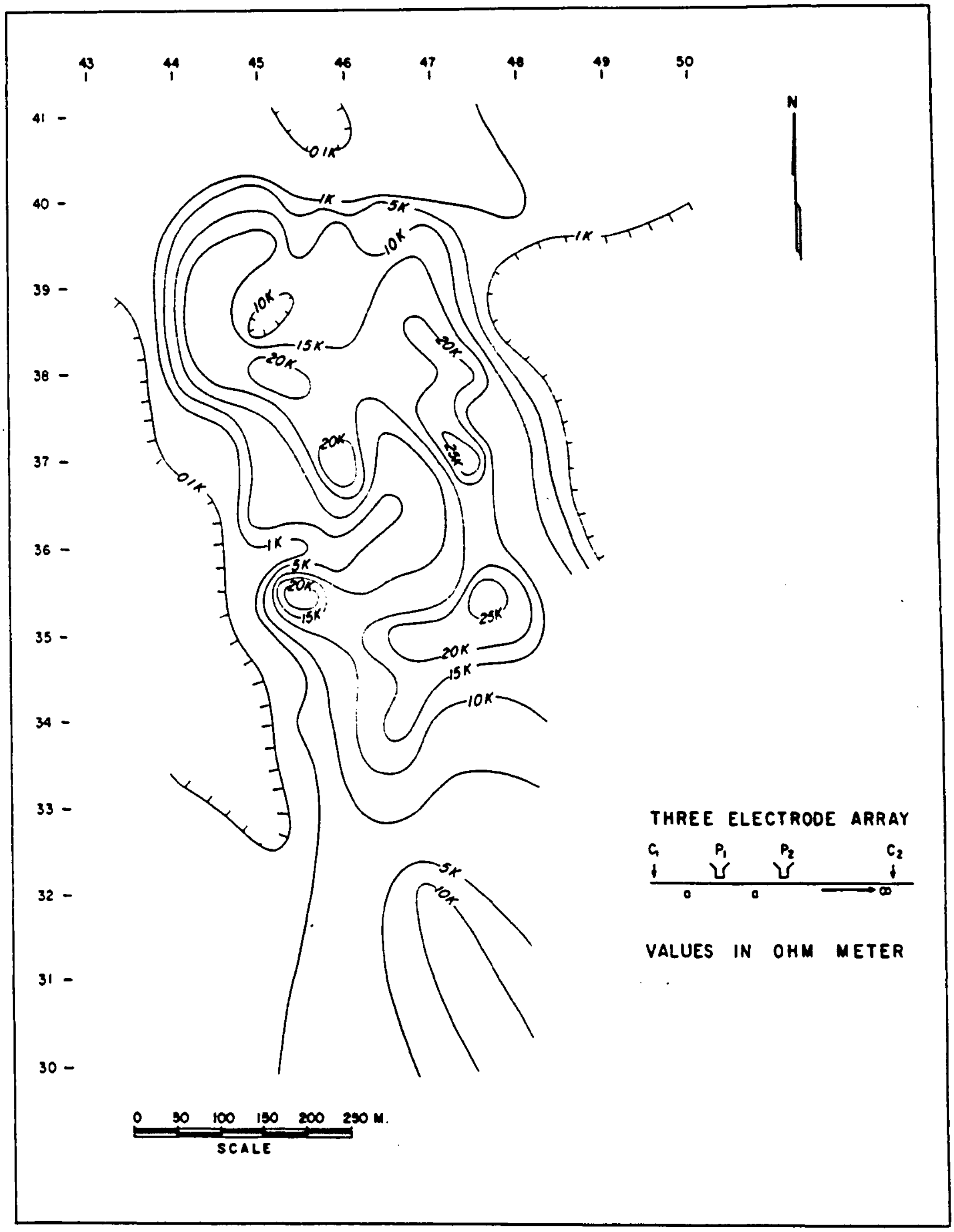

Fig. 34. Resistivity plan of Area II, Concepción del Oro project, electrode spacing 50 meters .

