DEVELOPMENT AND APPLICATION OF VAPOUR GEOCHEMISTRY TECHNIQUES TO MINERALS EXPLORATION IN OVERBURDEN COVERED AREAS OF NORTHERN CHILE

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RESUMEN

Alrededor del 47% del norte árido chileno, rico en minerales, un área equivalente 122.000 km², está cubierto por diferentes tipos de sobrecarga transportada. Se efectuaron investigaciones sobre técnicas de geoquímica de vapores, tanto en el plano nacional como en el de cooperación internacional, con el fin de satisfacer la necesidad de contar con herramientas adecuadas para la exploración de cuerpos mineralizados ocultos. Se presenta aquí los resultados de estas investigaciones, que incluyeron formas volátiles y adsorbidas de Hg, hidrocarburos y compuestos de azufre, como asimismo Rn^{222}. La respuesta de los diferentes gases, probada sobre varios depósitos de tipo pórfido cuprífero y sobre una veta de plata, fue variada, por lo que se hace una comparación de su utilidad relativa.

Se concluye que la dispersión de vapor es controlada, prepoderantemente, por estructuras y que puede ocurrir a través de sobrecarga no consolidada, potente, en algunos casos de más de 100 m de espesor, con una dispersión lateral menor. El mercurio es útil en la detección de mineralización de plata y, en algunos casos, de mineralización de pórfidos cupríferos oculta; el radón es útil en el trazado de grandes fallas cubiertas; los hidrocarburos gaseosos tienen una aplicación limitada; los gases sulfurados muestran un potencial considerable para la exploración de sulfuros ocultos.

ABSTRACT

About 47% of mineral-rich arid northern Chile, equivalent to 122,000 km², is covered by various forms of transported overburden. Research on vapour geochemistry techniques, both on a national and an international cooperation basis, was undertaken in order to satisfy the need for adequate tools to explore for concealed orebodies. Results from these research studies, which included volatile and adsorbed forms of Hg, hydrocarbons and sulphur compounds as well as Rn^{222} gas, are presented here. The response of the various gases, which was tested over several porphyry copper deposits and over a silver vein, was mixed, and a comparison is made of their relative usefulness.

It is concluded that vapour dispersion is primarily controlled by structures and that it can take place through thick unconsolidated overburden, sometimes in excess of 100 metres, with little lateral dispersion. Mercury is useful in detecting concealed silver and, in some cases, porphyry copper mineralization; Rn is useful in delineating buried major faults; hydrocarbon gases have limited applications; sulphur gases show considerable promise in the exploration for concealed sulphides.

INTRODUCTION

The lack of conventional geochemical expression of mineralization concealed beneath transported overburden or unmineralized cap-rocks is one of the principal problems in mineral exploration for such mineralization.

Since the early 1960's increasing attention has been given to the development and application of geochemical exploration techniques suitable for

FIG. 1.   Location Map.

the exploration for concealed orebodies. The main reason behind this interest is that exposed orebodies are becoming scarce as a result of centuries of prospecting and mining activities. New resources, represented by concealed orebodies, could occur under extensive overburden-covered areas existing in various parts of the world. Overburden may consist of a great variety of geological materials, ranging from relatively thin alloctonous soils of a few metres thickness, to unconsolidated glacial, fluvial, colluvial and piedmont materials of tens to hundreds of metres thickness.

Vapour geochemical exploration is based on the mobility of vapours derived from mineral deposits and the likelihood of these vapours reaching the surface through exotic cover. The basic assumption behind the determination of the soil or free atmosphere gas contents above mineral deposits as a prospecting technique, is that its normal composition will be altered by the introduction of gases derived from or related to the mineralization.

Chile is a country with important metallic mineral resources, particularly copper and molybdenum, and whose geological history has produced extensive areas covered by transported overburden. This is the case in the northern regions of Chile $(17°30'S$ to $31°S)$, which are the subject of the present paper and where semi-arid and arid climatic conditions predominate. The area located north of $31°S$ contains most of the known mineral deposits, as deduced from data collated by Ruiz *et al.*, 1965. Approximately 47% of the area located to the north of $29°S$, equivalent to some 122,000 km^2, is covered by alluvial, colluvial and

piedmont sediments and subordinate amounts of other continental and marine sediments (Fig. 2). Such vast expanses of transported overburden were the result of important landform development processes which took place during the Cenozoic (Mortimer, 1973).

The importance for Chile of having exploration techniques adequate for the exploration for concealed metallic orebodies in the northern regions stems from two main facts; namely, that most obvious deposits have already been found and that exploration in modern times has been mostly limited to previously known mineralization occurrences. Regarding the first point it is interesting to consider that the majority of known deposits have been found by prospectors—in numerous instances by pre-Columbian indigenous prospectors—such as, for example, the deposits at Cerro Colorado, El Abra, Chuquicamata and El Salvador. The second point is explained by the relative youth of geological exploration activities in Chile, which meant that, until now, most exploration activities were directed to the reconnaissance of known deposits by the use of modern machinery and mineralization models, instead of basic geological exploration; a case in point is the application of the "large tonnage, disseminated copper mineralization" model developed at Bingham, Utah, around 1915, to the exploration of the Chuquicamata, Potrerillos, El Teniente (Braden) and El Salvador deposits in Chile. All of these deposits were previously known only for their superficial or near-surface vein mineralization.

It can be estimated that the exploration for concealed deposits will become increasingly important in Chile, mainly due to the fact that most outcropping deposits have already been found but the bedrock beneath overburden-covered areas within well-known metallogenetic provinces has high mineralization potential. A good example of this is provided by the porphyry copper province (Fig. 3). In this province, more than 20 porphyry copper deposits and prospects are distributed over an area of some 20,000 km^2 of which about 40% is covered by postmineralization rocks and unconsolidated sediments. Ruiz (1975) estimated that probably several deposits remain undiscovered, since the province is far from being completely explored. The prophyry copper deposits at Cerro Colorado and Pampa Norte, included in this study, occur in the porphyry copper belt and are concealed under thick transported overburden.
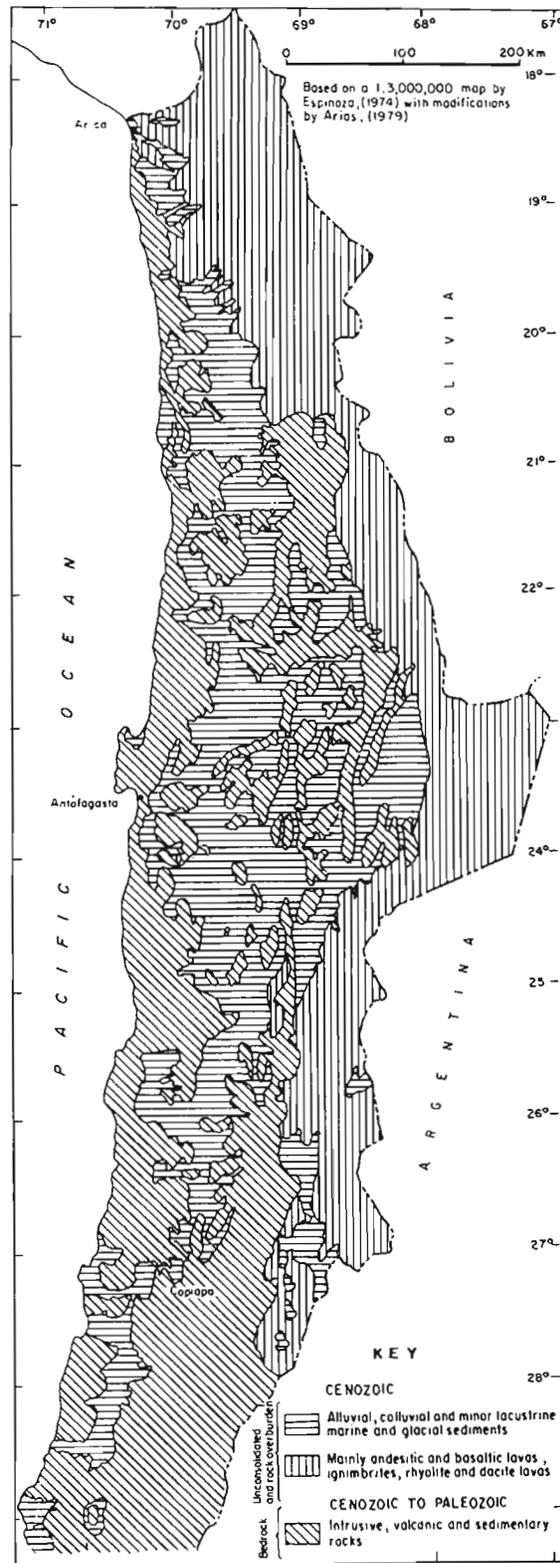

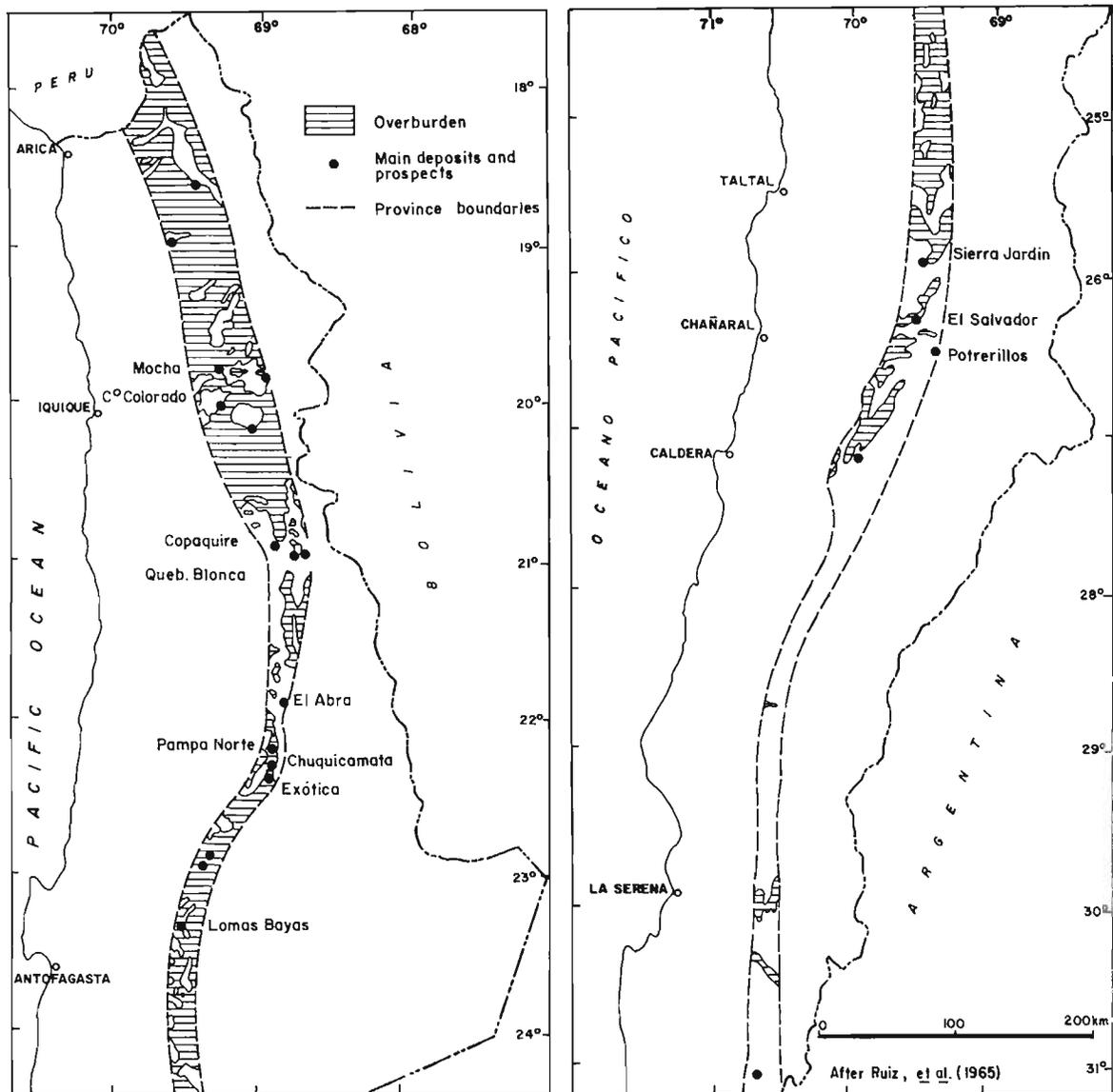FIG. 2.   Geology of the area north of latitude 29° south.

FIG. 3.   Porphyry copper province (northern part), after Ruiz (1975).

Those potential resources, and as yet undiscovered resources of Cu, Mo, Au, Ag and to a lesser degree Pb and Zn, in arid northern Chile, could be economically important as suggested by past production figures and favourable geological factors. Thus, in the period 1541-1975 total mineral production in Chile was 26,870,000 metric tons Cu; 100,944 metric tons Mo; 547 metric tons Au; and 12,127 metric tons Ag (Sutulov, 1976) and a substantial part of this production originated in the said region.

The testing of the applicability of vapour geochemical techniques to the early stages of exploration for porphyry copper and associated deposits in northern Chile was suggested by Cruzat (1971). In that same year the Instituto de Investigaciones Geológicas (IIG) initiated a programme in which over a period of three years, mercury prospecting techniques and apparatus were tested with some success in various prophyry copper deposits (Arias, 1975). Between September 1975 and January 1979, IIG and the Applied Geochemistry Research

Group (AGRG), of the Imperial College of Science and Technology, carried out a collaborative research programme under the general supervision of Professor J.S. Webb of AGRG. This collaborative research study was conceived to broaden the scope of previous studies carried out in Chile by IIG, and formed part of a broad-based AGRG investigation of vapour geochemistry in mineral exploration, funded by the Mineral Industry Research Organization (MIRO) of the United Kingdom.

The results presented in this paper are based on both studies (Arias, 1975; Arias, 1979).

One of the authors, J.A. Arias, formely at Instituto de Investigaciones Geológicas (IIG), was sent to London, in representation of IIG, where laboratory work was developed in close collaboration with J. Lovell and M. Hale, both of AGRG, co-authors of this paper. Field work was carried out entirely in Chile for both studies and was done under AGRG's staff supervision in the case of the IIG-AGRG collaborative effort.

PREVIOUS APPLICATIONS

Previous applications of vapour geochemical techniques on a world-wide basis are numerous and the readers are directed to review papers by Ovchinnikov *et al.* (1972), Bristow and Jonasson (1972) and McCarthy (1972) for detailed information on both techniques and apparatus.

It has been demonstrated that mercury is able to disperse readily from mineral deposits in arid climatic conditions (McCarthy, 1972; Robbins, 1973; 1975). The method was first outlined by Saukov (1946) and it has since been applied with varying degrees of success, and on occasions led to the discovery of new ore deposits. However, unsuccessful applications are seldom reported, with the result that the appraisal of the overall success rate of the mercury vapour technique is probably biased; the sometimes complex reasons behind the failure to detect mineralization are not investigated. Several review papers document the geochemistry of mercury and applications of the mercury vapour technique (James, 1962; Fursov, 1970; Jonasson, 1970; Evans, 1971; Jonasson, 1972; Robbins, 1972; 1975). Prominent among the papers on applications are those of Sergeev (1961), McCarthy *et al.* (1969) and Khayretdinov (1971). Development of highly sensitive instru-

ments for laboratory and for direct field measurement of Hg concentrations in the low ppb range was achieved in the early 1970's (Robbins, 1972). Successful prospecting applications in arid zones have been made over deposits concealed by various types of overburden, including thick soils, gravels and bedrock overburden (McCarthy, *et al.*, 1969; Robbins, 1972; 1973; 1975). In summary, it has been demonstrated through the work of the different authors mentioned above, that mercury vapour, derived from concealed mineralization of various types, is able to traverse considerable thicknesses of overburden and can be detected in anomalous concentrations in soil gas near the ground surface, and in atmospheric air.

In some cases, however, no Hg has been found in soil gas above known ore deposits such as disseminated gold deposits (Robbins, 1975) and porphyry copper deposits (McCarthy, 1972). McCarthy *et al.* (1969), reported successful detection of Hg and Pb-Zn mineralization, but they noted that anomalies were also detected over unmineralized faults. The difficulties outlined above conspire against a wider application of the technique and it is felt by the authors that these difficulties can only be palliated by more detailed research and by application at the interpretation stage of both local and regional geological knowledge. However, it is interesting to consider that the mapping of unmineralized fractures and faults using mercury has been suggested by Ovchinnikov *et al.* (1972), as an aid in finding areas of intense fracturing favourable to the emplacement of mineralization; these structures act as channelways for the degassing of deep crustal rocks, a form of mercury mobilization from primary sources.

The geochemistry of Rn (Rn^{222}; half-life 3.8 days) has been studied by various authors and the readers are referred to the papers by Israel and Bjornsson, 1967; Dyck, 1968; Andrews and Wood, 1972; Ovchinnikov *et al.*, 1972; Caneer and Saum, 1974; Perelman, 1977. The overall distances over which Rn^{222} is reported to migrate vary from tens to hundreds of metres according to different authors and more importantly according to the geological and physical environments where measurements were made. The existence of Rn anomalies over fractures, faults and deep crustal faults has been recognized for a long time, dating at least back to the 1920's; (Israel and Bjornson, 1967; Ovchinnikov *et al.*, 1972; Ahlbom, 1975). This

phenomenon can be used to advantage in prospecting for ore deposits associated with faults. The use of radon in the exploration for hydrothermal vein type deposits other than uranium deposits was first suggested by Dyck (1968). Nevertheless, since not every fault is mineralized, the existence of a Rn anomaly must always be compared with other data, in order to assess its significance. The applicability of Rn measurements for mineral exploration in Chile is based on the occurrence of measurable U contents associated with hydrothermal Cu and Ag vein type mineralization (e.g. at the Cachinal Ag deposit, where Kuntz (1928) described the occurrence of uraninite) and porphyry copper mineralization (Chuquicamata deposit). Also, the relatively large reported maximum migration distances for Rn suggested that it could be potentially useful in the exploration for deeply buried mineralization (e.g. Pampa Norte porphyry copper deposit).

Hydrocarbons occur in a wide variety of geochemical environments, including rocks, soils and ore deposits where they are present in small amounts. The ocurrence of solid and liquid hydrocarbons in rocks and in fluid inclusions, even those from ore deposits, was reported by Roedder (1972).

Several hydrocarbon gases, such as methane, ethane, propane, and butane have been reported to occur in fluid inclusions in rocks (Roedder, 1972) and ore deposits (Krantz, 1968; Danilova, 1968). It is estimated that, as Byman (1977) suggested, probably the most important hydrocarbon compounds in vapour geochemical exploration are simple volatile compounds such as methane, ethane, propane and butane.

The geochemistry of sulphur was reviewed by Wedepohl (1972), Byman (1977) and Perelman (1977). Sulphur gases can be produced by a variety of processes including oxidation of sulphide ores, the decomposition of organic matter, volcanic and hydrothermal activities, and seepage from natural gas deposits.

Liquid and gaseous sulphur compounds that can occur in soils include: sulphuric acid, hydrogen sulphide, methyl mercaptan, dymethyl sulphide, dimethyl disulphide, carbonyl sulphide, sulphur dioxide and carbon disulphide.

Byman (1977) reported that limited evidence exists of the possible emission of SO_2, H_2S and COS from oxidizing sulphide deposits. Although it is possible that these gases are derived from sulphides by the action of bacteria, as suggested by Perelman (1977), it is also possible that they are generated by decomposition of organic matter present in the soils. However, biochemically-bound sulphur is probably less important as a source of sulphur to the soils in arid and semi-arid environments, since biochemical activity is estimated to be very small in these environments. Preliminary data obtained by Byman (1977) on the role of micro-organisms in soils suggest that these play a minor role in the generation of sulphur gases. Byman (1977) also found that organic S gases are far more prevalent in soil gas than SO_2 and H_2S among the gaseous products from oxidizing sulphide deposits in wet areas.

In laboratory experiments, he was able to detect COS, CS_2 and $(CH_3)_2S_2$ over various oxidizing sulphides *in vitro*. The sulphides tested included pyrite, galena, chalcopyrite, arsenopyrite, stibnite and jamesonite. Wet samples produced greater quantities of the gases mentioned above. By contrast, SO_2 was only detected over freshly crushed pyrite. He further concluded that SO_2 and H_2S do not have any general application in the exploration for buried sulphide ore deposits.

DEVELOPMENT WORK

The research presented here was undertaken with the objetive of testing the applicability of selected vapour geochemical techniques to prospecting for concealed mineral deposits in arid zones of Nothern Chile. Vapours and gases studied include Hg, Rn^{222}, hydrocarbons and sulphur gases. Arid zones were chosen because of the estimated greater mobility of gases in environments lacking rainfall. This factor is known to interfere with Hg vapour (Robbins, 1973) and S gases (Byman, 1977) dispersion in more humid geological environments.