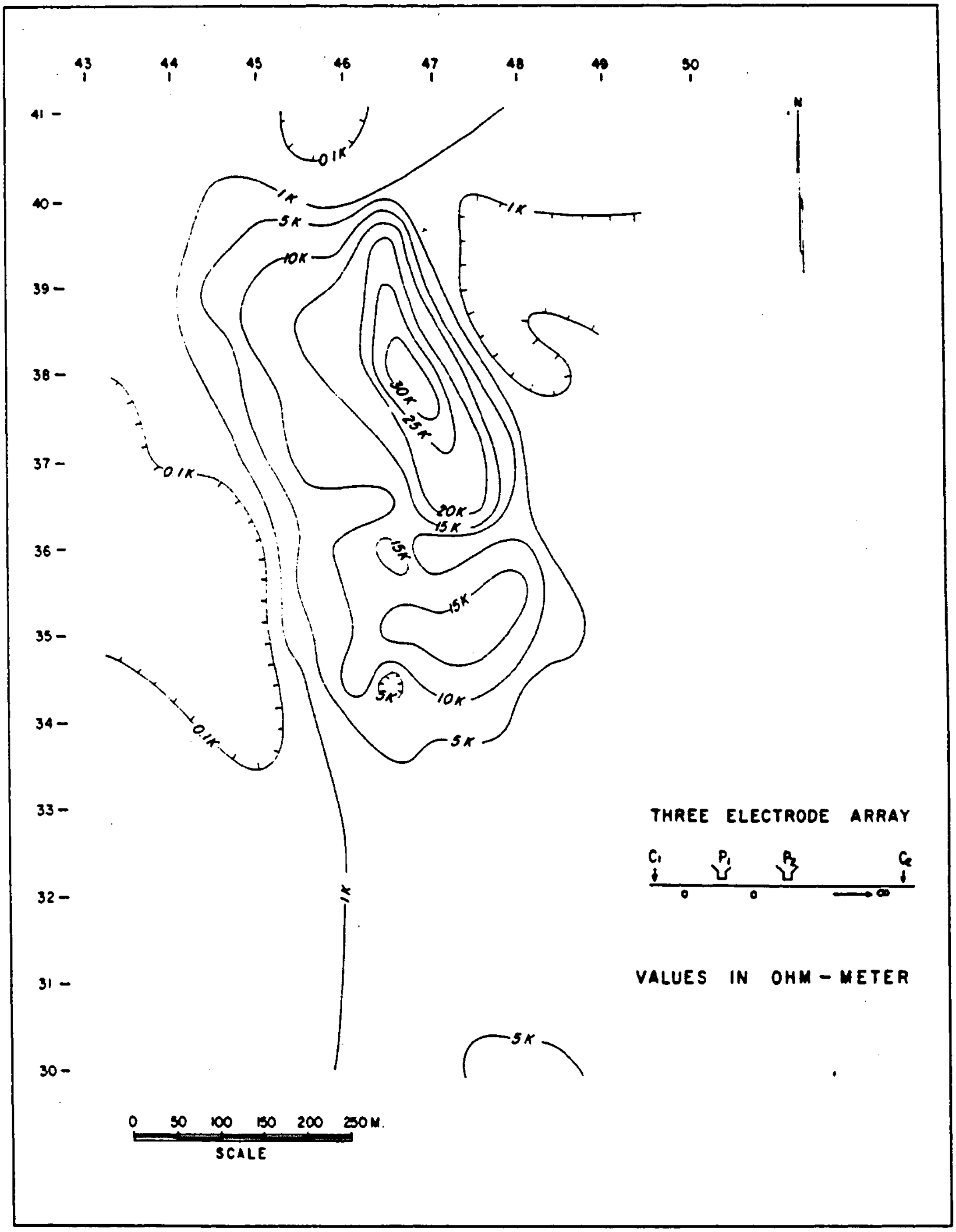

Fig. 35. Resistivity plan of Area II, Concepción del Oro project, electrode spacing 100 meters

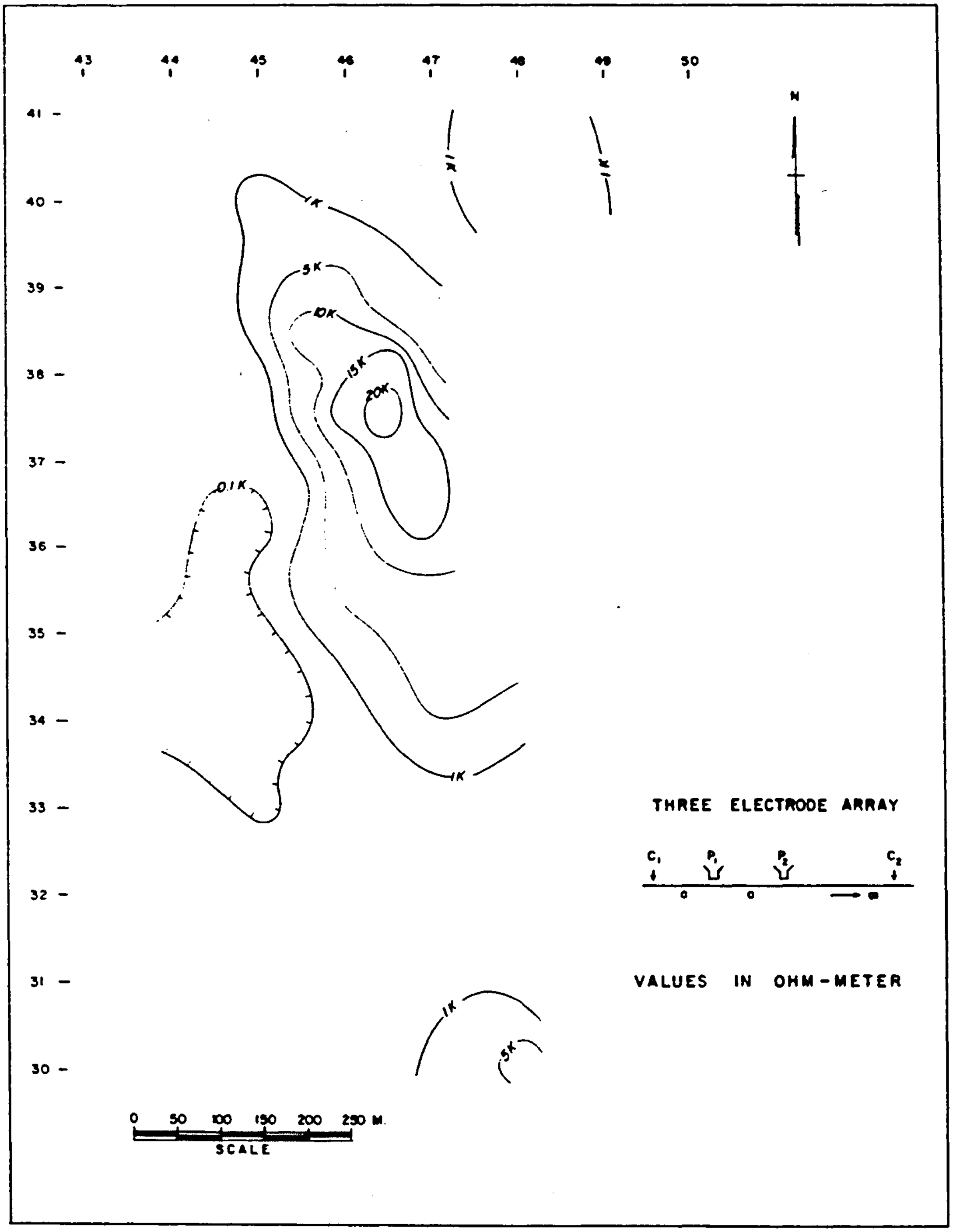

Fig. 36. Resistivity plan of Area II, Concepción del Oro project, electrode spacing 200 meters