Development work carried out in Chile concerning mercury vapour exploration techniques includes the testing of sampling techniques such as amalgamation of soil gas mercury vapour on silver foil, various forms of active soil-gas sampling, and testing of cold-vapour atomic absorption spectrometers in various field areas (Arias, 1975). Development work carried out in the UK between 1975 and 1979 concerned mainly active and passive down-hole soil gas sampling techniques (Fig. 4), mercury in soil samples analytical techniques

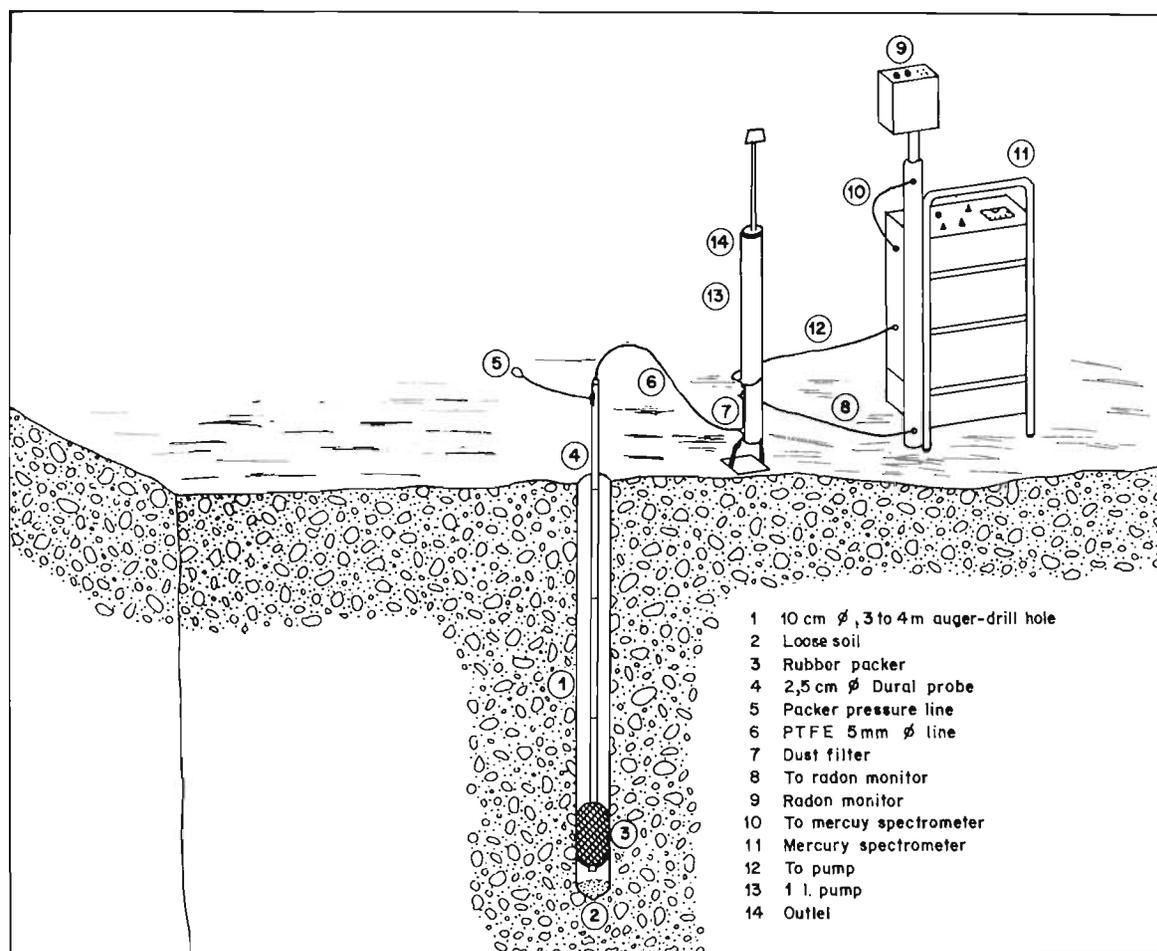| 1 | 10 cm ∅, 3 to 4 m auger-drill hole |
2	Loose soil
3	Rubber packer
4	2,5 cm ∅ Dural probe
5	Packer pressure line
6	PTFE 5 mm ∅ line
7	Dust filter
8	To radon monitor
9	Radon monitor
10	To mercury spectrometer
11	Mercury spectrometer
12	To pump
13	1 l. pump
14	Outlet

FIG. 4.   Sampling and instrumental arrangement for simultaneous determination of Rn and Hg in soil gas.

(Arias, 1979) and soil adsorbed gases analytical techniques (Arias, 1979; Lovell, 1979). This development work will be the subject of a future paper. A brief description of development work carried out in Chile follows.

The first field tests were carried out at the Los Mantos gold, copper and mercury mine, located at Punitaqui, 35 km S from the town of Ovalle. The ore deposits at Los Mantos consist of a series of mostly suboutcropping, complex fracture-filling veins, which occur in andesitic volcanic rocks of Neocomian age, intruded by a major granodiorite stock (MacAllister et al., 1949). The ore minerals are mainly cinnabar and copper sulphides in a quartz gangue. Mercury present in soil-gas samples (Arias, 1975) was sampled by means of hand-pumps and amalgamated on 1 g silver foil sponges which were placed on stream. These were later analyzed in a laboratory based USGS Mk II mercury spectrometer. Twenty, 1 l soil samples were

collected by means of a simple 0.25 l capacity hand-pump. The veins at Los Mantos were easily detected using the mercury vapour technique described (Arias, 1975). The mercury concentrations in soil-gas samples from Los Mantos ranged from 1 to 99 ng/l and the highest background/anomaly ratio was greater than 15. Local background was about 7 ng/l Hg for samples up to 500 m away from the mineralization.

Since it was felt that the 0.25 l capacity hand pump-Pirex amalgator tube combination was efficient but needed improvement, further short field tests were run at the El Abra porphyry copper deposit (Fig. 5) where, 1 l capacity hand-pumps equipped with non-return valves and enameled steel end-funnels for increased suction area, were used. Two gram silver foil collectors were used as amalgamators. The geology of the El Abra porphyry copper deposit was described by Ambrus (1977), and the copper mineralization is subout-

cropping, being partly concealed under a thin regolith up to 0.4 m thick in places. Sixty, 4 litre samples were collected in three different areas of this deposit; one area was located over suboutcropping oxidized copper mineralization, and the other two were external barren zones. Sampling was done at the bottom of 15 to 20 cm deep holes dug in the regolith; mercury analyses were done with a laboratory based USGS Mk II spectrometer. Samples within the mineralized area generally had measurable concentrations which ranged from 1 to 9 ng/l Hg; samples in the barren areas had less than 0.25 ng/l Hg. Samples collected above a highly fractured mineralized zone, gave low values (less than 1 ng/l Hg), and this is thought to be mainly the result of important dilution of soil gas by atmospheric air during sampling; this was probably due to the high permeability of the bedrock. Also, the comparatively low density of air at an altitude of 4,000 m a.s.l. (mean altitude of the studied area) should favour the rapid diffusion of soil gas into the atmosphere and this process might be helped by the action of the mountain winds. Wind entrainement, favoured by intense bedrock fracturing, is considered to be the most important soil gas dilution factor. These effects will apparently not be curtailed by the existence of a thin, highly permeable, regolith overburden over most of the area. Although a relatively small number of samples were collected, the results are considered satisfactory in that the modified —large suction area— sample collection system proved to be efficient and allowed the measurement of the small amounts of mercury (0.25-9 ng/l) present in the soil gas over the El Abra suboutcropping porphyry copper deposit.

The same hand pump-funnel technique was employed in a mercury vapour survey carried out at the Cerro Colorado porphyry copper deposit (Arias, 1975) which is described in detail later in this paper. The USGS Mk II mercury spectrometer was employed for soil gas sample analyses as in the previous cases. A surface sampling device, which consisted basically of a plastic-foam funnel, was developed in order to be employed in a fast survey technique in conjunction with the Scintrex HGG-3 portable mercury spectrometer.
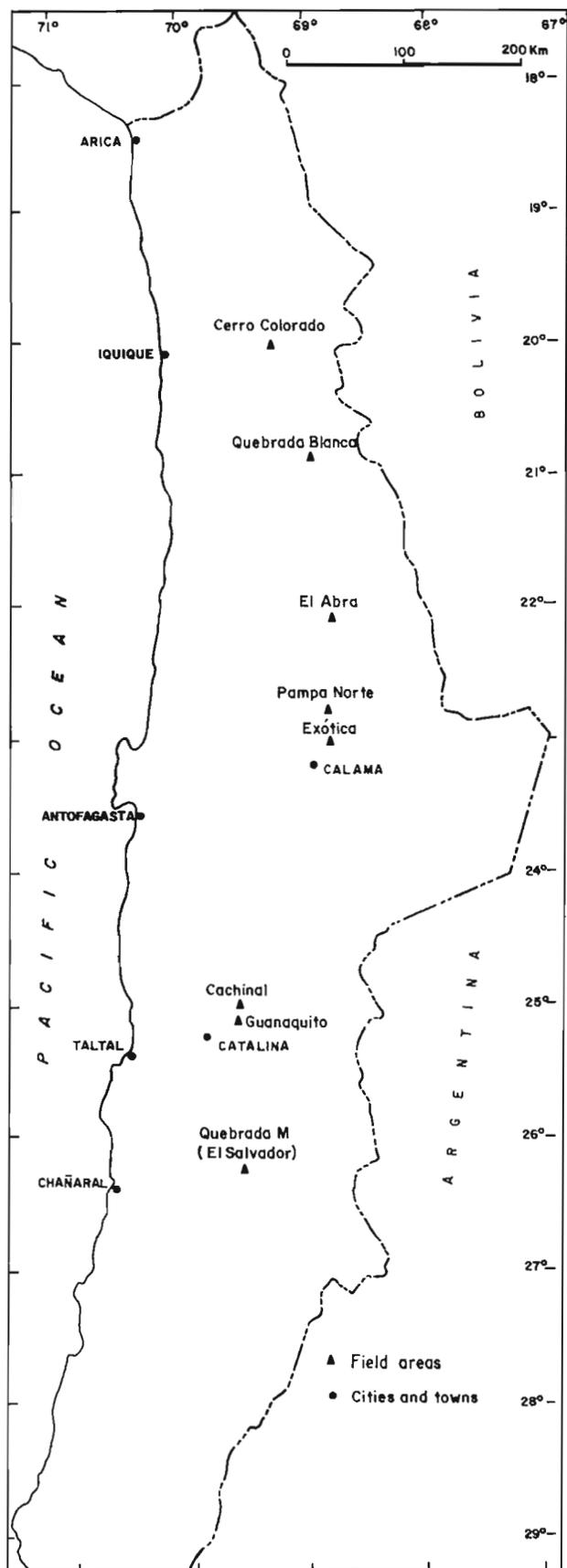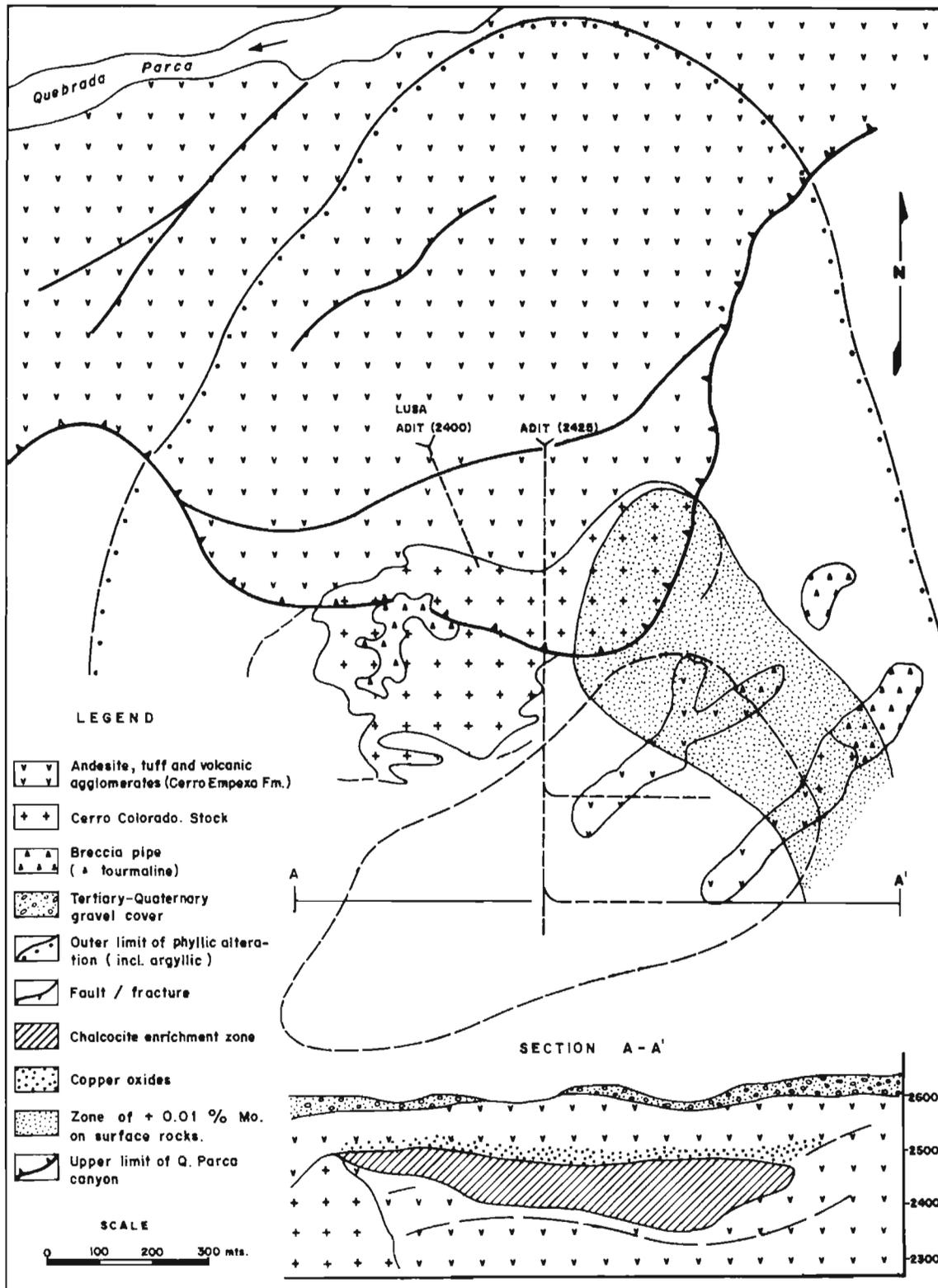

FIG. 5.   Location of field areas.

FIG. 6. Geologic map of Cerro Colorado prospect. From Int. Molybdenum Encyclopaedia, Vol. 1, page 67, by permission of the Editor.

APPLICATION OF SELECTED VAPOUR GEOCHEMISTRY TECHNIQUES

CERRO COLORADO (MAMIÑA) PORPHYRY COPPER DEPOSIT

This deposit is located some 10 km to the NW of the Mamiña village, 130 km E of the city of Iquique (Fig. 5). The mean altitude of the area is 2,600 m (a.s.l.) and the climate is that of a high altitude desert margin. Cerro Colorado hill is an inselberg which rises some 60 m from a W dipping depositional surface. The overburden, which covers the bedrock almost completely, is up to 45 m thick in places, and consists of Tertiary gravels and sands with intercalated tuffs and ignimbrites. The bedrock has been exposed in places by erosion along shallow SW trending gullies. The deposit itself is mostly concealed under the gravel formations and important thicknesses of leached bedrock.

The geology of the Cerro Colorado deposit was described in detail by Thomas (1962). The deposit occurs in andesitic rocks and related altered dacitic intrusions; small outcropping, quartz-eye porphyry and rhyolite intrusions occur in the mineralized area. Most of the outcropping area (about 2 km^2) is exposed by erosion of the altered rocks facing Parca gully, a major ravine some 400 m deep at Cerro Colorado.

The mineralization is known through diamond-drilling and an adit, Socavon Lusa, about 200 m long (Fig. 6), which was excavated some 200 m below the surface of the gravels overburden. Primary mineralization contains up to 0.32%Cu and consists of chalcopyrite, which occurs disseminated and in veinlets, and is accompanied by molybdenite and pyrite (Fam, 1972). Secondarily enriched mineralization is contained within a 70 to 130 m thick blanket-shaped body, and is primarily formed by supergene chalcocite. Chalcocite occurs in its "sooty" form in places and is accompanied by small amounts of molybdenite and chalcopyrite. The supergene chalcocite mineralization underlies strongly leached bedrock, which has maximum grades of 0.3%Cu and a thickness ranging from 90 to 170 m. Ore reserves calculated by Pérez and Gutiérrez (1974) on the basis of data from 5 diamond drill holes, are aproximately 150 million metric tons with a mean grade of 0.8%Cu.

Two independent induced polarization (IP) geophysical studies disclosed the presence of anomalies related to the mineralization. Vertical electrical sounding studies by IIG (Julio, 1972) revealed the occurrence of a high resistivity horizon and an underlying low resistivity horizon; these were interpreted as the overburden (gravels and leached bedrock) and mineralized horizon, respectively. Induced polarization studies and 16 diamond drill holes were done in the area by Nippon Mining Corporation between 1973 and 1975 but detailed results are not available. Kakegawa (pers. comm., 1975) confirmed the occurrence of mineralization in important quantities.

A colorimetric, rock geochemical survey by Thomas (1962), based on 300 samples of 0.5 kg each, indicated the occurrence of a wide zone with anomalous contents of Cu and Mo which included the eroded side of the Cerro Colorado and the outcrops exposed by shallow gullies excavated in the piedmont gravels. Copper contents ranged from 500 to 32,000 ppm and molybdenum contents from 25 to 250 ppm (Fig. 7). The zone with anomalous contents of Cu and Mo occurring to the east of Cerro Colorado, shown in Fig. 7, and which develops in altered rocks exposed by erosion, indicates an extension of the mineralization in that direction.

Two surveys of mercury vapour in soil gas were undertaken at Cerro Colorado, one in 1972 and the other in 1974. The first study was done with a semi-portable USGS Mk II mercury spectrometer and the second with a portable Scintrex HGG-3 mercury spectrometer. The first piece of equipment required the collection of soil gas mercury on silver foil amalgamators, whereas the second is capable of direct mercury determination in a soil-gas sample.

1972 Soil Gas Mercury Survey

Soil-gas samples were collected by an amalgamation technique in which 1 g silver foil collectors were used on stream to amalgamate soil-gas mercury vapour. Sampling stations were 20 to 100 m apart, and generally followed geophysical survey lines (Fig. 7). The area surveyed by the amalgamation mercury vapour technique is of approximately 1.5 km^2. The results of this survey are shown in Fig. 7, which also contains the geochemical anomaly contours obtained by Thomas (1962) and the IP geophysical anomalies measured by IIG (Julio, 1972).