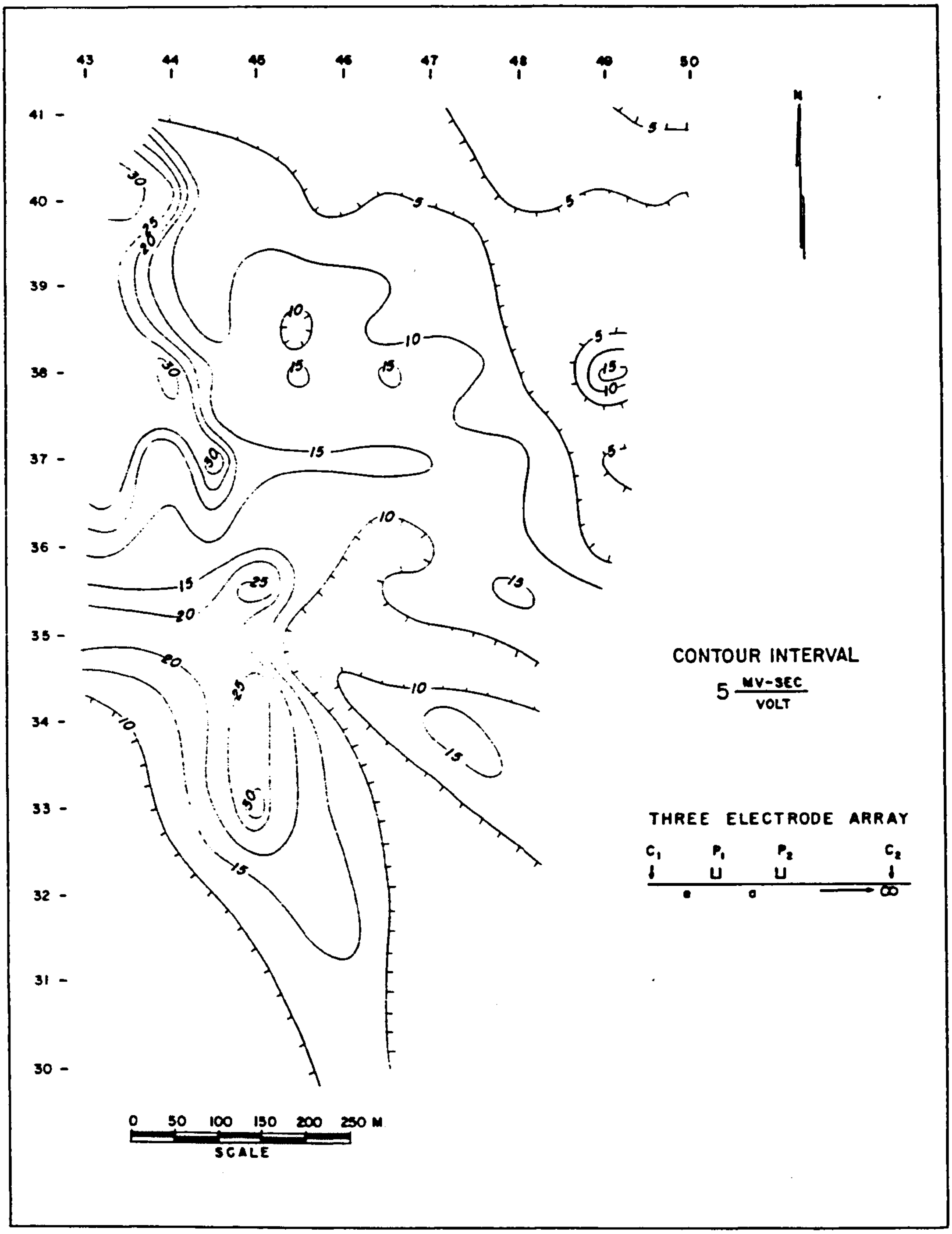

Fig. 37. Chargeability plan of Area II, Concepción del Oro project, electrode spacing 50 meters

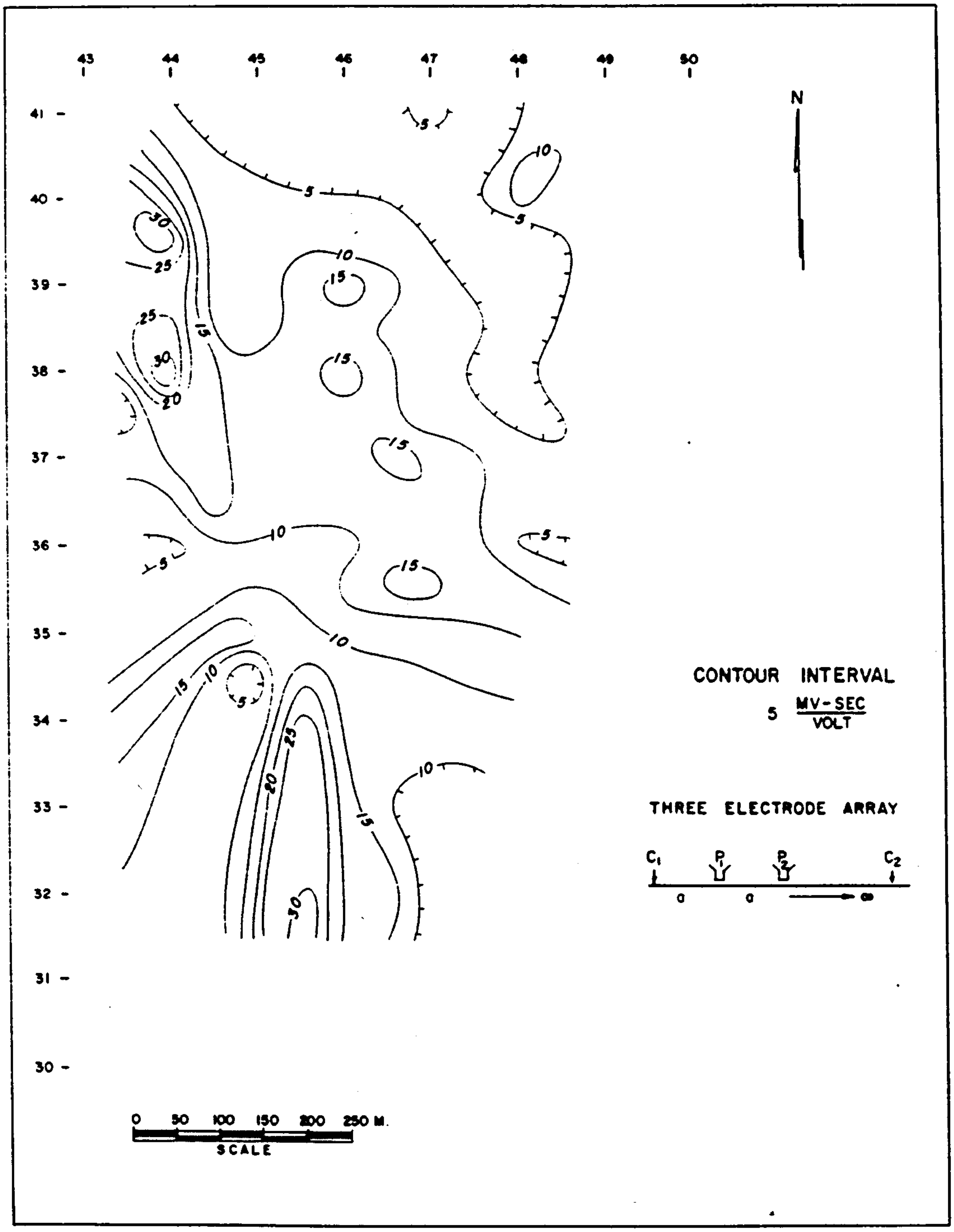

Fig. 38. Chargeability plan of Area II, Concepción del Oro project, electrode spacing 100 meters