Mercury vapour concentrations in soil gas range
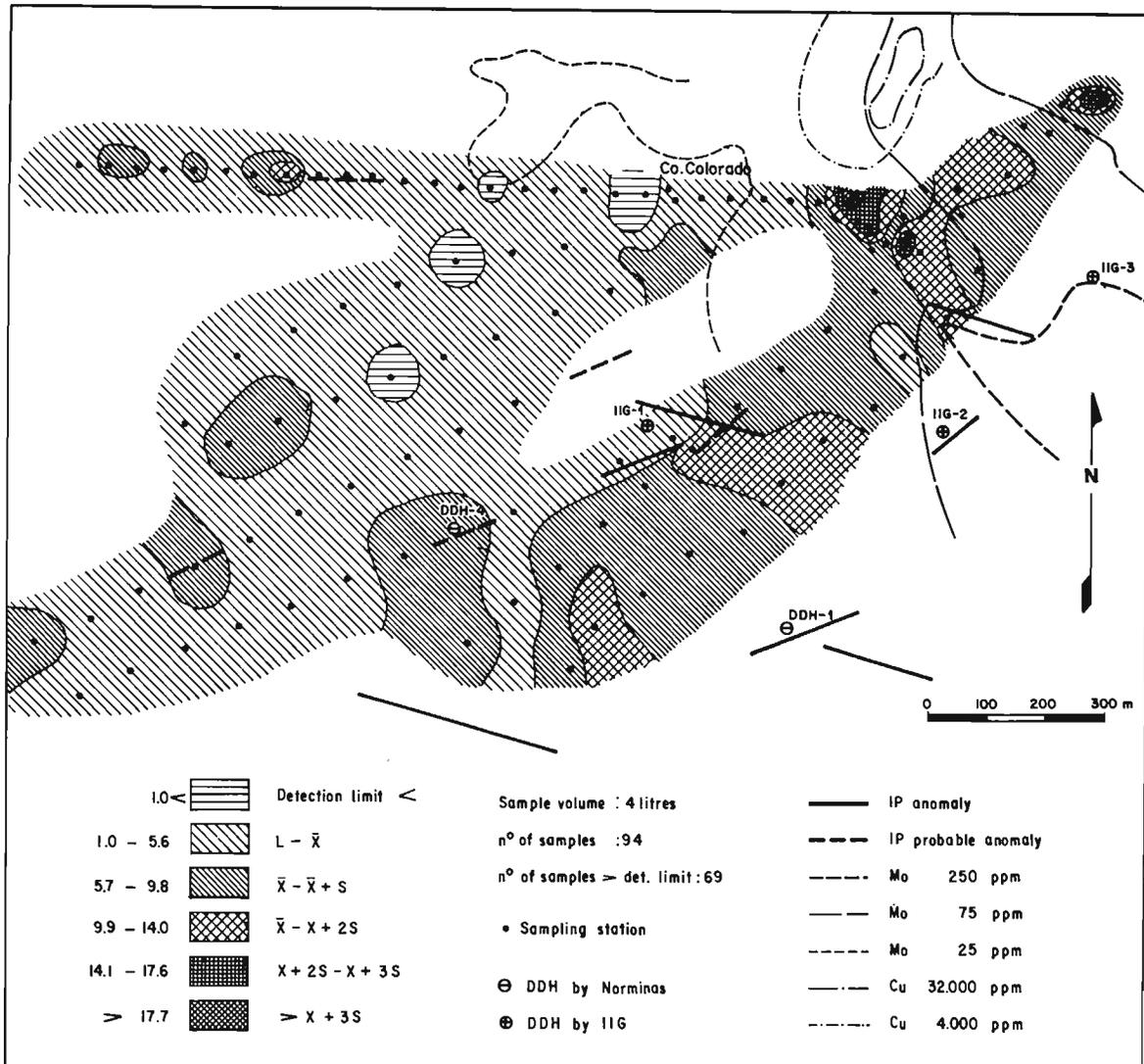
FIG. 7.   Cerro Colorado, Mercury vapour in soil gas, 1972 survey.

from 1.0 ng/l to more than 25.0 ng/l Hg. The mean of the 94 samples collected was 5.6 ng/l. Only 5 out of 96 samples collected within the study area had concentrations lower than the detection limit of the apparatus employed in the analysis (1 ng/l Hg). The samples had a volume of 4 l and were collected by means of a 1 l hand-pump from shallow, 30 to 40 cm deep, holes dug in the loose soil developed on top of the gravels. In some places, the holes were dug in the loose regolith overlying the suboutcropping bedrock. Fig. 7 shows that samples with concentrations above 5.6 ng/l, in all 43 samples, are mostly located in the eastern section of the surveyed area. It is interesting to note that this same zone contains most IP anoma-

lies as well as diamond-drill holes S_1, S_2, S_3, DDH-1 and DDH-2; diamond-drill holes were located on the basis of geological mapping, geophysical and geochemical considerations. The highest concentrations measured, i.e. > 18 ng/l Hg correspond to samples taken from that same area. Also, anomalous ($\overline{X} > \overline{X} + 2S$; i.e., > 14 ng/l) samples occur mostly within the zone with rock Mo contents greater than 25 ppm (Fig. 7). Samples collected outside the surveyed area, at distances of up to 3 km from it, had mercury concentrations of less than 1 ng/l.

In spite of the fact that, for various reasons, it would not be reasonable to expect an exact correspondence between geophysical, rock geochemical

and mercury vapour anomalies, it is interesting to remark that they are in a certain way spatially related. Some factors which could influence mercury vapour dispersion are: the shape and intensity of fracturing of the intrusive bodies; temperature of formation of the ore deposit and paragenesis; leaching and reactivity of the leached capping rocks; differences in the mercury productivity of the various rock units and ore minerals; activity of oxidation processes; and structural control.

Three soil-gas samples were collected inside the Lusa adit, where sulphide oxidation was actively taking place. Of these, one sample had less than 1 ng/l Hg and the other two had concentrations which were lower than the arithmetic mean of the data population ($\overline{X}$ = 5.6 ng/l Hg), respectively, 2.7 and 3.4 ng/l Hg. These rather low values could perhaps be explained by increased dilution of mercury vapour by atmospheric air in open rock fractures in the adit, as compared to near surface soil-gas, whose movement is relatively more restricted.

An area with soil-gas mercury concentrations between 9.8 and 14 ng/l (area shaded with a squared pattern) is located near several IP geophysical anomalies and in the vicinity of diamond-drill hole IIG-1 (308 m deep) (FAM, 1972). This diamond-drill hole showed the occurrence of an 88 m thick secondary enrichment ore zone with 1.32% mean Cu grade, underlain by a primary ore zone 90 m thick and with a 0.32% mean Cu grade. The supergene mineralization zone is overlain by 90 m of leached bedrock with a mean grade of 0.2% Cu and by up to 40 m of gravels.

It is interesting to note that a zone with mercury concentrations greater than the arithmetic mean ($\overline{X}$ = 5.6 ng/l), which occurs in the south-central part of the surveyed area, contains a geophysical anomaly. Here, DDH-4 showed the presence at depth of a 70 m thick supergene mineralization zone with a mean grade of 0.82% Cu.

The western part of the surveyed area had mostly soil-gas mercury concentrations ranging from 1 to 5.6 ng/l, with a few small (100 to 200 m wide) zones with concentrations which ranged from 5.6 to as much as 14 ng/l Hg. Of these, two occurred either near (see top-left of Fig. 7) or above (bottom-left of Fig. 7) probable IP geophysical anomalies.

1974 Soil Gas Mercury Survey

The results from this survey are shown in Fig.

8. The surveyed area is about 6 km^2. Soil-gas mercury concentrations, which were measured on site with a field-portable Scintrex HHG-3 mercury spectrometer, range from 0.02 to 1.0 ng/l. The samples were collected by means of a 200 cm^2 suction area foam-funnel. The concentration for any given station is the arithmetic mean of three successive measurements; reproducibility between samples is good (Table 1) and it is discussed below.

TABLE 1.   RESULTS FOR TRIPLICATE SOIL GAS SAMPLES (ng/l Hg)

Station	1	2	3
1–1	0.26	0.24	0.24
1–2	0.4	0.4	0.4
1–3	0.15	0.18	0.2
2	0.04	0.048	0.054
3–1	1.0	1.3	0.6
3–2	b.d.l.*	b.d.l.	b.d.l.
3–3	0.5	0.6	0.5
4–1	0.4	0.2	—
4–2	0.26	0.28	0.20
5	0.09	0.15	0.15
6	0.04	0.03	0.03
7	1.0	1.2	1.0
8	0.6	0.6	0.6
9–1	0.9	0.08	0.09
9–2	0.14	0.1	0.08
10	0.09	0.06	—

*b.d.l. = below detection limit; double numbering, e.g. 1–3, indicates additonal station near main station 1.

A total of 107 out of 161 surveyed stations, showed mercury concentrations greater than the detection limit of the HGG-3 spectrometer (about 0.02 ng/l Hg); ten out of the 54 samples with mercury concentrations below the detection limit, occurred in stations outside the surveyed area, at distances ranging from 1.5 to 5 km, and they are assumed to represent the regional background value. The arithmetic mean of the 107 measurements above detection limit is 0.083 ng/l Hg.

The occurrence of cupriferous mineralization at depth in the surveyed area had been previously shown by diamond-drilling by Norminas and IIG, and further proven by diamond-drilling by Nippon Mining (Fig. 8). Figure 8 shows that the area with mercury concentrations ranging from 0.02 to 1.0 ng/l contains most diamond-drill holes. These were

LEGEND

0.02 <		Detection limit
0.02 – 0.08		L – $\bar{X}$
0.09 – 0.23		$X – \bar{X} + S$
0.24 – 0.37		$\bar{X} + S – \bar{X} + 2S$
0.38 – 0.51		$\bar{X} + 2S – \bar{X} + 3S$
> 0.52		$\bar{X} + 3S$

Sample volume 0,25 litres
n° of samples   161
n° of samples   o 107
n° of samples   X+3S 12

• Sampling station

Diamond drill holes
  NP Nippon Mining
  ⊕ DDHN Narminas
  O IIG

▲—▲ Limits of Q. Parca canyon
– – – Outline of 1972 survey area
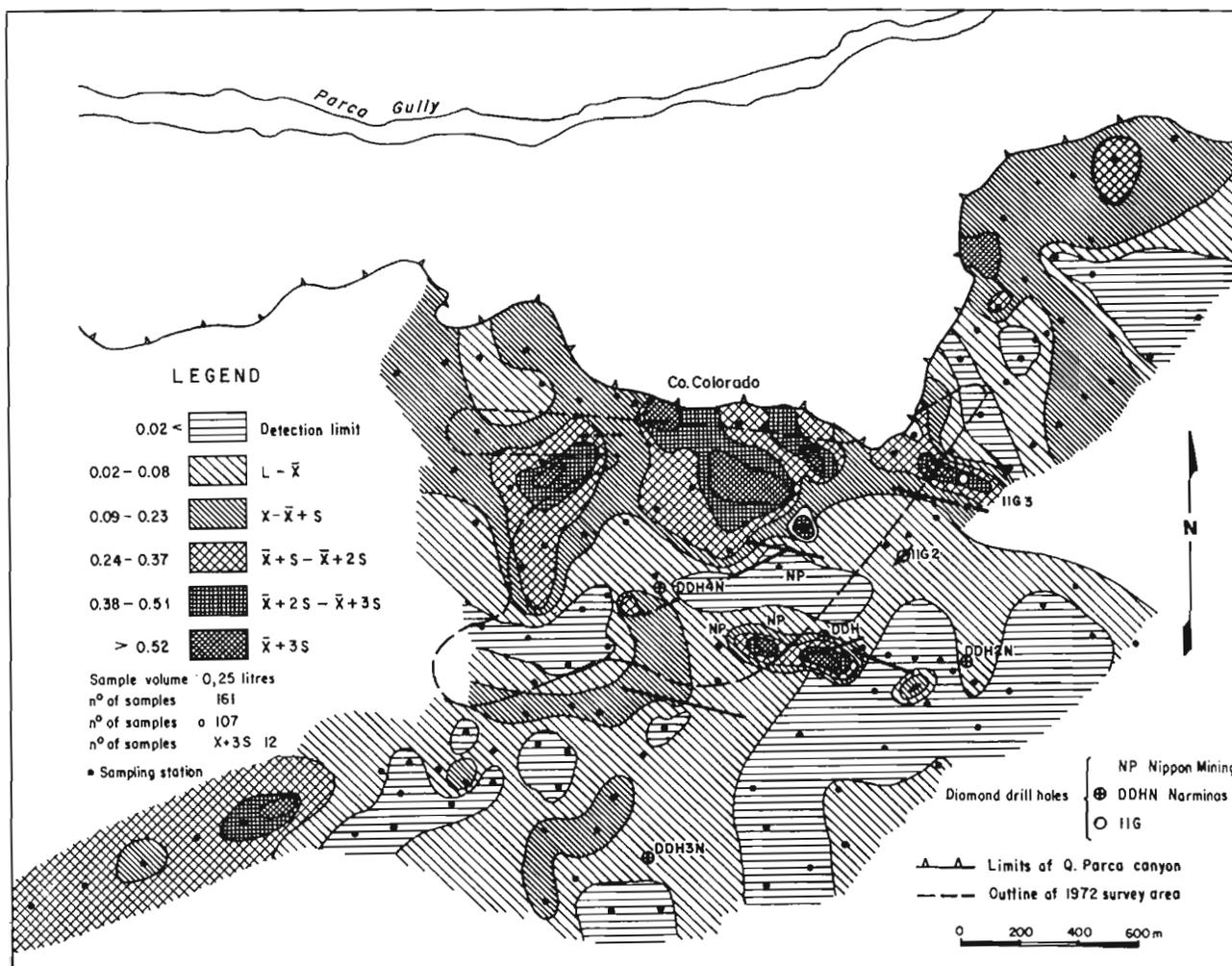
0   200   400   600 m

FIG. 8.   Cerro Colorado. Mercury vapour in soil gas, 1974 survey.

sited on the basis of geological mapping and IP geophysical data. One of the diamond-drill holes (IIG-3) was located on the basis of geological mapping and rock geochemical (Mo) data (Fig. 7). It is estimated that the results for at least part of the 44 stations with mercury concentrations below the detection limit, may reflect the hampering effect on gas migration of a compact sub-outcropping saline horizon occurring in the Cerro Colorado area.

Three principal anomalous sectors ($\overline{X} > \overline{X} + 2S$; > 0.37 ng/l), are seen on Fig. 8. They are as follows: 1) the NE sector, near diamond-drill hole IIG-3; 2) the area surrounding Cerro Colorado hill, located in the north-central part of the map which contains diamond-drill holes by IIG (IIG-1) and Nippon Mining; 3) a small area in the centre of the map which is adjacent to diamond-drill hole DDH-1 and contains another hole drilled by Nippon Mining. The largest of these anomalous 1,000 metres. It is estimated that this anomaly may represent the occurrence of buried mineralization in the sector. The anomalous areas have mercury concentrations in soil-gas greater than 0.37 ng/l ($\overline{X} > \overline{X} + 2S$ in Fig. 8).

Direct comparison of the 1972 and 1974 surveys is not possible because samples were collected at different stations in both surveys and sampling densities were very different (respectively, 62 and 27 samples per square km). Nevertheless, comparison of results for the 1.5 km^2 area common to sectors is the one surrounding Cerro Colorado, the other two being relatively small; probably, this is partly influenced by the comparatively thin overburden occurring in that area. The southwestern sector of the map contains several high content samples which together span more than both studies (outline shown with dashed line on Fig. 8) indicates: 1) An approximate coincidence of high content sample stations (respectively, greater than 5.6 and 0.08 ng/lt Hg); 2) and a general occurrence of high mercury contents in samples from within the area that contains IP anomalies and diamond-drill holes.

CONCLUSIONS AND DISCUSSION

The following conclusions are based on the results of the soil gas mercury vapour surveys carried out in the overburden covered Cerro Colorado disseminated copper deposit: 1) Measured mercury in soil gas concentrations fall within the detection range of both noble metal preconcentration and portable spectrometer direct reading techniques; 2) The sampling techniques developed, e.g. sampling by means of enameled metal funnels applied to shallow holes and surface sampling by means of a foam-funnel, appear to perform adequately; 3) Important thicknesses of permeable overburden materials, such as gravels and leached, fractured bedrock, do not appear to hamper mercury vapour migration; 4) Compact saline horizons (caliches) may seriously hamper gases migration; 5) The general coincidence of areas characterized by detectable amounts of mercury in soil-gas and geophysical and geochemical anomalies gives support to the applicability of the mercury vapour technique in the exploration of overburden covered areas; 6) The speed and relative low cost of mercury vapour surveys as compared to, for example, ground geophysics, suggest the first technique might be used advantageously in the early exploration stages for overburden covered mineralization; 7) Reproducibility for consecutive samples from a same station is acceptable, but rather extreme changes can occur at short range (a few metres) from a given sampling station.

Wiht regard to point 1) it is important to recall that no successful detection of disseminated copper mineralization by the soil-gas mercury vapour technique has been previously described in the literature.

In spite of the fact that the sampling techniques employed appear to be adequate, it is interesting to notice that sampling in shallow holes by amalgamation on noble metal (Ag) collectors gave results 1 to 2 orders of magnitude larger than those obtained by direct soil gas measurement (respective maximum concentrations were 25 ng/l Hg and 1.0 ng/l Hg; respective sample population means were 5.6 ng/l Hg and 0.08 ng/l Hg); it is considered that the observed difference could be due to the increased soil gas dilution near the surface of the terrain as compared to soil gas at 30 to 40 cm depth. By contrast, the first study demanded 12 days/geologist and the second only 7 days/geologist; the comparison shows a considerable advantage for the direct measurement technique.

If abstraction is made of the knowledge of mineralization occurrence, it can be stated that both techniques can help defining an exploration target at a low cost. However, it is important to keep in mind for future studies the considerable dilution

68°48'

COPAQUIRE
Molybdenum porphyry prospect

WEST FAULT

COLLAHUSI
Porphyry copper deposit

MICHINCHA SALT PAN

21°00'

21°00'

QUEBRADA BLANCA
Porphyry copper
deposit

68°48'

Loa river
headwaters

N

	VOLCANOES (TEPTIARY- QUATERNARY)		UNDIFFERENTIATED SEDIMENTARY ROCKS
	IGNIMBRITES (TERTIARY)		GRANODIORITE (TRIASSIC-CRETACEOUS ?)
	GRAVELS (TERTIARY)		ANDESITES AND VOLCANICLASTIC ROCKS
	QUEBRADA BLANCA INTRUSIVE COMPEX (36-42 m.y.)		RHYOLITES
	INTRUSIVE RHIOLITES		GRANODIORITE- DIORITE (247-262 m.y.)
	GRANODIORITE PORPHYRY (59 m.y)		GRANITE AND ASSOCIATED METAMORPHIC ROCKS (431 m.y.)
	GRANODIORITE (CRETACEOUS ?)		PORPHYRY COPPER DEPOSITS WITH Cu GRADES ABOVE 1%
	ALTERATION ZONES		FAULTS

Modified from J. Hunt et al. ; Congreso Minería de cobres porfídicos , Santiago , Noviembre 1980
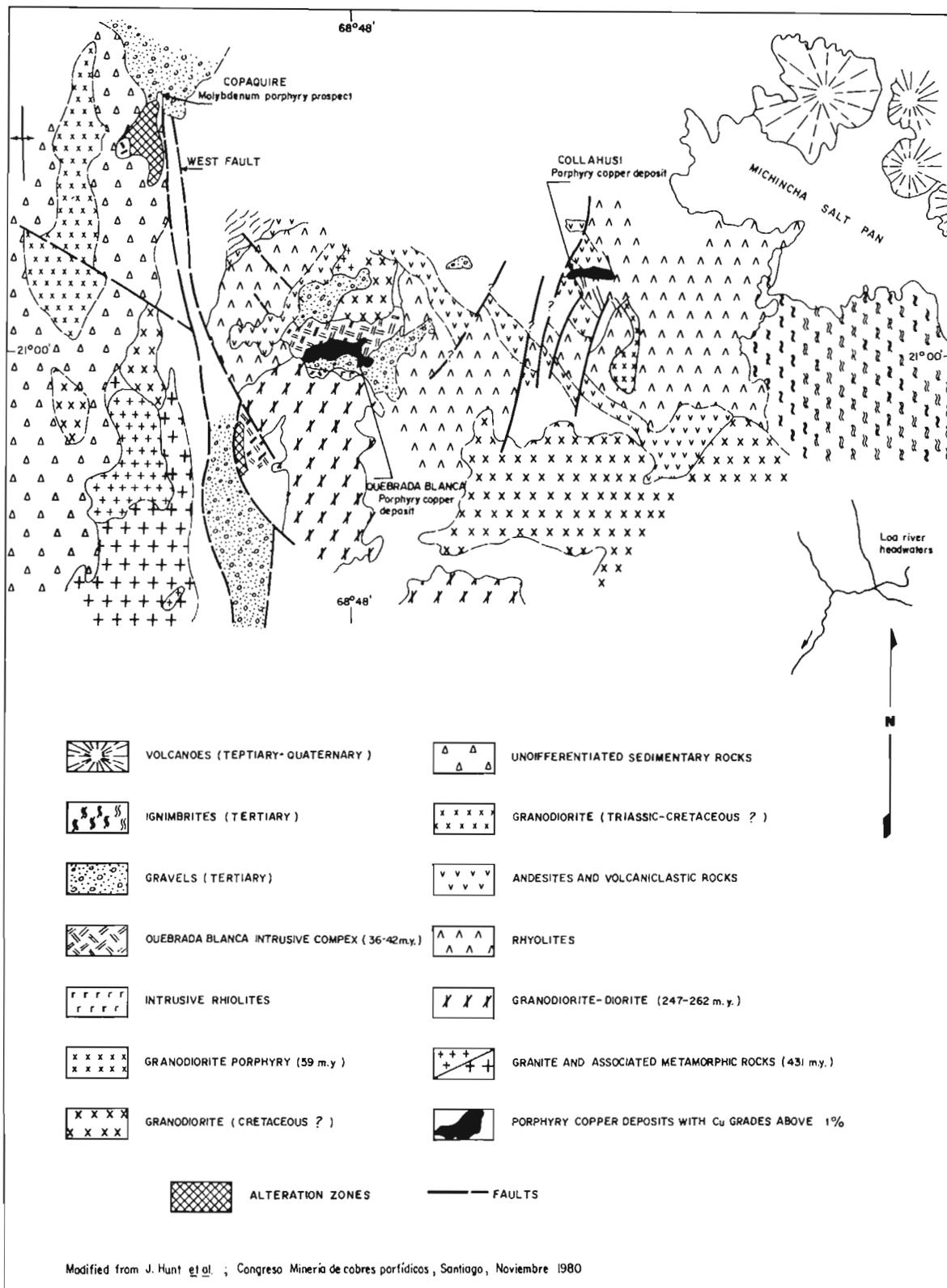
FIG. 9.   Collahuasi mining district.

of near surface soil gas, apparently shown by the direct soil gas measurements.

It appears that the hampering effect of a compact saline layer (caliche) can be somewhat reduced by the sampling of a sufficiently large number of stations. Although the occurrence of a caliche horizon might be considered responsible for part of the 44 samples (out of a total of 161 samples) with below detection mercury concentrations found in the direct measurement study, the low number of below detection samples found in the shallow hole sampling (amalgamation) study suggests that perhaps near surface soil-gas mercury dilution could be more properly considered responsible of such a large number (roughly 30% of the samples) of below detection samples found in direct measurement study.

Even considering that the aforementioned conclusions are guaranteed by the available geological, geophysical and geochemical evidence, it must be emphasized that further applied research in similar deposits is required to assess the usefulness of the mercury vapour technique as an aid in early exploration stages for disseminated copper mineralization concealed by thick overburden.

Long-term reproducibility was not studied at Cerro Colorado, but taking into account the basic differences between both preconcentration and direct measurement techniques, it is interesting to notice that some similarities are observed between the results of both studies, as shown by several areas with relatively high mercury concentrations detected in both instances. The outline of the surveyed area of Fig. 7 has been drawn in Fig. 8 to allow comparisons. The areas to which reference is made above include the following: the zone near diamond-drill hole IIG-3; the area located south of DDH-1; the area south of DDH-4 Norminas; the areas south and west of Cerro Colorado hill. Concerning point 7, Table 1 shows a rather important variability for consecutive samples from the vicinity of station three (samples 3-1 to 3-3); the other triplicated or duplicated samples (1, 4 and 9) show mercury contents of a similar order of magnitude. It should be kept in mind though, that the quantities of mercury in any sample are very low (range 0.03 to 1.3 ng/l) and near surface soil gas dilution or differences in soil permeability could easily explain the observed differences between samples.

QUEBRADA BLANCA PORPHYRY COPPER PROSPECT

The prospect is located 18 km west of the ancient copper mining district at Collahuasi, in the northern extreme of the Region of Antofagasta (Fig. 9). The mean elevation of the area is 4,000 m (a.s.l.). The climate is of the high desert margin type and it is characterized by wide temperature changes of up to 30°C in dayly cycles. Strong, cold westerly winds blow over the area during most of the year.

The geology of the area was first described by Fam (1972). A Cretaceous monzonitic-dioritic altered intrusive complex outcrops in the prospect area and is accompanied by hydrothermal breccias with or without tourmaline. The complex intrudes Jurassic volcanic country rocks. Tertiary denudation processes created a relatively low-relief landscape, formed by a west-southwest dipping infill plain from which some inselbergs rise; intermontane basins were filled by modern sediments. Aproximately 50% of the prospect area is covered by modern sediments, and the rest is in part concealed by a thin residual soil overburden.

Hydrothermal alteration and mineralization occur mainly in a quartz-monzonite stock located in the central part of the prospect and in diorite "roof-pendants" in the monzonite stock. Mineralization as observed by Fam (1972), consists of disseminated and veinlet-forming pyrite, and of finely disseminated chalcopyrite which is partially replaced by supergene covellite; molybdenite occurs in quartz veinlets.

A residual soil geochemical survey was undertaken in the Quebrada Blanca area by IIG in 1973 (Arias and Fam, 1974). As a result of this survey and on the basis of the analysis of 400 soil samples collected mostly over geophysical survey lines, a central area within the prospect, characterized by copper contents greater than 236 ppm, was defined (Fig. 10). An IP geophysical survey was also carried out in the prospect area by IIG in 1973. The IP anomalies detected during this survey are also shown in Fig. 10.

An on-site, soil-gas mercury vapour survey was carried out in the prospect area in 1974, using a Scintrex HGG-3 field portable spectrometer. The survey stations were those of seven geophysical IP survey lines and some additional stations were
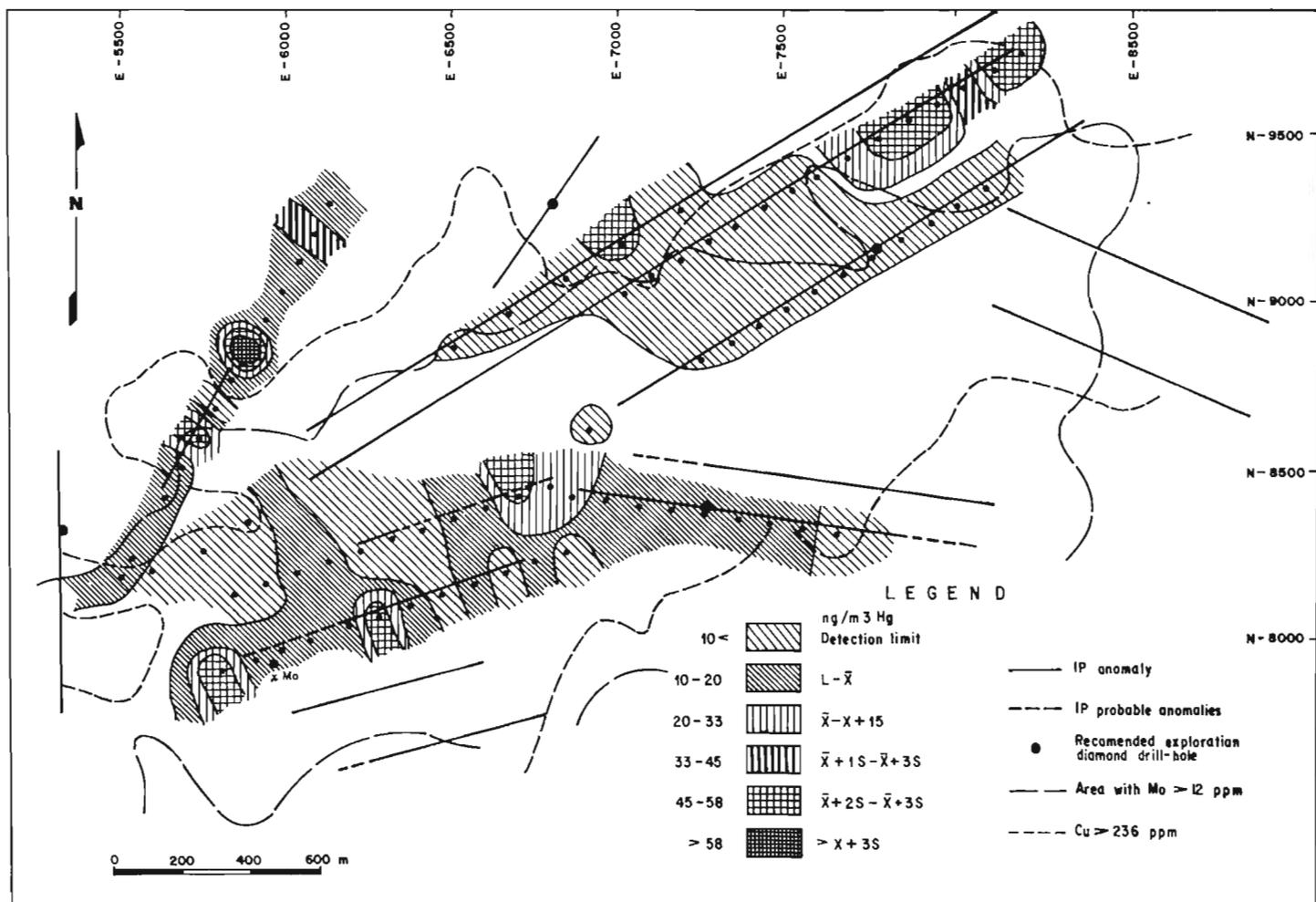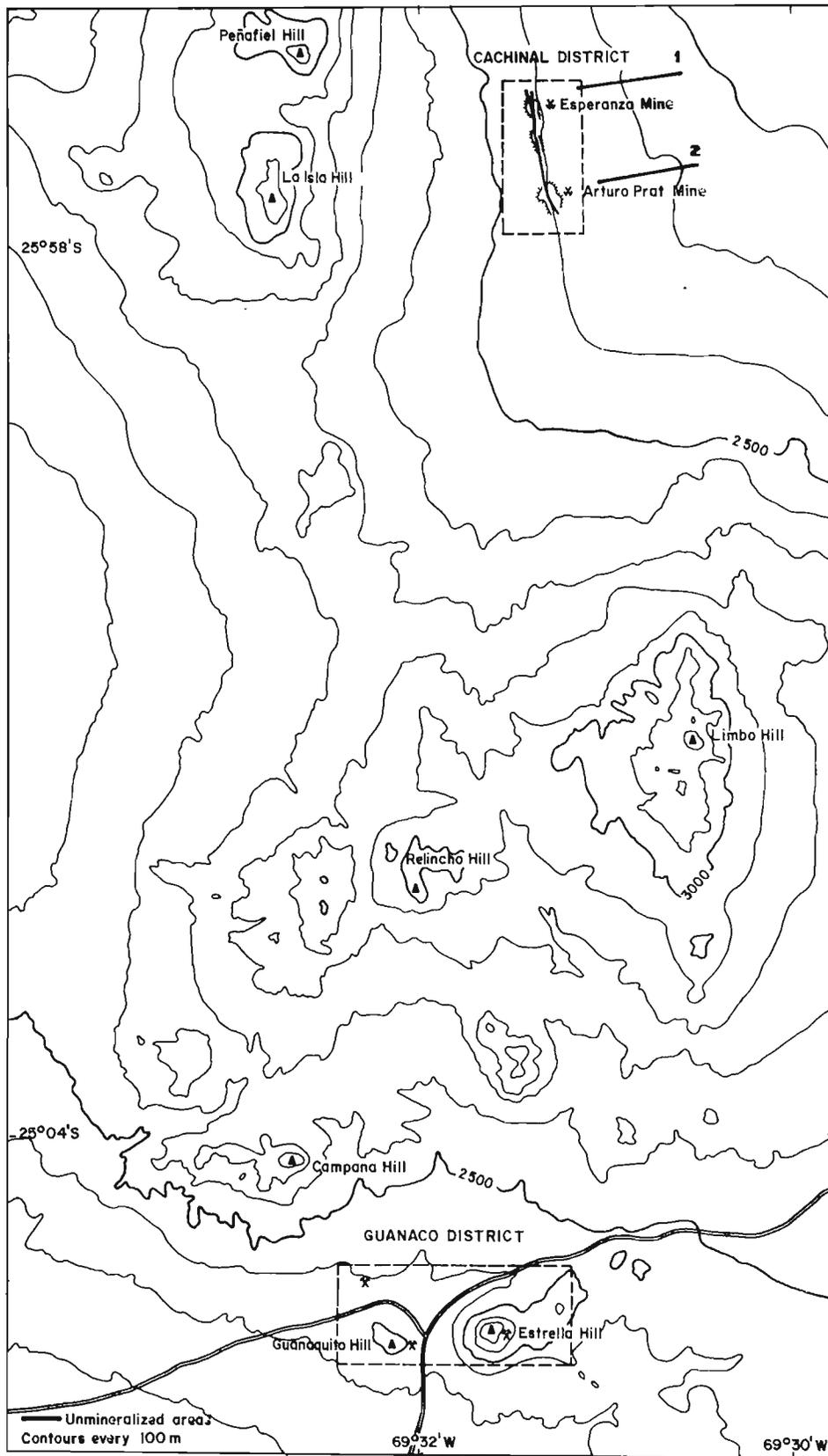
FIG. 10. Quebrada Blanca. Mercury vapour survey.

FIG. 11. Guanaco and Cachinal Districts.

sited between them (Fig. 10).

Soil gas samples were collected by means of the surface sampling foam-funnel technique. During sample collection air temperatures in the prospect area were commonly below 0°C, reaching −5 to −6°C, which created operational problems (early battery exhaustion), thus slowing down the survey.

Eighty-two stations were sampled and the results are shown in Fig. 10, thogether with geophysical IP, and geochemical survey results. The measured mercury concentrations in soil-gas were very low (arithmetic mean of 45 measurements was 0.02 ng/l = 20 ng/m³) and they range from 10 to 40 ng/m³. Of the 82 stations sampled, only 45 (i.e., about 55%) had mercury concentrations above the detection limit of the spectrometer (about 0.02 ng/l Hg).

Results are considered inconclusive but the area is remarkable in that a large proportion of the stations had mercury concentrations below detection limit. Sub-anomalous values (between 33 and 45 ng/m³ Hg) occur in the NE extreme of the area, and in the central and southern parts. The latter has two stations with relatively high mercury contents which are close to a molybdenum mineralization occurrence. The mentioned mineralization was exploited in the past through a shaft shown in Fig. 10. The highest mercury concentration measured lies isolated on Traverse A, in the western part of the area.

CACHINAL SILVER VEIN-TYPE DEPOSIT

The Cachinal Ag district consists of several vein-type deposits associated with sub-volcanic intrusive and extrusive rocks occurring in an overburden covered pediment surface on the eastern slope of the La Isla range (69°32'W and 24°58'S). The range is located 105 km on an airline to the northeast of Taltal (Fig. 5). Major N-S faults occur in the area and are related to the mineralized veins. The geology of the district has been described by Greiner (1978), Chong (1976) and Moreno (1974). Kuntz (1928) described the ore mineralogy at some of the main deposits (Fig. 11). At Cachinal, Cretaceous and Tertiary volcanic rocks lie unconformably over Jurassic marine sediments (Chong 1976). Hypabissal domes, necks and dykes associated with possibly Miocene to Palaeocene subvolcanic units intrude the stratified series. The composition of the intrusives ranges from inter-

mediate to acid (Chong, 1976) and they are mainly porphyries of rhyolitic composition, and subvolcanic granites.

Although most of the area is covered by colluvial overburden, small outcrops exist, and mine workings and prospecting trenches allow examination of the bedrock in places. The Arturo Prat mine is on a small hill which rises some 25 m above the surface of the pediment. The pediment slope ranges from 5 to 7%. Overburden thickness ranges from less than 2 m to 15 m as measured at two different sites located some 500 m to the east of the main vein.

The most abundant rocks are quartz-feldspar porphyries; some porphyry breccias, andesites and aplites are also found. The rocks are hydrothermally altered. The porphyries usually are intensely silicified and argillized or exhibit intense potassic alteration; porphyry breccias show similar alteration and their fragments are generally made of feldspar porphyry and aplite; aplites are fine grained and altered to a mass of quartz and sericite. Barren granodiorites occur from 260 to 380 m to the west of the vein. Alunitization and kaolinization of the quartz-feldspar porphyries occasionally was observed, but potassic alteration (mostly sericitization), is apparently the most prominent hydrothermal feature. Limonites are usually found in veinlets and disseminated, and possibly resulted from *in situ* oxidation of mineralization. Hematite and limonite commonly stain the porphyries and breccias.

The two principal mines are Arturo Prat and Esperanza and they exploited respectively the southern and northern parts of a large mineralized structure which strikes N15°W. Silver ores were mainly exploited from a 1.5 km stretch between the Esperanza and Arturo Prat mines (Fig. 11). Greiner (1978) has suggested that similarly mineralized structures could perhaps exist to the east.

Chong (1976) described the vein mineralization as a system of veins (Arturo Prat and Carmen veins) which bifurcate and coalesce along the strike of a major structure which runs for at least 2.5 km and strikes N15°W. Ore mineralization occurs mostly in the relatively wide, intensely brecciated portions of the veins as ore-shoots. The brecciated ore zones are reported to be 1 to 6 m wide and sometimes may reach more than 10 m (Greiner, 1978).

A leached upper zone of unspecified thickness occurs directly underneath the overburden. Mine-
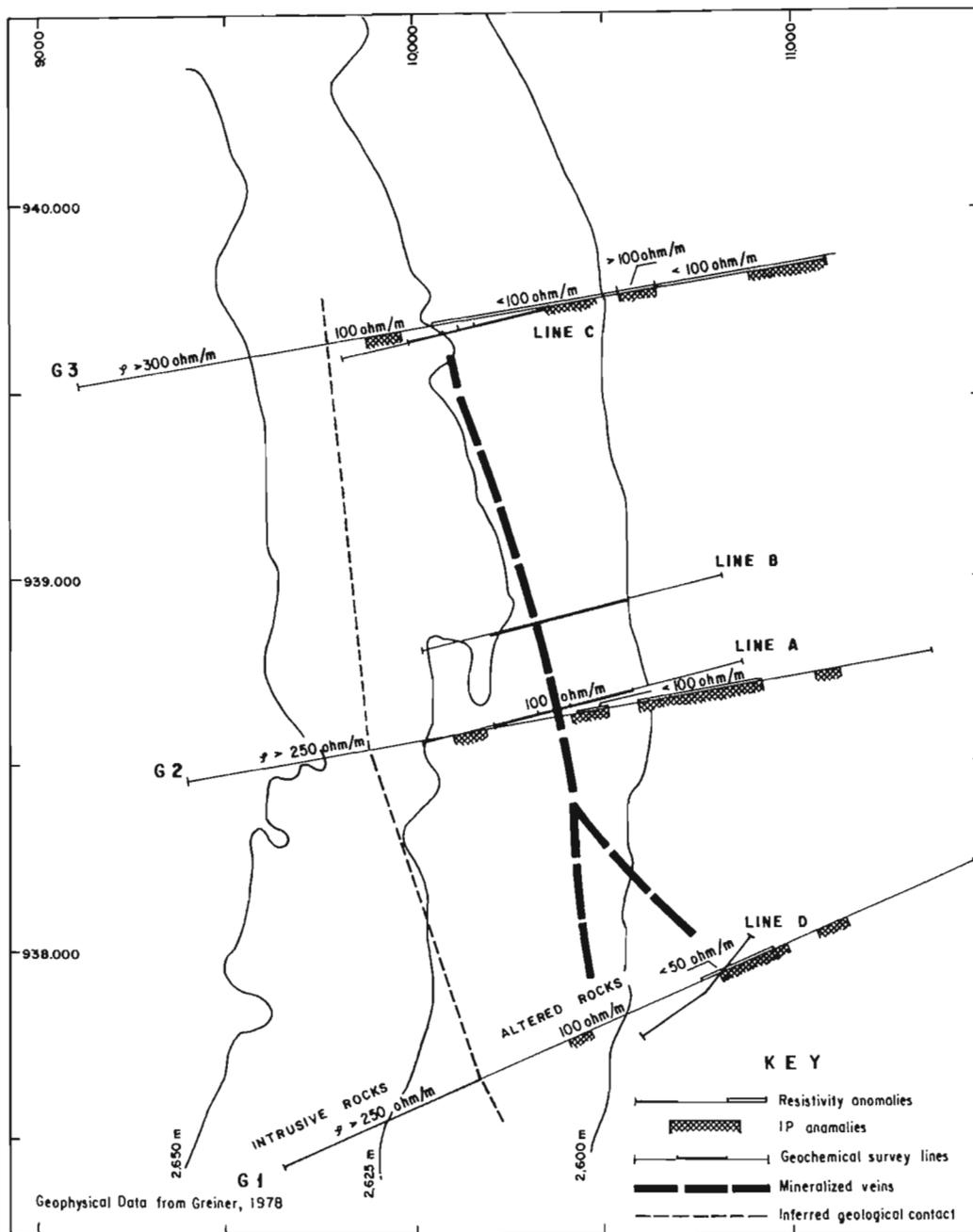
FIG. 12. Geochemical and geophysical survey lines at Cachinal.

ralization reaches depths of 300 and 350 m in the Esperanza and Arturo Prat mines (Greiner, 1978). Kuntz (1928) recognized a maximum mineralization depth of some 320 m.