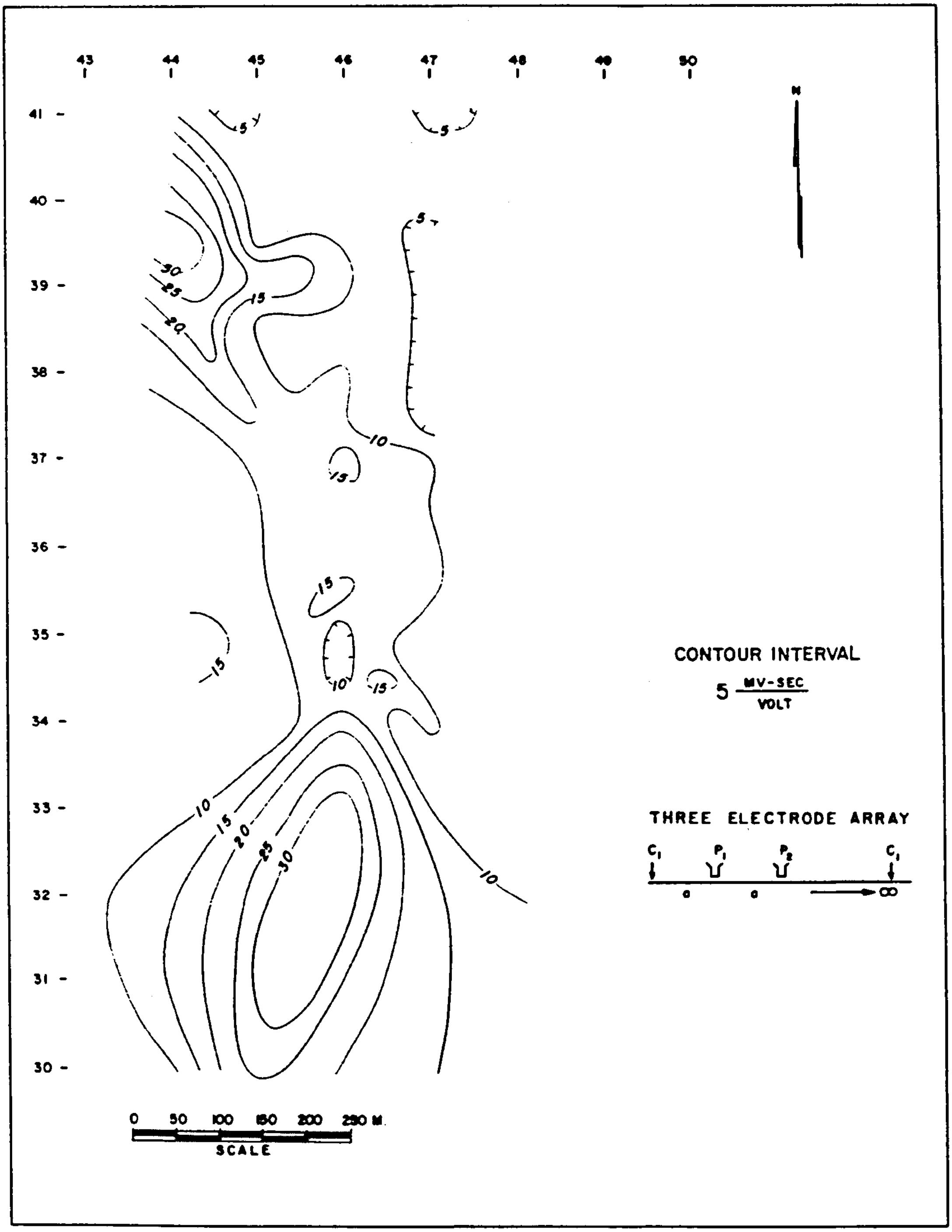

Fig. 39. Chargeability plan of Area II, Concepción del Oro project, electrode spacing 200 meters

San Carlos mines this locality was selected to be drilled to find the causes of the anomaly.

In addition to the profiles used for the exploration of the target areas, 41 vertical electric soundings (VES) were made to complete the IP and resistivity surveys. The electrode spacings used for the VES ranged from 5 to 200 m, using a Wenner array. The resistivity values obtained were interpreted using the master curves given by Orellana and Mooney (1972). Almost all of the VES were done in perpendicular directions over the same point to obtain more information in areas with strong anistropy produced by the steeply dipping sedimentary rocks.

An IP test survey was carried out on a portion of level 10 of the Aranzazu mine. A lack of horizontal diamond drill holes in this level prevented the use of the gradient array, which has been selected by Mathisrud and Sumner (1967) as the most approprate array for underground IP surveys. Instead a three-electrode array was used with electrode spacings of 2, 5, and 10 meters. Readings of chargeability and resistivity were taken over the east wall every two meters. The equipment used was a battery-powered Crone IP transmitter and receiver with an output of 250 watts. The potential electrodes designed for the test were plastic containers where the copper electrode was placed in contact with the rock through a plastic sponge-type material soaked in an electrolyte solution (copper sulfate). The electrodes were immersed in the solution before each reading and were kept in position by pressing the plastic handle of the electrode against the wall. The current electrodes were common steel stakes.

A portion of the results obtained can be seen on Figure 40. Negative IP effects were observed, as predicted by Mathisrud and Sumner (1967), but they were not as large or as many as could be expected, being restricted to the sides of the chargeability anomalies. The chargeability anomaly located at station 015 that correlates with a low in the resistivity values was explored by the mining company, and ore mineralization was found within approximately 3 meters of the level wall (Hernández M., pers. comm., 1979), which gave the test a very satisfying result. Over 120 meters of level 10 were explored with this method, but its use was limited by the impossibility of removing tracks and pipes from the other levels.