The primary ore zone occurs at depths of 120 to 150 m. Samples of primary ores (non-representative) described by Chong (1976) contain sphale-

rite, argentiferous galena, chalcopyrite, pyrite, tennantite and enargite. Secondary mineralization includes covellite, and hematite. Various limonites are recognized as supergene products. Kuntz (1928) described ores formed by kerargyrite, chlorargyrite, bromargyrite, argentite and subordinated pyrargyrite and native silver. Chong (1976) also reports
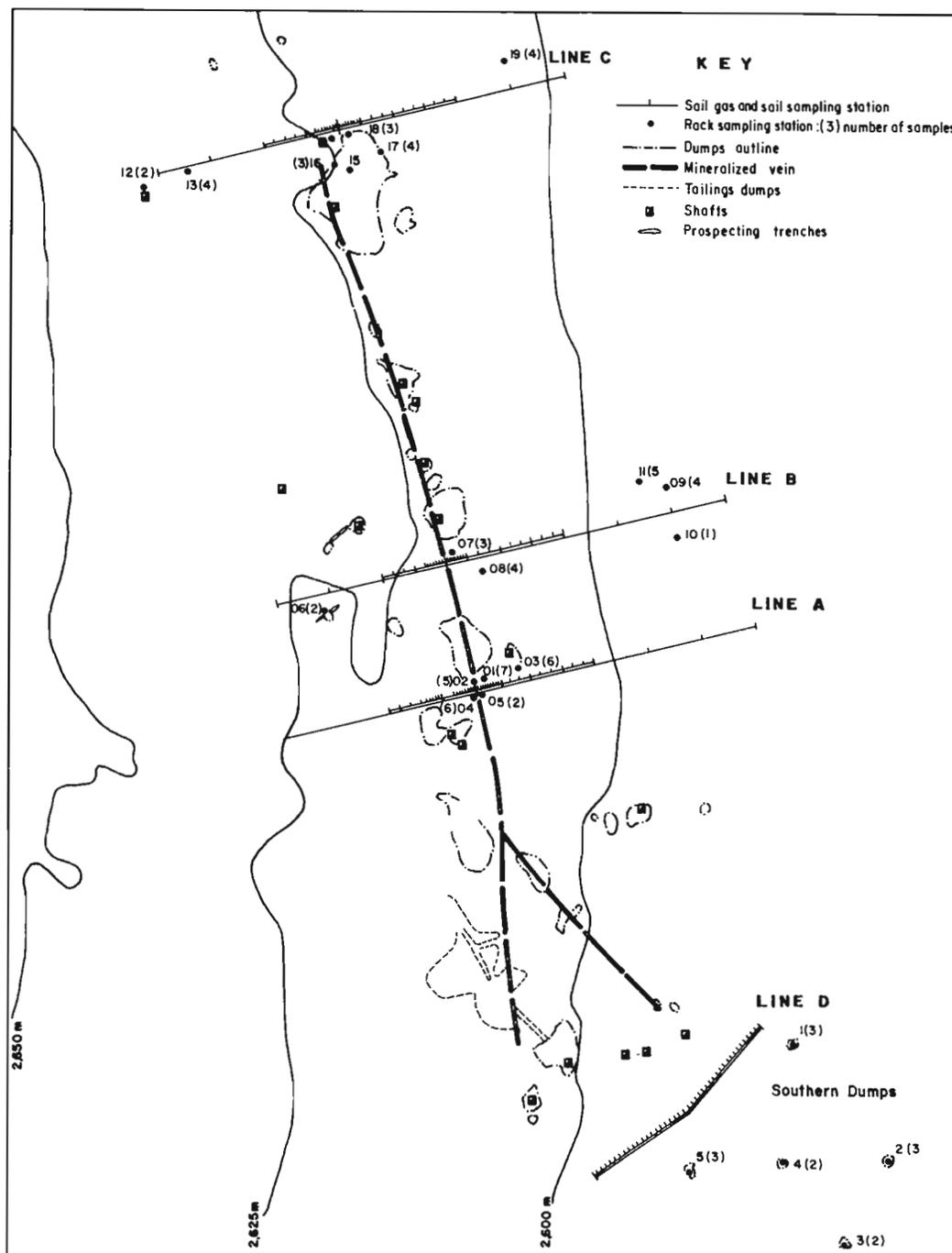
FIG. 13.   Location of rocks, soil and soil gas sampling stations at Cachinal.

sulphoarsenides and sulphoantimonides of silver and traces of uraninite. Lead oxides and carbonates were formed by supergene enrichment of argentiferous galena ores.

Geophysical IP and resistivity surveys were run at Cachinal by ENAMI (Empresa Nacional de Minería, Chile). Their results are shown in Fig. 12.

Two presumably unmineralized areas were chosen at Cachinal for use as background control areas (Fig. 11). They are located about 500 m to

the east of traverses A and C at Cachinal (Fig. 13), and they extend for 1,000 m in the same direction as the traverses. The areas are located over the same colluvial overburden slopes found at Cachinal and the overburden materials are predominantly granodiorite and altered acid porphyries. No caliches were found to occur in the unmineralized areas.

The results of analyses of bedrock samples (Table 2, Fig. 13) range very widely, since these samples represent barren bedrock, leached bedrock, weakly mineralized and ore grade mineralized rocks. The samples from the southern dumps are

taken to represent barren bedrock and their Ag - contents are low (generally < 0.6 ppm). Copper, lead and zinc contents for these rocks are, respectively, lower than 83, 72 and 554 ppm.

No correlation exists between Ag and either Cu or U contents in rocks, a fact that possibly reflects the heterogeneity of the samples and the intense leaching of the bedrock. Silver contents in rocks range from 0.2 to 540 ppm (only 5 out of 45 samples from traverses A and B had silver contens > 100 ppm). Most of the U values obtained for the rocks from traverses A and B do not exceed the 5 ppm average U concentration for granitic rocks

TABLE 2: RESULTS OF ROCK GEOCHEMICAL ANALYSIS FOR CACHINAL SAMPLES

ORIGIN	Ag ppm	Cu ppm	Pb ppm	Zn ppm	U ppm	Hg ppb
— Southern Dumps						
Concentration Ranges	0.2−2.7	6−83	5−72	51−554	−	28−800
Arithmetic Mean (13)*	0.5	16	21	147	−	200 (10)**
Standard Deviation	0.7	12	22	131	−	228
— Line A						
Concentration Ranges	0.2−182	4−3,600	80−14,200	65−28,000	1.7−8.7	16−2,225
Arithmetic Mean (26)*	33	416	3,355	5,052	3.2	297 (21)**
Standard Deviation	45	794	4,112	6,224	1.4	524
— Line B						
Concentration Ranges	0.2−540	2−2,800	16−30,000	20−4,200	1.2−6.9	−
Arithmetic Mean (19)*	36	190	5,678	917	3.8	−
Standard Deviation	123	636	22,852	1,336	1.4	−
— Line C						
Concentration Ranges	1.1−530	7−8,500	91−100,500	49−16,000	−	4−>1,000
Arithmetic Mean (33)*	54	500	6,649	2,401	−	176 (23)**
Standard Deviation	99	1,472	17,454	3,585	−	261

* Numbers in parenthesis are number of samples;
** Number of samples analyzed for mercury.

(Rich *et al.*, 1977). Geochemical results showed that there was no wide dispersion of Ag around the veins. Mercury dispersion on the other hand, was wide judging from the fact that the rocks from the southern dumps area, located up to 500 or more from the known mineralization, had a mean Hg value similar or somewhat lower than that of the rocks from the mineralized area. Intense leaching of the bedrock was demonstrated by the analysis of deep soils from traverse A, which consisted mostly in decomposed bedrock, and which showed Ag contents smaller than 2 ppm even above mineralization. Leaching of the bedrock samples was

also observed in hand-specimens, and limonites were found to occur in numerous samples. It can be concluded therefore, that leaching of the bedrock did cause the removal of, for example, most of the Ag, Cu, and possibly some of the Pb and Zn from the upper part of the deposit. However, U was apparently not strongly depleted by leaching or may have been retained by adsorption onto limonites.

Mercury in Soil-Gas

The results of on-site Hg determination along four traverses over mineralization at Cachinal are

TABLE 3: MEAN AND RANGE OF HG CONTENTS IN SOIL GAS AT CACHINAL

		$\overline{X}$	Hg (ng/l) Range	No. of samples in Traverse
Line A:	1st Measurement	3.3	0.3 —>66.0	40*
	2nd Measurement	3.2	1.4 — 60.5	40
	3rd Measurement	3.1	1.9 — 19.8	40
Line B:	1st Measurement	2.8	0.7 — 9.2	35
	2nd Measurement	6.0	2.9 — 13.6	35
	3rd Measurement	5.4	3.0 — 12.8	35
Line C:	1st Measurement	1.9	0.2 — 17.6	35
	2nd Measurement	3.7	1.3 — 12.3	35
	3rd Measurement	3.9	1.8 — 13.6	35
Line D:	1st Measurement	7.1	0.4 — 41.5	36
	2nd Measurement	7.9	1.8 — 24.0	36
	3rd Measurement	7.6	2.4 — 20.9	36
Background Samples:	1st Measurement	<0.11	0.04— 0.17	7
	2nd Measurement	<0.14	0.04— 0.66	13
	3rd Measurement	<0.15	0.04— 0.44	17

* highest sample excluded.

shown in Table 3 and Figs. 14 to 17. Mean Hg contents for successive measurements (Table 3) differ slightly (e.g. on lines A and D) or is markedly higher for the second and third measurements (Lines B and C). It can be seen in Figs. 14 and 17 that only occasionally —usually in the anomalous areas— does the first measurement have the highest mercury contents. The reproducibility is good between the second and third mesurements, and fair between the first and subsequent measurements in any one borehole as shown by their generally close agreement in the diagrams and by their similar mean Hg contents.

The previous comment does not include the highest anomalies. The differences observed between the first and subsequent measurements possibly indicate dilution of the soil-gas by atmospheric air in the immediate vicinity of the borehole and the closely agreeing results of the second and third measurements represent the undiluted soil gas.

Traverses A and B (Figs. 14 and 15) have high

Hg values (13.6 to 66 ng/l) over the estimated position of the veins. These anomalies are clearly detached from minor anomalies and a noisy background. The occurrence of mineralization on line C (Fig. 16) is signalled by a low contrast peak occurring at stations 5 and 10E. However, the Hg values on the wings of these traverses and outside known mineralization tend to be rather high (up to 7.0 ng/l Hg). Only stations far outside mineralization (420 E and 520 E on Fig. 14) have values close to background.

Line D (Figs. 13 and 17) traverses the projection of a SE trending vein and results showed up to four distinct anomalies to occur. The comparison of these results with those over mineralization on line A gives support to their anomalous character. The Hg content of samples occurring between anomalies tends to be high (up to 9 ng/l). As seen in Figs. 14 to 17 only limited coincidence of IP and resistivity anomalies with Hg anomalies was found.

FIG. 14.   Mercury in soil gas on line A at Cachinal.

FIG. 15.   Mercury in soil gas on line B at Cachinal.

FIG. 16. Mercury in soil gas on line C at Cachinal.

KEY

Samples:
— 1 st
— — 2 nd
.... 3 rd
—— IP anomalies
—•— Resistivity anomalies

FIG. 17. Mercury in soil gas on line D at Cachinal.

KEY

Samples
— 1 st
— — 2 nd
.... 3 rd
▮ Vein projection
—— IP anomalies
—•— Resistivity anomalies

FIG. 18. Distribution of silver and arsenic in soils from line A at Cachinal.

The chances of spurious Hg vapour anomalies arising from the overburden materials over the area of the veins are estimated to be minor, since drilling showed there the occurrence of decomposed bedrock at depths up to 2 m and soil geochemical data showed low ore metal concentrations to occur on line A residual soil material (Fig. 18). This is consistent with geological data indicating a thick leached zone on the upper part of the deposit. It is concluded, therefore, that the high anomalous mercury contents occurring over the area of the veins on lines A and B are derived from mineralization occurring at depth. The wide dispersion of mercury for up to 200 m on either side of the veins would give rise to the background noise observed in all lines.

It seems justified to consider the anomalies observed on the eastern side of lines A and B as related to possible concealed and unknown mineralization. A similar conclusion is put forward for line D, where at least four anomalies occur which could be related to hitherto unknown mineralization. The generally lower mercury levels measured over line C (Fig. 16) are consistent with reported geological data (Kuntz, 1928) which suggested that mineralization was poor in the vicinity of this line and it was unlikely to continue further north. One exceptionally high value was detected on line C (station 320 E; Fig. 16), which coincides with an IP anomaly, and might indicate the occurrence of mineralization; a similar anomaly occurs at station 160 E.

Limited exhaustion tests which consisted of pumping a series of consecutive sub-samples at any one site, indicated that soil-gas Hg contents decreased slightly (e.g. from 3.0 down to 2.6 ng/l for station 200 E on line A) and then remained approximately constant in up to four successive sub-samples. This is taken to indicate a continuous supply of mercury vapour from the bedrock and no dilution of the soil-gas after the pumping of up to 4.5 l of soil-gas. The extraction of a 5 l volume of soil-gas would affect a volume of approximately 0.025 m^3 of overburden (assuming a porosity of 20%) By comparison, exhaustion tests carried out at stations 200 to 420 E on Line C, showed almost complete depletion of the soil-gas mercury content at most sites. These results are estimated to indicate a weaker source of mercury in depth and possibly, dilution by atmospheric air due to the greater permeability of the overburden on this line. Al-
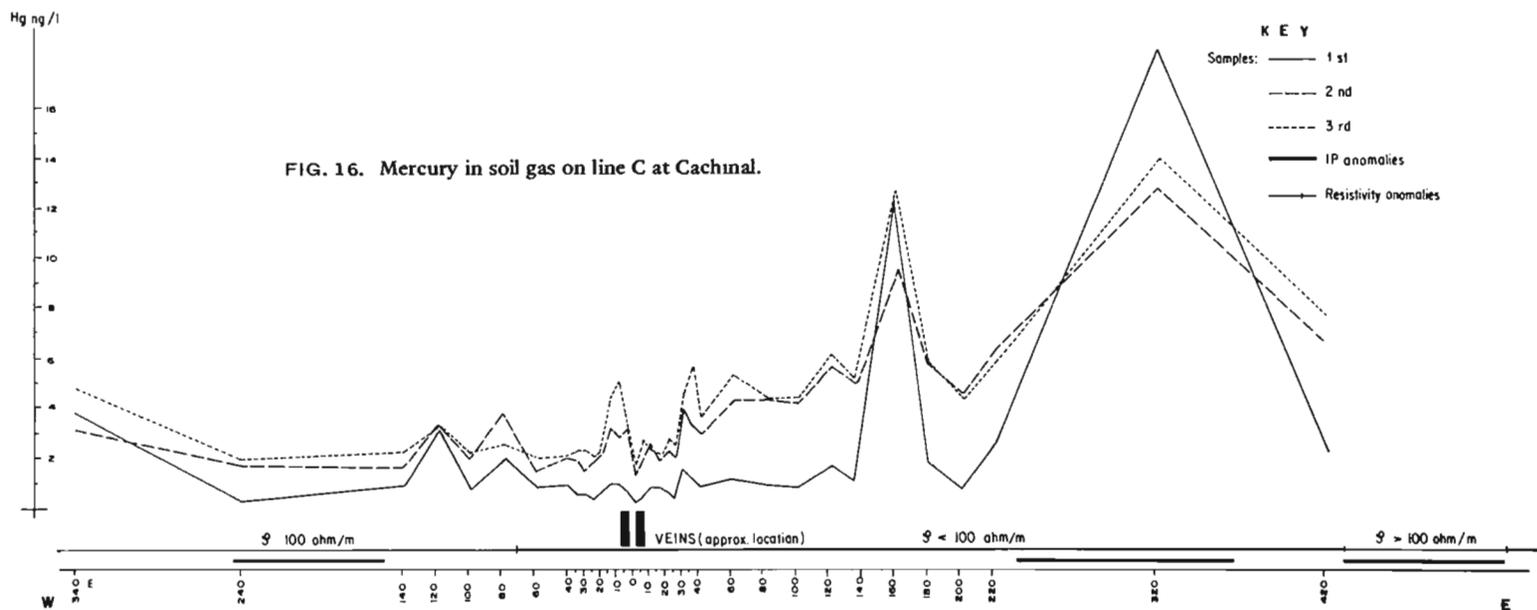
though the limited amount of data do not allow a definite conclusion, it is suggested that exhaustion tests might provide a means of assessing the potential of anomalous areas, by testing the relative strength of their anomalies.

Results for the traverse over unmineralized terrain (Table 3) located along line A (traverse 2 on Fig. 12) and extending from 570 to 1,570 m to the east of the veins appear to be reproducible, although of the 20 stations sampled many results are below the detection limit of the Scintrex HGG-3 spectrometer (about 0.02 ng/l Hg) (Table 3). However, a relative depletion of the first sub-sample for every station (Table 3) is deduced from the fact that more measurements above detection limit were made in subsequent samples.

The mercury contents for the traverse over unmineralized terrain were very low and ranged from 0.04 to 0.66 ng/l Hg (Table 3). Of the 60 samples, collected at 20 stations located 50 m apart, only 37 were above the detection limit of the spectrometer (about 0.02 ng/l Hg). The values found on this traverse are taken to represent the background mercury content in soil-gas over unmineralized bedrock.

In summary, it can be concluded that the occurrence of known veins is readily detected by measurements of soil-gas mercury, although the anomalies obtained might span only a few metres. Lesser anomalies, especially those occurring up to 200 m east of the veins on lines A and B, might correspond to concealed mineralization of perhaps a more disseminated nature, as deduced from their lower Hg contents and wider span. The mercury vapour anomalies appear to be strongly controlled by faulting (the highest values found occur over the large structure associated to the main veins) and this could explain in part the noisy background generally observed, specially on line D. The anomalies on line D appear to correspond to buried mineralization and this is supported by their similitude with the easternmost anomaly, which is related to a possible vein. However, the lack of correlation with IP and resistivity anomalies decreases their significance, and suggests that they may correspond to fractures which tap mercury vapour originating from the primary halo but are otherwise not related to the occurrence of mineralization.

Geological and ground-water data indicate that active oxidation of sulphides mineralization takes place at depths of up to 320 m (Kuntz, 1928). It

is concluded therefore that mercury vapour originates primarily from the oxidizing sulphides and might also be released in smaller amounts from secondary mineralization occurring above the present ground-water level. The latter is based on the fact that high levels of mercury are generally associated with Ag minerals (Jonasson and Boyle, 1972).

Analysis of a number of rock samples (Table 2) for the Cachinal area, which were collected at random from mine dumps and prospecting trenches, showed compartively low mercury contents (up to 2.2 ppm). However, these samples do not adequately represent the mineralization, since only exceptionally were Ag contents found to exceed a few hundred ppm.

Radon in Soil Gas

The total activity count measured by the Rn detector represents the sum of the activities of Rn and any thoron that might be present in the soil-gas sample being analyzed. Although no attempt was made during this study to measure the thoron contribution to the total sample activity, it is estimated that this is small and the analytical procedure provides an opportunity to evaluate its contribution as explained below. The thoron which might be present in the soil-gas samples can only be derived from the overburden materials, since its short half-life (56 seconds) only allows its migration over short distances of the order of a few centimetres. Furthermore, it is unlikely that Th^{232}, the parent of thoron, is enriched in the overburden due to its low mobility as compared to U. The decrease in the total activity counts observed between the first and further sub-samples could be due to the smaller contents of thoron likely to be found in the second and third sub-samples. The reason for this is that these sub-samples remained inside the duraluminium probe for three to six minute before being analyzed, due to the operational time lapse between analyses; this period is sufficiently long for an important part of the thoron to decay inside the probe. The probe and detector cell have comparable inner volumes of about 0.5 l. On the other hand, the first soil-gas sub-samples are drawn inside the radon detector and analyzed immediately, and any thoron present will decay inside the detector cell, and will thus contribute to the total α activity count. It is concluded therefore
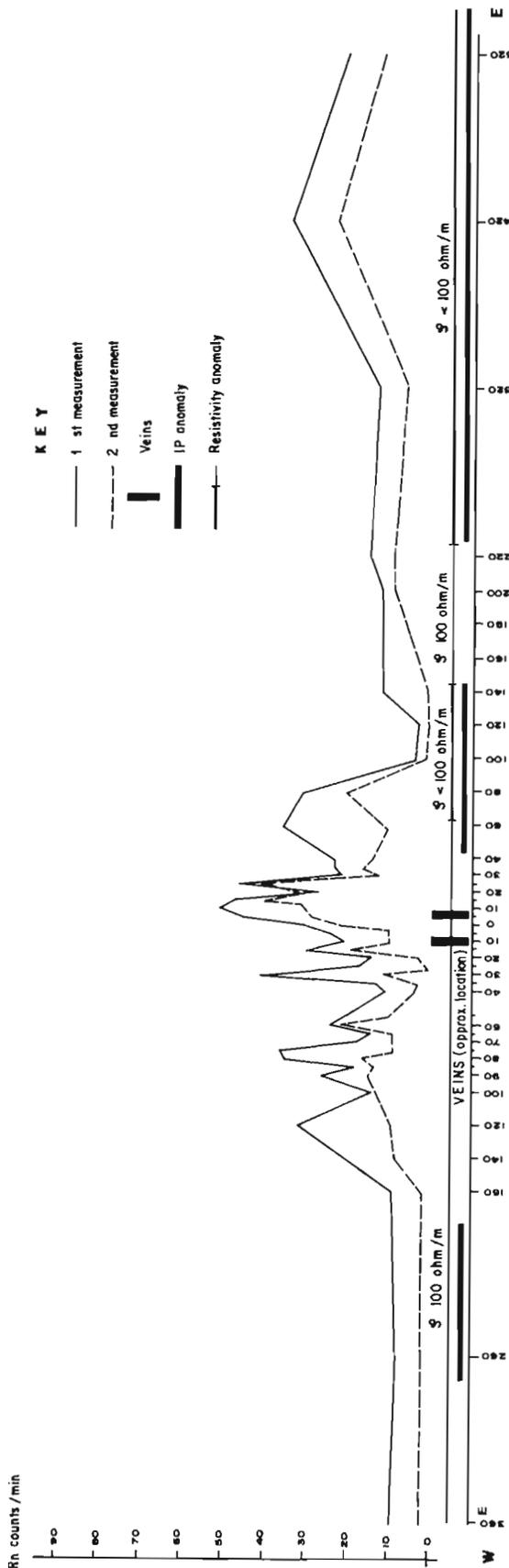
FIG. 19.　Radon in soil gas on line A at Cachinal.

that generally, the activities of the second and third sub-samples can represent more faithfully the actual Rn content of the soil-gas. However, this apparent deviation can be a statistic artifact due to the random variation of radioactive decay.