The IP surveys carried out around the Concepción del Oro stock showed at least 26 locations where IP and resistivity anomalies coincided or the anomalies were found to correlate with evidences of mineralization. Only four of these have been drilled. Disseminated pyrite was found as the source of the anomaly located in the west section of Area II (DDH 1022) located in the contact between La Peña and Cuesta del Cura formations. The other three anomalies that were drilled showed values of copper ranging from 0.3% to 0.7% and significant values for lead, zinc, and molybdenum (Martínez B., 1975); in particular, DDH 1066 showed economic values, and a detail drill-hole exploration program was programmed in its vicinity.

Various problems have stopped the drilling of all the anomalous areas selected, but implementation of a massive drilling program is forecast for the near future. Once this program is completed there will be

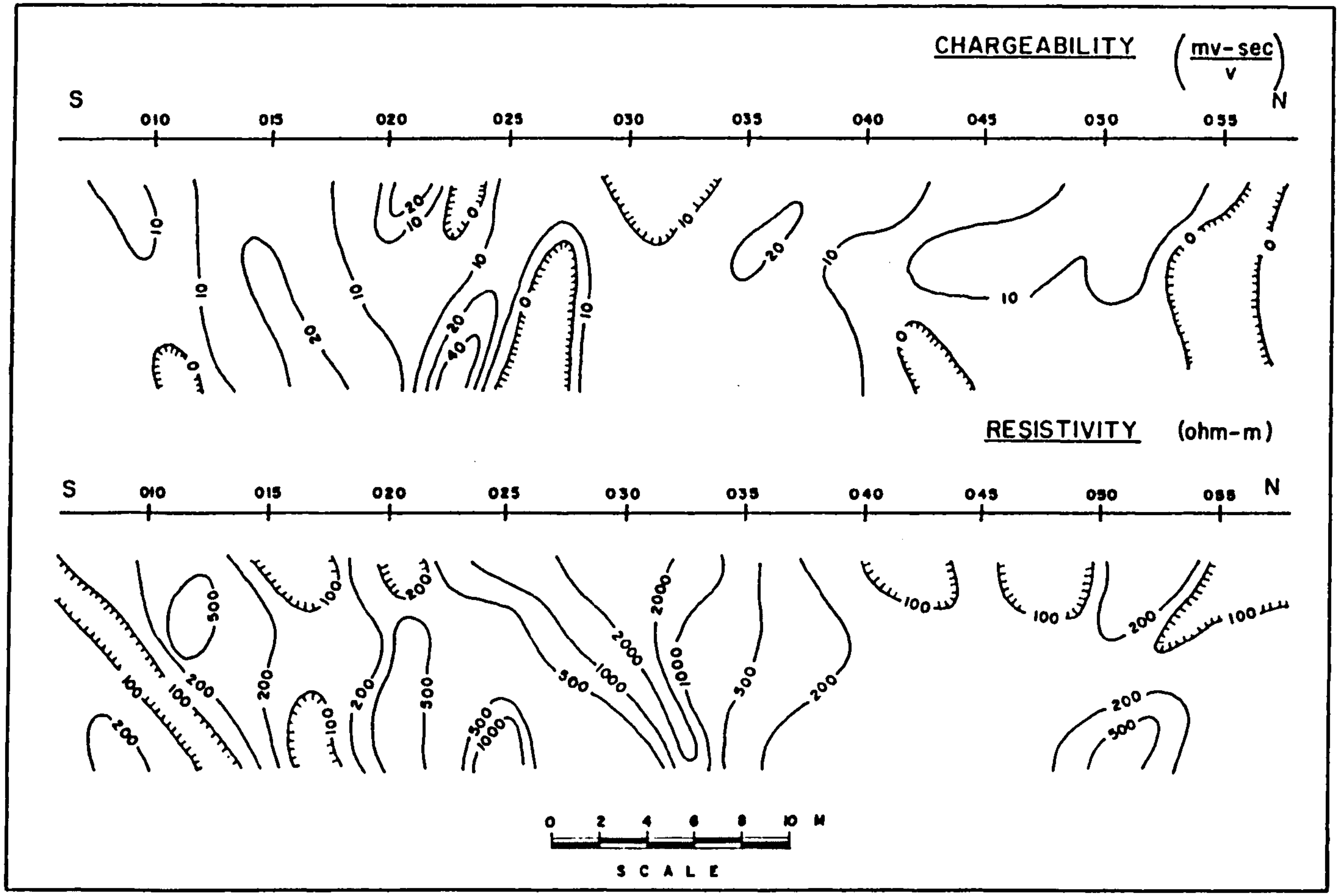

Fig. 40. Chargeability and resistivity pseudo-sections of a portion of level 10, Aranzazu mine

enough information to evaluate the results obtained with the IP and resistivity surveys.

CONCLUSIONS

A final evaluation of the results obtained with the integrated exploration program for the Concepción del Oro district is not possible at this time because the drilling program formulated for the areas located around the Concepción del Oro stock has not been completed and because there are also other areas in the district in which the geology and encouraging results obtained with the regional exploration suggest that a detail exploration program should be conducted to evaluate their mineral potential.

Because no two mining districts are exactly alike, a good knowledge of the geology of the district as well as an understanding of the different forms in which the mineralized bodies can be found are the basis for the design of the regional exploration programs for that district. Most old mining districts have been studied by several people, and for many districts only a careful bibliographic research is needed to obtain all the needed geologic information. For other areas, where such bibliographic references are not available, geologic studies of the district should be the first step in the exploration program.

In the Concepción del Oro district, the geologic study, which included both library search and field studies, permitted establishment of the close relationship between the intrusive bodies and the ore deposits. This relationship provided a logical basis for the aeromagnetic survey. This survey permitted the location of all intrusive bodies and a proper interpretation of the magnetic data permitted the selection of target areas in which detail exploration should be conducted. Among these areas is the Melchor Ocampo area for which detail exploration is strongly recommended. Here the nature of the magnetic anomaly obtained during the aeromagnetic survey suggests the presence of a near-surface intrusive body intruding sedimentary formations that around the Concepción del Oro are mineralized.