The results of on-site determination of Rn in soil-gas, using an EKCO Rn detector, at traverses A, B, C and D at Cachinal are shown in Table 4 and Figs. 19 to 22. It can be seen in Table 4 that within consecutive measurements, the first measurements usually had the highest Rn contents and a significant relative decrease was observed for further measurements, which were reproducible. These same situation was observed for the other traverses, including a background traverse (Traverse 2 of Fig. 11). The observed differences can be explained by the presence of overburden derived thoron in the first soil-gas sub-samples or by the Rn contribution of overburden materials, which have a rhyodacitic composition. However, the comparatively smaller differences observed for the areas above mineralization of traverses A and C suggest a predominance of Rn over thoron, which implies a larger supply of Rn derived from sources at depth. On traverse A (Fig. 19) all the high Rn measurements occur in a 220 m wide area centred on the mineralization. However, contrast is small compared to regional background (respective averages of 22 and 27 counts/min) and no anomalous features clearly related to known mineralization are observed for traverses B and D. Generally, no correlations were found between either IP or resistivity anomalies and high Rn contents on the various traverses.

It can be concluded therefore, that limited useful prospecting information was obtained by Rn measurements in soil-gas on traverse A but the strong control of gas migration through fractures obscured the results for the rest of the area. The high Rn background contents limit the usefulness of the technique. Also, it is concluded that three consecutive measurements provide sufficient prospecting information. The relative strength of Rn anomalies can be assessed by comparing first and further measurements. The use of 2 to 4 m deep boreholes for Rn in soil-gas prospecting allows the obtention of reliable information, and although the cost of borehole drilling might be a disadvantageous aspect of the technique, this is palliated by the fact that the holes can be used simultaneously for other vapour measurements.

Soil-Adsorbed Hydrocarbons

The term hydrocarbons is used here in a broad sense, implying organic compounds, containing C-H bonds the burning of which is the source of the response in the flame ionization detector of a gas chromatograph. The existence of hydrocarbons in different types of samples was deduced from the gas chromatographic response due to C-H bonds in components of the gas sample. The data were obtained in the form of total hydrocarbon contents measured in arbitrary peak height units (PHU) and peak area counts (PAC), and they are semi-quantitative.

Volatile forms of hydrocarbons were detected and measured by gas chromatography (GC) in overburden soils. Soil gas chromatography techniques (developed by Lovell, 1979) were used for

TABLE 4: MEAN AND RANGE OF Rn CONTENTS IN SOIL GAS AT CACHINAL*

		$\overline{X}$	Range	No. of Stations
Line A:	1st Measurement	23	1—51	41
	2nd Measurement	13	1—41	41
	3rd Measurement	12	1—33	39
	Anomalous Area (1st Measurement)	27	11—51	28
	Local Background	9	4	9
Line B:	1st Measurement	27	10—55	35
	Anomalous Area (1st Measurement)	29	14—55	23
Line C:	1st Measurement	19	3—39	35
Line D:	1st Measurement	27	4—63	36
Regional Background:	1st Measurement	22	6—33	20
	2nd Measurement	13	6—21	20
	3rd Measurement	13	3—27	20

* results in counts/min.

the analyses of soil-adsorbed gases. All soil-adsorbed gas analyses by GC used a 150°C desorption temperature and a 1 hour heating period. Reproducibility of these analyses was found to be acceptable (generally better than 10%) for all samples. All analyses were made in the −75 μm soil size− fraction of the samples after tests showed that this fraction gave the highest gas yields.

Soils from different depths collected on traverses A, B, C and D, and on one traverse over unmineralized terrain at Cachinal (traverse 1 on Fig. 11) were analyzed for volatile hydrocarbons and the results are listed in Table 5. Results showed that generally higher hydrocarbon content (up to 32 PAC) were found in surface and near surface soils (up to 0.5 m deep) whereas deeper soils had markedly lower total hydrocarbon contents (8 PAC or less; Table 5). The higher hydrocarbon contents of the surface and sub-surface samples can be explained by the comparatively higher gas collection efficiency of the clay-rich soils, as compared to the soils collected at a 3 m depth, which consist of rather coarse decomposed bedrock material.

Surface area determinations were made in −75 μm soils from traverse A at Cachinal (the analyses were kindly made in a Monosorb instrument, belonging to the Dept. of Mineral Technology at Imperial College, London, by Mr. C. Emmit). The results showed that the available specific surface area averages range from 5.0 to 10.0 m²/g. By comparison a highly efficient molecular sieve, such as Phase Separations 13x, has a specific surface area of 700 to 800 m²/g.

Resuts for soils from traverse A are shown in Fig. 23 and although it can be seen that the highest values occur above mineralization, contrast is small and many high values occur outside the mineralized area. Nevertheless, when comparing these results with those from the background traverse
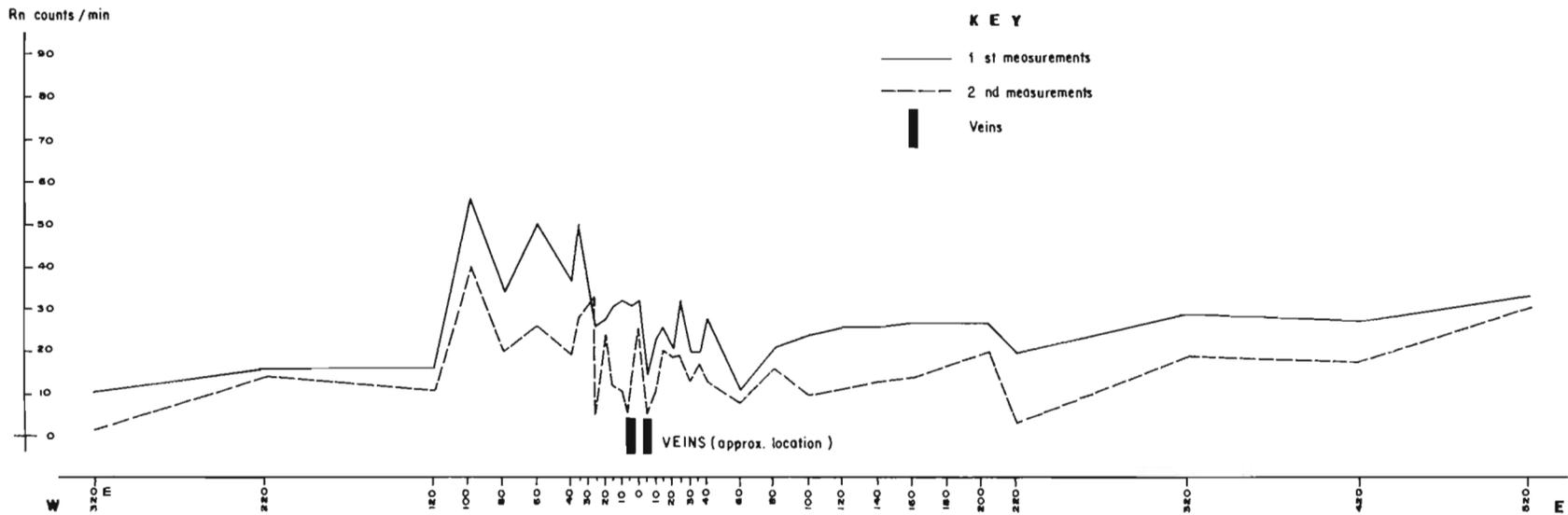
Rn counts / min

KEY

—— 1 st measurements

— — — 2 nd measurements

▌ Veins

VEINS (approx. location)

W ⋯ E

FIG. 20. Radon in soil gas on line B at Cachinal.

Rn counts / min

KEY

—— 1 st measurement

— — — 2 nd measurement

▌ Veins

▬▬ IP anomaly

—+— Resistivity anomaly

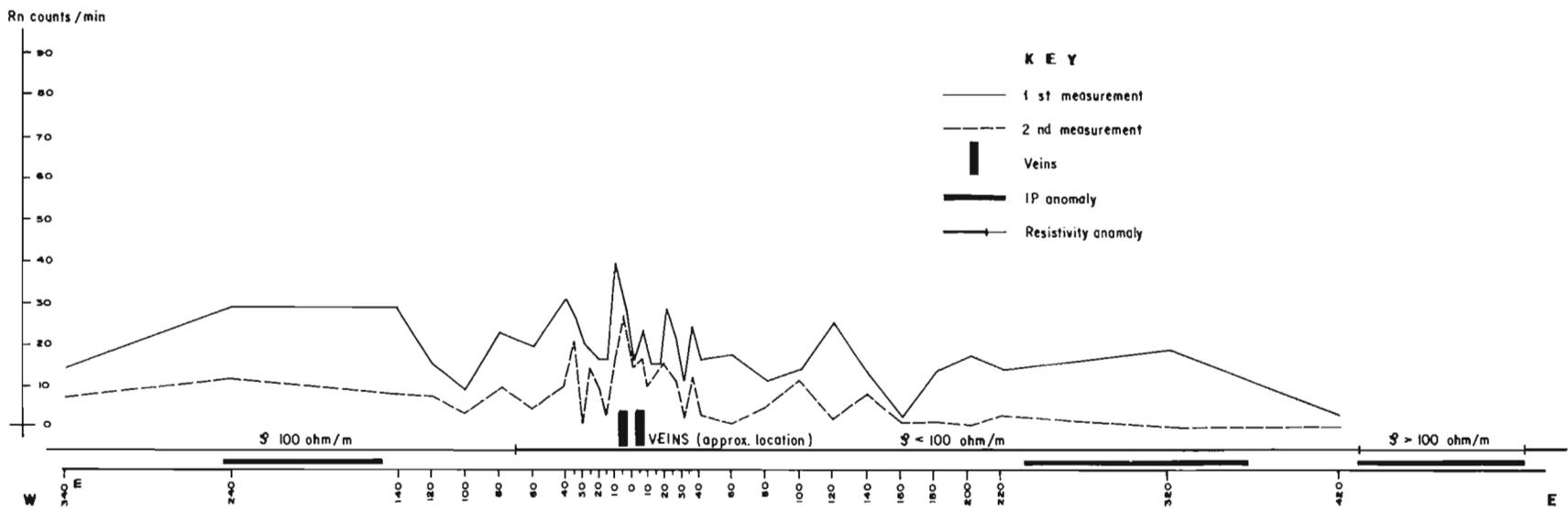𝜗 100 ohm/m   VEINS (approx. location)   𝜗 < 100 ohm/m   𝜗 > 100 ohm/m

W ⋯ E

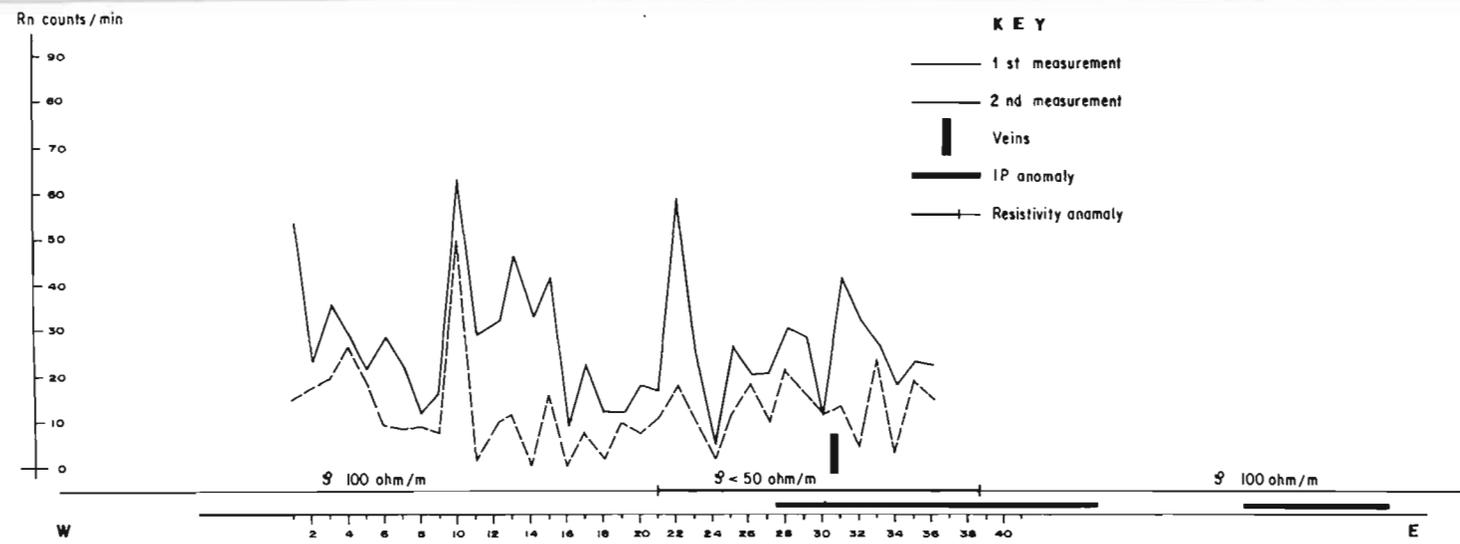FIG. 21. Radon in soil gas on line C at Cachinal.

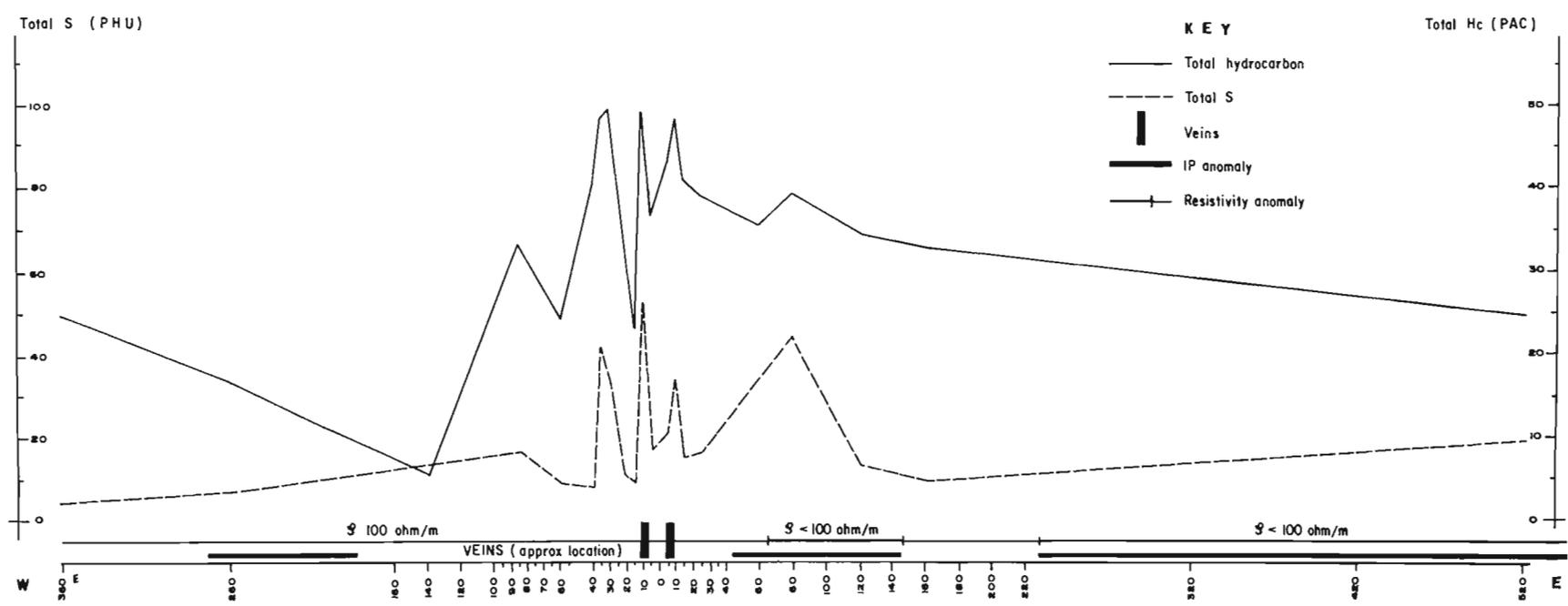FIG. 22.   Radon in soil gas on line D at Cachinal.

FIG. 23.   Hydrocarbon and sulphur gases in soils from line A at Cachinal.

(Table 5) they are clearly much higher. Hydro-carbon-gas contents were much lower for the other traverses and only those on traverse B (Fig. 24) indicated the occurrence of mineralization. No correlation of the results with geophysical anomalies was observed.

In summary, it can be said that hydrocarbon-gases adsorbed in soils appear to be of little use in prospecting for Ag vein type mineralization. It must be emphasized though that relatively little is known about the association of hydrocarbon-gases with mineral deposits. The results for soils showed

TABLE 5: TOTAL HYDROCARBON CONTENTS IN SOILS FROM CACHINAL

	Samples Depth	$\overline{X}$*	Range	No. of Samples
TRAVERSE A				
Surface Soils	0 to 5 mm	32	6—45	20
Sub-surface Soils	5 mm to 5 cm	34	17—49	21
Deep Soils	3 m	15	3—26	22
TRAVERSE B				
Sub-surface Soils	5 mm to 5 cm	16	4—28	16
Deep Soils	0.5 m	6	4—11	21
TRAVERSE C				
Surface Soils	0 to 5 mm	7	4—13	17
Sub-surface Soils	5 mm to 5 cm	6	4— 9	20
Deep Soils	0.5 m	5	3—11	24
Deep Soils	1.0 m	7	2—18	26
Deep Soils	2.0 m	6	3—13	22
Deep Soils	3.0 m	4	2— 8	27
TRAVERSE D				
Surface Soils	0 to 5 mm	28	19—41	34
Sub-surface Soils	5 mm to 5 cm	24	16—35	31
Deep Soils	0.5 m	27	4—47	30
Deep Soils	1.0 m	8	3—21	31
Deep Soils	2.0 m	6	3—12	32
Deep Soils	3.0 m	5	3—10	33
Background Traverse:				
Sub-surface Soils	5 mm to 5 cm	6	2—12	19

* All results expressed in arbitrary peak area count units (PAC) times 10^{-3}; 49 PAC aproximately equal to 500 ng/ml equivalent CH_4.
All samples were from the -75μm size fraction of soils.

apparently wide dispersion patterns for hydro-carbon gases and it is concluded that they are not good prospecting indicators.

Sulphur Gases

The total soil-adsorbed S analysis showed an acceptable reproducibility (generally better than 10%) for all samples. The -75μm soil size-frac-

tion was used for the obtention of all data here presented unless otherwise stated. This was done so after desorption tests showed that this fraction gave the highest S gas yield.

Soils collected at different depths from traverses A, B, C and D and from one traverse over unmine-ralized terrain at Cachinal (Traverse 1 on Fig. 11) were analyzed for their S gases content; the results are listed in Table 6.