Any regional geochemical survey in an old mining district will be affected to a certain degree by the contamination produced by the smelters, mines, and prospect pits in the area. This contamination requires that the results be carefully analyzed to extract the useful information. In the Concepción del Oro district, the regional geochemical survey tended to confirm the relationship between the intrusive bodies and the mineralization, with all geochemical anomalies located downstream from sills, dikes, and stocks.

Not all the available regional exploration techniques will be required to provide useful information in any particular district. In the Concepción del Oro district, the analysis of linear features obtained from Landsat images does not appear to have contributed any indication of the known ore deposits or the location of the intrusive bodies.

Once the regional exploration has indicated the location of target areas, the selection of the methods to be used in the detail exploration will again depend on the types of mineral deposits to be located. Sometimes a geophysical method that seems appropriate based on the physical properties of the mineral deposits fails because of outside factors. The gravity survey carried out in Area II failed because the large terrain corrections obscured the data. So if possible, outside factors that may affect the results should also be examined to determine the applicability of such methods.

In the Concepción del Oro district, induced-polarization and resistivity surveys appeared to be the most appropriate detail geophysical methods, and several anomalies were found by these methods. The results obtained with the test conducted on level 10 at the Aranzazu mine confirmed that IP methods can be successfully used underground. Old mining districts in which there are normally several hundred meters of accessible underground workings are ideal targets for this type of exploration.

The preliminary results of the integrated exploration program for the Concepción del Oro district confirmed the apparent success of this type of exploration applied to an old mining district.

Integrated exploration programs for the revitalization of old mining districts facing exhaustion of their known ore reserves seem to warrant the required investment, and with new methods, equipment, and interpretative techniques in the future their rate of success will increase. These exploration programs, together with innovations in mining methods and more efficient processing of ore minerals, are the basis for prospective revitalization of old mining districts not only in Mexico but also in many other parts of the world.

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FIGURE 18 TOTAL INTENSITY AEROMAGNETIC MAP, CONCEPCION DEL ORO AREA

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FIGURE 4 SIMPLIFIED GEOLOGIC MAP OF CONCEPCION DEL ORO, MEXICO. (MODIFIED FROM PRIEGO, 1973)

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