TABLE 6: TOTAL S GASES IN SOILS FROM CACHINAL

	Samples Depth	Total Sulphur + X̄	Range	No. of Samples
TRAVERSE A				
Surface Soils	0 to 5 mm	10	3— 30	19
Sub-surface soils	5 mm to 5 cm	20	6— 45	19
Deep Soils	3 m	6	2— 11	22
TRAVERSE B				
Sub-surface Soils	5 mm to 5 cm	38	7—168	16
Deep Soils	5 m	61	2—200	20
TRAVERSE C				
Surface Soils	0 to 5 m	6	4— 10	17
Sub-surface Soils	5 mm to 5 cm	14	10— 22	20
TRAVERSE D				
Surface Soils	0 to 5 mm	12	10— 14	35
Sub-surface Soils	5 mm to 5 cm	19++	++12— 32	30
Deep Soils	0.5 m	138	10—912	29
Deep Soils	1.0 m	82	11—544	31
BACKGROUND SOILS				
Traverse C*				
Sub-surface Soils	5 mm to 5 cm	3	3— 8	20

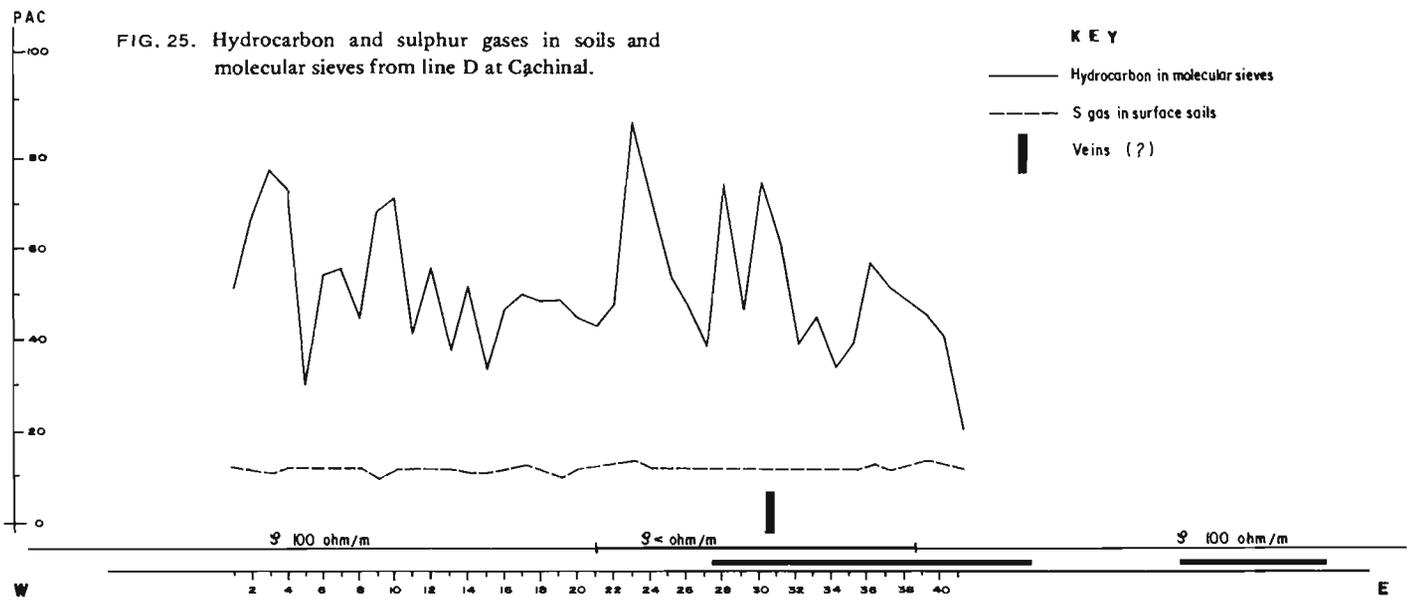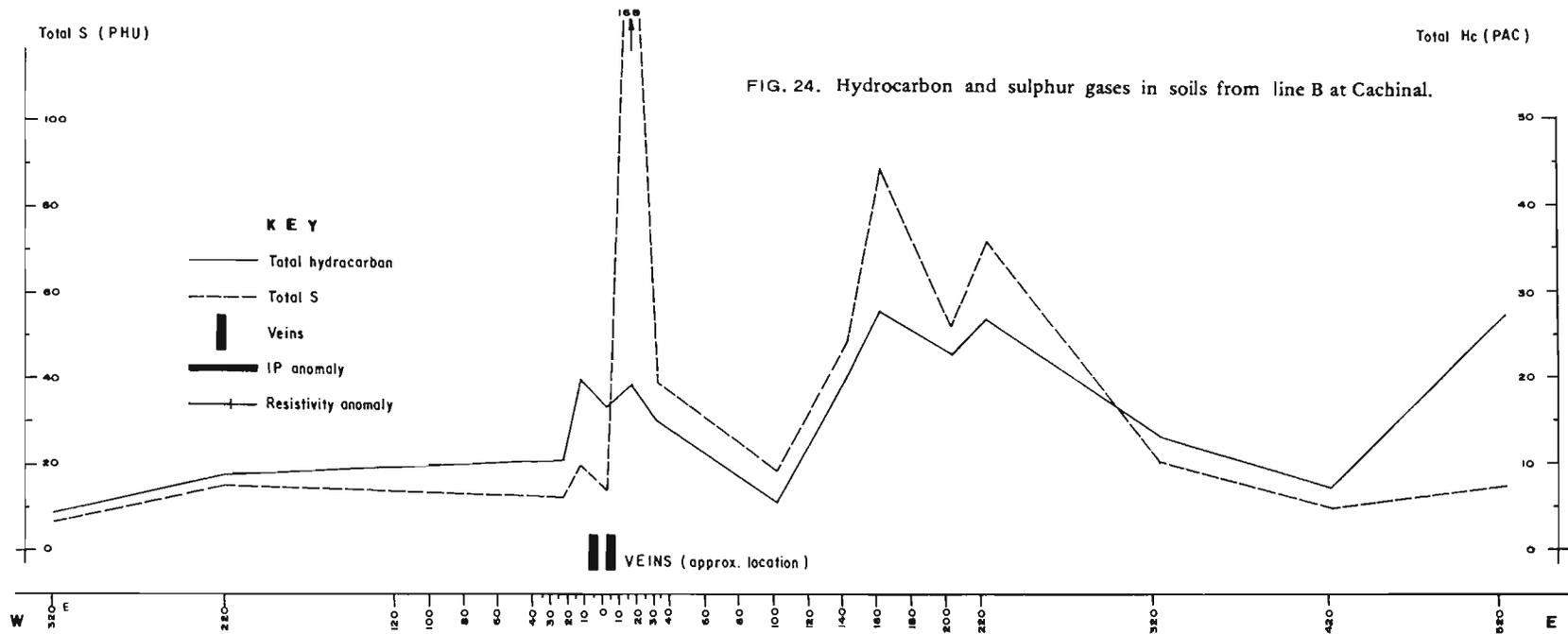Note: + Results in PHU; ++ Two high values (864 and 92 PHU) excluded;
     * Soils from 420 to 1,420 m.E. of veins on line C;
       All samples −75 μm fraction.

Surface soils (Table 6) generally have lower S-gas (up to 12 PHU) contents than sub-surface soils (e.g. Traverses 1, C and D). Deep soils from traverse A have low S values (mean 6 PHU), which are possibly related to its coarse, clay-poor nature (mostly decomposed bedrock materials).

On traverse A, the results from surface soils showed relatively low S gas values; one high S-gas value (21 PHU) occurred over station 10W (Fig. 23) which coincided with the mineralization. Relatively high S gas values occurred beyond the mineralization at stations 65W, 85W and 120W, but were not related to geophysical, IP or resistivity anomalies. The results from deep soils from traverse A showed even lower S gas contents (mean 6 PHU, range 2 to 11 PHU) as compared to surface soils and no indication of the mineralization was given

by them. By far the best results were those of sub-surface soils from traverse A (Fig. 23) which had the largest range of S gas contents (6-45 PHU). It can be seen that most of the high S-gas values (up to 45 PHU) occur above the area of the mineralization. Two distinct peaks appear to coincide with the occurrence of the veins, although the peak at stations 30 and 35 W could also be related to concealed mineralization or an important structure, given the fact that the location of the veins is only approximate. One high S gas value (49 PHU) occurs at station 80E which coincides with geophysical, IP and resistivity anomalies but otherwise no correlation was observed between these variables. Sulphur gas contents of less than 20 PHU occur beyond the area of the veins.

FIG. 24. Hydrocarbon and sulphur gases in soils from line B at Cachinal.

Total S (PHU)

Total Hc (PAC)

KEY

— Total hydrocarbon

— — Total S

Veins

IP anomaly

Resistivity anomaly

VEINS (approx. location)

FIG. 25. Hydrocarbon and sulphur gases in soils and molecular sieves from line D at Cachinal.

KEY

— Hydrocarbon in molecular sieves

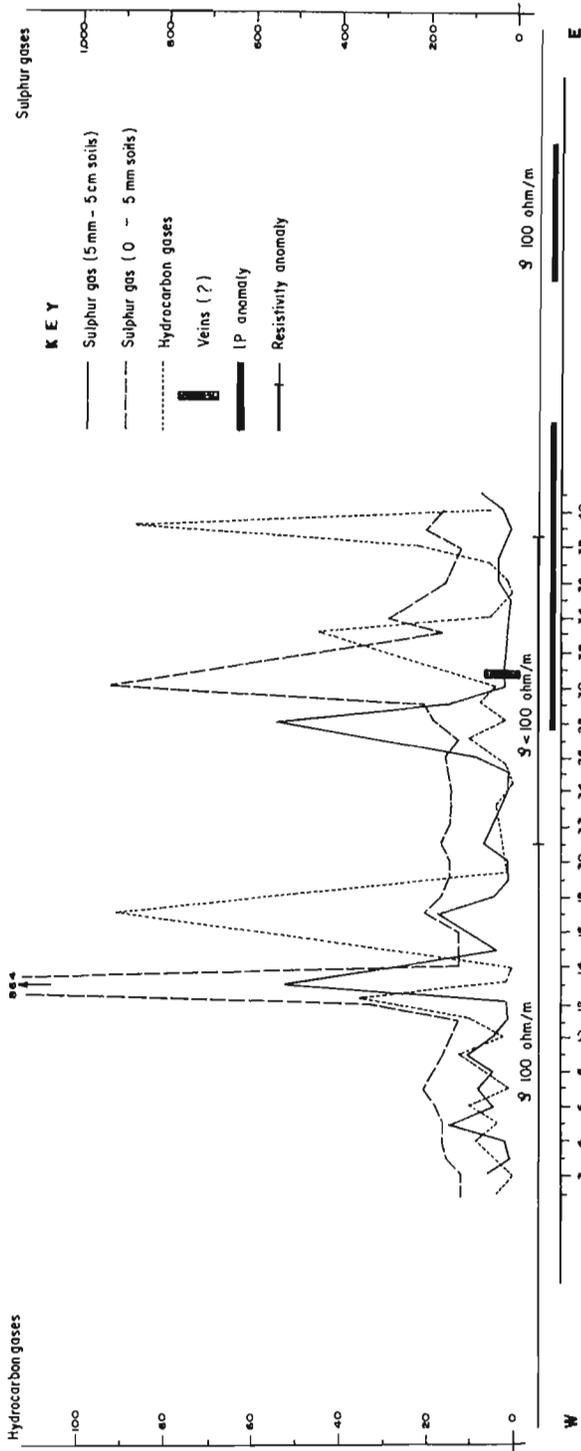— — S gas in surface soils

Veins (?)

FIG. 26. Sulphur gases in soils from line D at Cachinal.

Results from sub-surface soils from traverse B (Fig. 24) are based on the analysis of only 16 samples and show the highest S gas value to occur approximately over the location of the veins (station 15E). High S gas values (up to 110 PHU) occur at stations 140 through to 220. The reason for this anomaly is not known, but may perhaps be related to the occurrence of concealed and as yet undiscovered minerlization; however, no geophysical or geological evidence exists which could support the previous contention. Sulphur gas values beyond the areas described above are lower than 20 PHU. The results for deep soils from this traverse showed higher S gas values (mean 61 PHU, range 2 to 200 PHU) than those of sub-surface soils. However, the pattern of these values was similar to that of sub-surface soils (Fig. 24).

Results for traverse C surface soils are low (mean 6 PHU) and their range is also limited (4-10 PHU), a pattern similar to those of the traverse over unmineralized terrain (mean 3 PHU, range 3 to 8 PHU). No features which could be related to the mineralization or to geophysical IP and resistivity anomalies are observed. The results for sub-surface soils from traverse C were comparatively higher (mean 14 PHU), but their range was relatively small (10-22 PHU) as compared to those of sub-surface soils from traverses A, B and D.

Although the occurrence of mineralization beneath the gravels on traverse D has not been confirmed; some results of interest were obtained. The results from surface soils showed low S gas values (mean 12 PHU, range 10-14) and no indication of the presence of the conjectured vein of station 31 (Fig. 25) was observed, but the deeper soils showed higher S gas values. Thus, sub-surface and deep soils from this traverse (Fig. 26) showed several very high S gas contents (up to 864 PHU) to occur above the area stations 13, 17 and 27 to 40. The second highest S gas value for sub-surface soils occurs at station 30, above the estimated location of conjectured mineralization and within geophysical IP and resistivity anomalies. Two high S gas contents occur in deep soils (up to 600 PHU) at stations 27 and 33, and it is estimated that they could perhaps reflect a dispersion halo associated with a conjectured concealed vein (Fig. 26). The fact that several high S gas values occur over station 13 suggests that they could indicate the occurrence of mineralization, although no geophysical or geological evidence exists to support

KEY

CENOZOIC

o o o	Miocene-Pliocene gravels

PALAEOCENE TO MIDDLE EOCENE

/	Latite post-mineral dykes; ± 41 m.y. old.
+ + +	Granodioritic porphyry intrusives; ± 41 m.y. old.
x x x	Quartz porphyry intrusives; ± 45 m.y. old.
v v v	Quartz rhyolite intrusives; ± 45 m.y. old.
r r r	Rhyolite intrusives; ± 50 m.y. old

LOWER

≡	Undifferentiated volcanic
/////	Indio Muerto series volcanics; ± 50 m.y. old
w—w	Indio Muerto unconformity.
/////	Rhyolitic pyroclastics (probably Hornitos Fm. equivalent)
w—w	Hornitos unconformity

MESOZOIC — UPPER CRETACEOUS

v v v	Mainly andesitic sandstone and conglo-merates (probably Cerrillos Fm. equivalent)
w w w	Mainly andesitic flows and flow breccias (probably Cerrillos Fm. equivalent)

/	Fault
✕	Fold axis
∴∴	Recent stream detritus
—·—	Projection of principal copper centres
/	Limit of megascopic wall rock alteration

0 _____ 1 _____ 2 km.
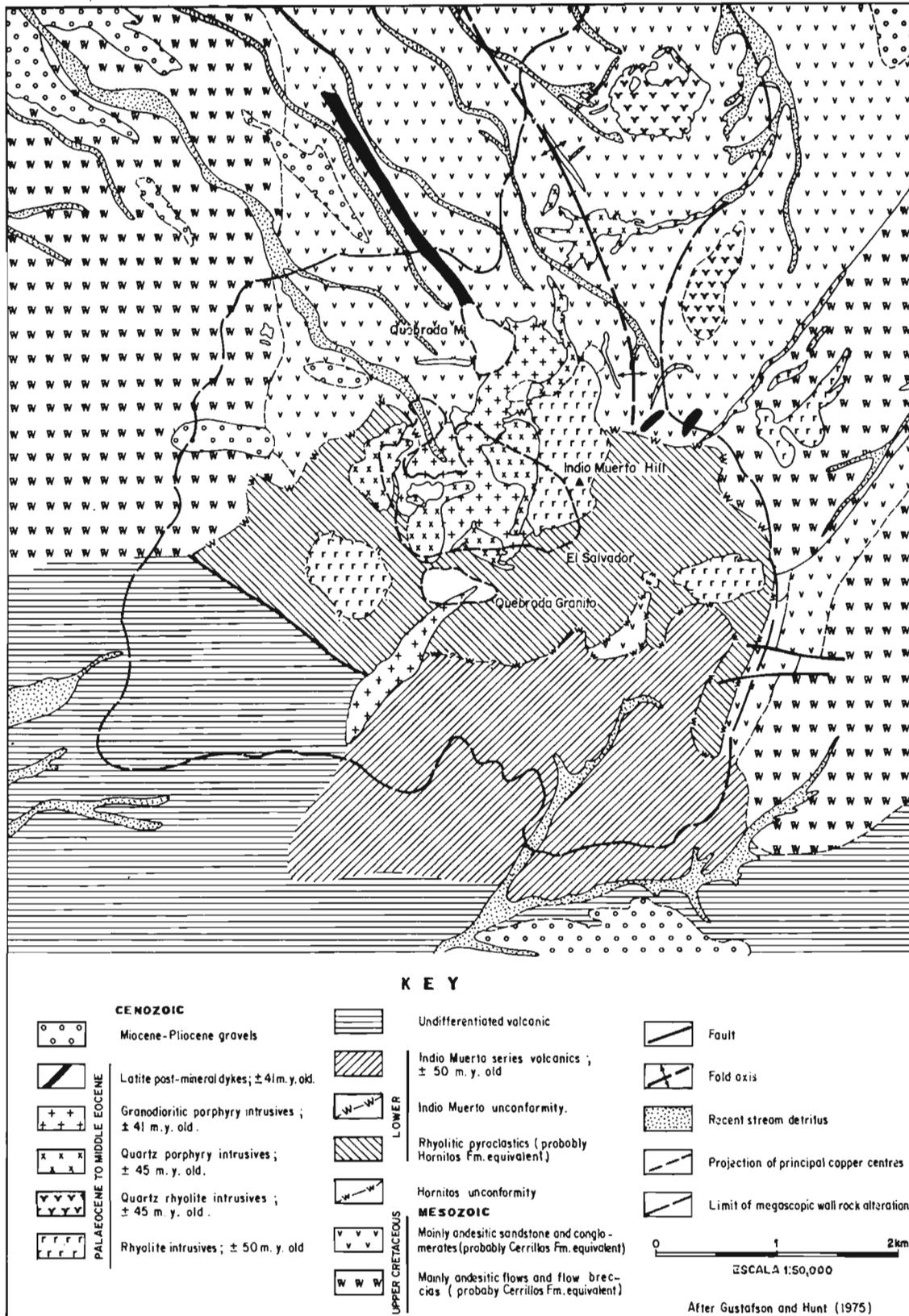
ESCALA 1:50,000

After Gustafson and Hunt (1975)

FIG. 27. Indio Muerto district geological map.

this contention. It is interesting to note that S gas contents in sub-surface soils outside the anomalous areas are fairly uniform and all lower than 20 PHU.

The low S gas values found on line C could be explained by the weak mineralization reported for this area by Kuntz (1928) and by the coarser nature of the overburden in this area. This could have a double effect, due to the greater permeability of coarse overburden and the relatively reduced adsorptive capacity of clay-poor coarse soils.

From the results described above it can be concluded that the application of soil-adsorbed S gas prospecting techniques to the exploration of the concealed Ag mineralization at Cachinal can be regarded as moderately successful. The fact that most anomalies comprise one or two samples (i.e., have little lateral dispersion) suggests a strong structural control of gas dispersion by faults. This fact restricts the applicability of this technique to detailed scale surveys. Near-surface soils appear to give sufficient prospecting information, but this depends on the adsorptive capabilities of the soils concerned.

QUEBRADA M DISSEMINATED COPPER DEPOSIT

This deposit forms part of the Indio Muerto district, which comprises several mineralized centres, the most important being the El Salvador porphyry copper deposit (Fig. 27). The geology of the Indio Muerto district was studied by Gustafson and Hunt (1975). The Quebrada M deposit (Fig. 27) is emplaced in the Upper Cretaceous andesitic rocks which occur in the northern part of the Indio Muerto district. The deposit is one of the main mineralized centres outside the El Salvador deposit itself and its southern end is in contact with the granodioritic porphyry intrusives which occur at El Salvador. The bedrock at Quebrada M consists mainly of porphyritic andesites and less abundant andesitic conglomerates as shown by diamond drilling logs. Intercalated with these are rhyolites, sandstones and andesite agglomerates. Intrusive feldspar and granodiorite porphyries, such as those found at the El Salvador deposit, cut them in places. Hydrothermal alteration is more intense towards the major granodioritic intrusives, where biotitization, argillization and sericitization of the host rock is observed. Towards the northwestern limit of the deposit, however, milder sericitization and propylitic alteration are predominant.

Intense supergene leaching has produced kaolinization of the upper part of the deposit. The Quebrada M deposit is covered by up to 15 m of rather coarse, feebly mineralized rock debris, derived from the erosion of the leached capping rocks from the Indio Muerto hill (Fig. 27), and by relatively thin (generally less than 2 m) colluvial soils which occur on the ridges flanking the gully at Quebrada M.

The Quebrada M deposit has an upper leached ore zone which overlies a secondary ore zone. The latter is underlain by primary sulphide mineralization. The thickness of the leached ore zone, characterized by equal amounts of copper oxides, relic sulphides and limonites ranges from 40 to 80 m. Ore grades range from 0.1 to 0.4% total Cu and only exceptionally reach 1.0% Cu. Rare oxide and mixed oxide-sulphide ores occur in places. Grades commonly reach 1.3% Cu and as much as 4.1% total Cu grades are found in oxide ore sections; mixed ore, although rare, can reach up to 2.3% total Cu. The thickness of secondary sulphide ores varies greatly between 15 and 90 m; the ore is composed mainly of chalcocite, covellite and pyrite, with minor chalcopyrite; grades are consistenly higher than 1% total Cu and reach up to 2.5% Cu in places. The mineralization is richer near the El Salvador deposit, whereas the northwestern end of the deposit is characterized by a pyrite rich ore with very low copper grades (below 0.1% total Cu). The primary sulphide mineralization underlies the secondary sulphides and its maximum extent is not known; grades are generally lower than 0.3% total Cu but can be as high as 0.5% Cu in places; the primary mineralization consists of chalcopyrite and pyrite.

Mercury analysis on 51 diamond-drilling core samples showed that 16 of these had mercury contents between 45 and 100 ppb (Arias, 1979). The rest of the samples had mercury contents of less than 9 ppb. Olade (1977) reported similar contents, i.e., 5 to 100 ppb, for porphyry copper deposits.

An IP geophysical survey was carried out at the deposit by IIG, in 1975, which showed the occurrence of anomalies with a fairly good coincidence with mineralization as shown by diamond-drilling data.

No underground water has been observed in the district (A. Tobar, pers. comm., 1976) which agrees

with the observation by Mortimer (1973) of depressed water table levels in the central and western parts of the Atacama desert. Futhermore, A. Tobar (pers. comm., 1976) estimated that the water table could perhaps be more than a hundred metres below the Quebrada M level.

MERCURY VAPOUR IN SOIL GAS SURVEY

Soil-gas mercury contents were measured by means of a Scintrex HGG-3 portable spectrometer at two different unmineralized areas and on one traverse located over that part of the Quebrada M deposit covered by transported overburden. The unmineralized areas were located up to 7 km respectively south and southwest of Quebrada M. The samples were collected in 1.5 to 2.5 m deep auger-drill holes by means of a specially developed in-hole probe (Fig. 4).

All measurements made at nine stations in the unmineralized areas were below the detection limit of the instrument employed (about 0.02 ng/l Hg). The mercury concentrations measured in the traverse over the deposit ranged from 0.11 to 1.0 ng/l. Consecutive measurements showed mean mercury contents of 0.25 ng/l and 0.30 ng/l (respective ranges were 0.11 −0.77 and 0.1 −1.0 ng/l Hg) for the mentioned traverse. A tendency to increase was observed for the second consecutive measurements taken in any given day at most stations (e.g. 0.30 ng/l Hg with respect to 0.26 ng/l Hg; and 0.26 with respect to 0.20 ng/l Hg, for two different sampling days). No major difference was observed between samples from the area above copper disseminated mineralization and the pyritic area outside it. Due to the absence of a water table, the measured mercury vapour contents of soil-gas at Quebrada M can only be explained by the release of Hg from the mineralization produced without active oxidation of the sulphide ore.

Extensive dispersal of mercury may have occurred due to relatively high formation temperatures of the late and post-mineral (hot-spring) mineralization stages (respectively 350-600° and 350°C) which were responsible for most pyrite mineralization (Gustafson and Hunt, 1975). This may, in turn, explain the relatively low Hg content of the bedrock (5 to 100 ppb) and the similar contents of Hg in soil-gas found for the copper ore zone and the area occurring up to approximately 700 m from the deposit. It is estimated that no

significant contribution of Hg vapour to the soil gas was made by the overburden materials, which consist of feebly mineralized, intensely leached rocks derived from the Indio Muerto hill (Fig. 27). Also, it seems that the relatively thin (up to 15 m) overburden does not constitute an obstacle for mercury migration.

In summary, mercury contents in soil-gas from one traverse surveyed at Quebrada M are up to one order of magnitude higher than the values measured over unmineralized areas. However, the mercury levels are nevertheless low and this is explained by: 1) the low mercury contents of the mineralized bedrock;. 2) the lack of active oxidation of sulphides. It is concluded that prospecting for a concealed disseminated copper deposit where no active oxidation of sulphides is taking place, by the Hg vapour technique, is unlikely to provide useful data.

In addition, a comparison of mercury contents of the -75 μm size fraction of soils from the unmineralized and mineralized areas at Quebrada M failed to provide a distinct indication of the occurrence of mineralization at Quebrada M. Respective ranges were 3-12 ppb and 2-91 ppb Hg. These contents are within the ordinary range for mercury abundance in soils (70 ppb; Jonasson and Boyle, 1972).

RADON IN SOIL GAS SURVEY

Radon measurements in soil-gas were taken on one traverse over the Quebrada M deposit using an EKCO portable Rn monitor. The results indicated very low Rn contents for two consecutive measurements (respective arithmetic means were 6 and 4 counts/min; respective ranges were 1-10 and 1-11 counts/min). These values are similar to the atmospheric background of the area which is smaller than 5 counts/min Rn. Repeat measurements in the sampled traverse, made on a different day, showed similar low Rn contents in soil-gas.

It was concluded, from the results described, that no indication of the occurrence of mineralization was given by the measurement of Rn contents in soil-gas at Quebrada M. The low Rn contents found in soil-gas are consistent with low U contents showed by the analysis of 11 diamond-drill core samples from the deposit (average 1.4 ppm U). Also, it was estimated that the contribution to the soil-gas Rn burden from the over-

TABLE 7: TOTAL SOIL-ADSORBED HYDROCARBON GAS CONTENTS FROM QUEBRADA M SOILS*

	Sample Depth	$\bar{X}$	Range	No. of Samples
QUEBRADA M				
Soils	0.4 to 1.1 m	11	8—17	10
BACKGROUND AREA				
Soils	0.5 to 1.8 m	10	7—16	7

* Results in arbitrary "peak height units" (PHU).

burden materials was possibly small, since its materials are derived from the feebly mineralized, intensely leached cap-rocks from the Indio Muerto hill.

It was finally concluded that the detection of the mineralization by measurements of the Rn content of soil-gas at Quebrada M was not feasible due mainly to the low contents of U in the mineralized bedrock, the high permeability of the overburden and the lack of a water table. The latter can help to create accumulation of radioactive elements from a deep primary source closer to the surface (Israel and Bjornsson, 1967) and enhance Rn release (Andrews and Wood, 1972).

Soil-Adsorbed Hydrocarbon Gases

Sub-surface soils (0.4 m to 1.1 m) from a single traverse over this deposit were analized for their total adsorbed hydrocarbon gas contents by means of a gas chromatographic technique developed by Lovell (1979). A limited number of samples from unmineralized areas were also analyzed for hydrocarbon gases. All soils analyzed were from the −75 μm size fraction of the sample. The results are shown in Table 7.

Results from soils in Table 7 show similar mean values for both mineralized and unmineralized areas (respectively 11 and 10 PHU), as well as similar ranges (respectively, 8 to 17, and 7 to 16 PHU). Thus, no indication of the occurrence of mineralization is given by adsorbed hydrocarbon in soils. The clay-poor nature of the soils may have influenced the low hydrocarbon gas contents found. It is concluded that no useful prospecting information is given by soil-adsorbed hydrocarbon gases over unoxidizing disseminated sulphide cop-

per deposits. Nevertheless, further research in other areas is required to prove or disprove this contentión.

Soil-Adsorbed Sulphur Gases

Results from the analysis of 10 overburden soil samples, collected at depths of 0.4 to 1.1 m from a single traverse at Quebrada M, showed low total S gas values (mean 10 PHU); these contents are similar to those of six soil samples from an area considered to represent regional background (mean 6 PHU).

The low S-gas contents found in Quebrada M soil can be explained by the absence of active sulphide oxidation in the area. Also, the clay-poor nature of the soils could be responsible for their limited adsorptive capacity. It is concluded that the prospecting of concealed disseminated copper sulphide mineralization not undergoing active oxidation is not feasible by measurement of the adsorbed S gas in clay-poor soils.

PAMPA NORTE PORPHYRY COPPER DEPOSIT

This deposit is part of the Chuquicamata district, which comprises the Chuquicamata, Pampa Norte and Exotica copper deposits (Fig. 28). The geology of the Chuquicamata deposit, whose porphyries are similar to those at Pampa Norte, was described by Ambrus (1975). The Pampa Norte deposit is the northern extension of Chuquicamata and its geology was described by Tufiño (1973). At Pampa Norte, granodiorite porphyries of possible Eocene age and similar to those at Chuquicamata are the host-rocks to mineralization (Fig. 28). The length of the porphyries is of the

WEST FAULT

Pampa Norte deposit

Chuquicamata deposit

Exótica deposit

CENOZOIC

Miocene gravels

Chuquicamata parphyry with intense quartz-sericite alteration

Chuqui parphyry and granitoid porphyries of various textures

Fortuna granodiorite

Laja granodiorite

El Mineral dacitic porphyry

MESOZOIC

Jurassic

Andesitic volcanics

Marine and/ar continental coarse sediments

Marine sediments, mainly lime - stone and shales

Elena granodiorite

Este granite

PALEOZOIC

Migmatitic granites

Mesa granite

Geological contacts; inferred and observed

Fault; inferred and observed

Contours every 200 m
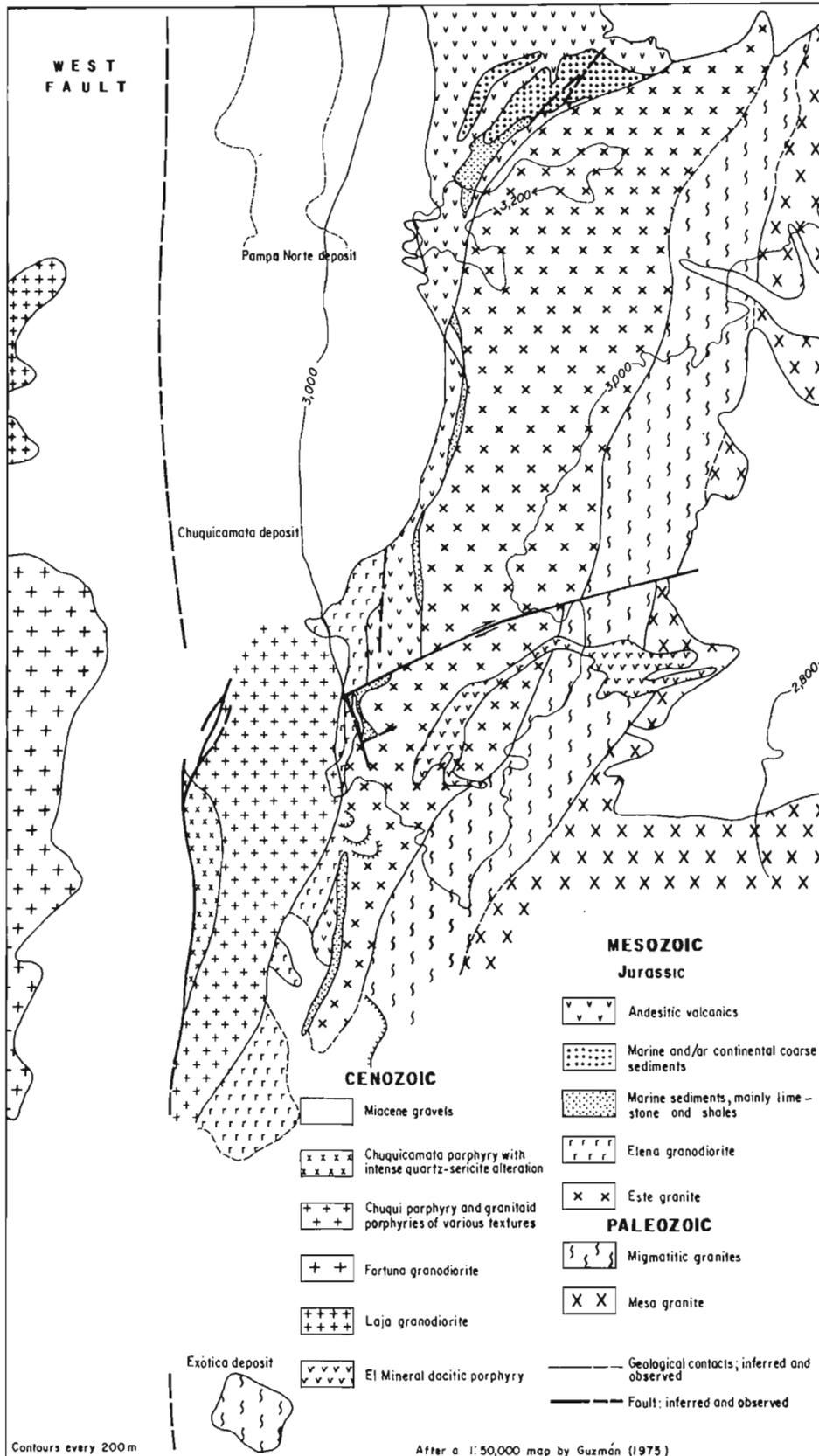
After a 1:50,000 map by Guzmán (1975)

FIG. 28. Chuquicamata district geological map.

order of 10 or more km in a north-south direction, and its average width is some 800 m, wedging towards the south. The West Faults is a vertical regional structure, observable for at least 200 km from Chuquicamata to the north (Fig. 28) and which bounds Pampa Norte deposit on the west; the trace of the fault is visible along most of its length, where it cuts rock formations as well as relatively young unconsolidated sediments. The structural features of the fault are very complex and two main tensional fracture systems striking NE and NW are recognized.

Three main types of granodioritic porphyry are recognized at Chuquicamata (Ambrus, 1975) and they were subjected to various alteration processes; they are called West Porphyry, East Porphyry and Banco Porphyry, and are collectively referred to as Chuquicamata porphyry (Fig. 28). Ore mineralization at Pampa Norte occurs in the West and East Porphyries, whereas at Chuquicamata it occurs in all three types. Ambrus (1975), stated that the West Faults predates the mineralization, since primary mineralization features are controlled by it. Overall control of the mineralization and alteration at Pampa Norte is exerted by locally dominant structures derived from the West Fault. Tufiño (1973) recognized potassic and sericitic alteration at Pampa Norte. The potassic alteration is uniformly distributed throughout most of the deposit. Sericitic alteration is limited in extent and is mostly associated with highly fractured zones.

Vast areas of the Chuquicamata district are covered by gravels of Miocene age (Mortimer and Saric, 1975). The Pampa Norte deposit is completely buried by unconsolidated piedmont gravels up to 150 m thick (average is 90 m). Thus, geological information on the deposit is based exclusively on the study of diamond-drill cores. Although 154 drill holes, representing 36,000 m of rock core, have been put into the Pampa Norte area, the maximum depth and lateral limits of the deposit are not known. The overburden at Pampa Norte is composed mainly of piedmont gravels (Fortuna gravels), talus debris and mud-flow deposits, with some alluvial gravels. These materials are poorly sorted and stratified and mostly unconsolidated. The fragments in them are mainly of the same intrusive rocks which occur in the Chuquicamata area.

The surface of the gravel oberburden is covered by a thin (0.2 to 1 m thick) clayey soil horizon,

itself underlain by a saline horizon (caliche) of up to 6 m thickness; the caliche horizon is continuous and formed mainly by gypsum. Fragments of granodiorite, granite and andesite are embedded in the caliche.

Mineralization at Pampa Norte extends form coordinates N 6,500 to N 12,000 (Chuquicamata grid system) and laterally form E 3,500 to E 4,500 (Fig. 29). The area most intensely drilled, which extends from N 10,200 to N 12,000 coordinates (Fig. 29), was chosen as the study area. Leached, oxides and sulphides ore zones are distinguished at Pampa Norte, as shown in a typical section (Fig. 30). The leached ore zone has Cu grades of up to 0.36%, of which about half is soluble copper. The occurrence of limonites together with minor amounts of up to 0.2 % oxidized copper ore, present mainly as atacamite with minor brochantite and antlerite, is characteristic.

The oxide ore zone locally underlies the leached zone as shown in Fig. 30, and has mean grade o 0.90% total Cu; main Cu mineral is atacamite with minor brochantite and antlerite. Commonly the oxide ore zone is overlain and at the same time underlain by a leached ore horizon of variable thickness. However, oxide ores are also found to occur in the bedrock surface and in direct contact with the underlying sulphides.

A sulphide mineralization zone, formed by secondarily enriched sulphides and hypogene sulphides occurs at depths ranging from 210 to 310 m below the surface. Only exceptionally is sulphide mineralization found at depths of less than 200-300 m due to intense leaching. Ore grades can be as high as 1.60% total Cu, although they are generally lower than 0.9% Cu. The secondary sulphide mineralization is formed by a thin, 2 to 50 m thick, enriched horizon with a comparatively smooth surface and underlain by primary sulphide ore of still unknown extent. The main secondary Cu mineral is chalcocite, which shows typical replacement textures. Covellite is rare and together with chalcocite replace chalcopyrite and bornite which are the primary ore minerals. Pyrite is rare at Pampa Norte. Minor molybdenite mineralization was described by Tufiño (1973) as occurring associated with quartz veins.

Diamond-drill cores from selected holes at Pampa Norte (Fig. 29) were analyzed by AAS for Cu and Fe, and for Hg by a cold-vapour AAS technique. U analyses were done by NAA in a
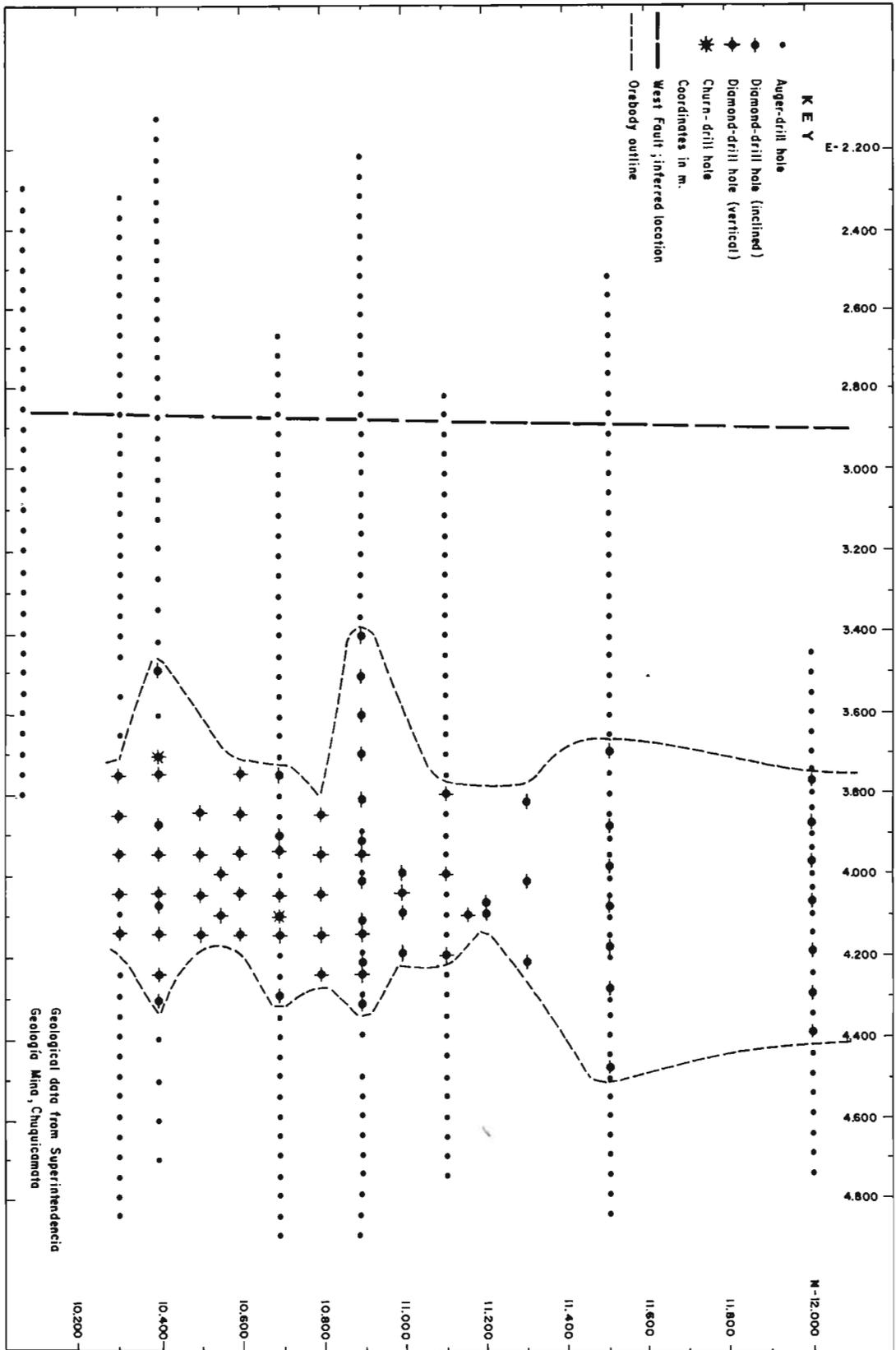
FIG. 29.   Location of sampling stations at Pampa Norte.

TABLE 8: SUMMARY OF ANALYTICAL RESULTS FOR DIAMOND-DRILLING CORES FROM PAMPA NORTE

ORIGIN OF SAMPLES			Cu (%) $\bar{X}$	S	n	Fe (%) $\bar{X}$	S	n	U (ppm) $\bar{X}$	S	n	Hg (ppb) $\bar{X}$	S	n
Traverse N10,050:	DDH 1287	(E3,600)	1.5	1.2	24	—	—	—	3.8	2.2	24	6	3	21
	DDH 1296	(E4,000)	1.6	0.8	12	—	—	—	7.5	6.9	12	6	3	12
	DDH 1298	(E4,100)	1.5	1.7	32	—	—	—	9.3	10.0	31	6	3	25
	DDH 1277	(E3,800)	1.6	1.9	35	—	—	—	5.1	2.2	35	2	1	31
Traverse N10,400:	DDH 1178	(E4,150)	0.75	0.63	15	0.31	0.17	15	3.5	1.8	9	8	5	10
	DDH 1167	(E3,950)	0.70	1.10	11	0.52	0.40	11	2.9	1.6	10	6	4	4
	DDH 1170	(E3,750)	0.67	1.00	14	1.07	2.36	15	—	—	—	8	5	10
Traverse N10,700:	DDH 1152	(E4,050)	1.06	0.60	21	0.63	0.52	21	—	—	—	9	4	24
	DDH 1134	(E4,150)	2.44	2.11	15	0.53	0.27	15	—	—	—	5	4	9
Traverse N10,900:	DDH 1117	(E4,250)	1.36	1.59	14	0.60	0.60	14	5.2	2.5	7	18	13	10
	DDH 1119	(E4,150)	1.61	1.27	12	0.50	0.30	12	2.8	—	2	—	—	—
	DDH 1124	(E3,950)	0.88	1.59	18	0.80	1.5	18	3.0	2.2	8	8	6	12
Traverse N11,100:	DDH 579	(E3,800)	0.88	0.95	17	0.64	0.48	17	4.7	5.5	8	13	9	16
	DDH 563	(E4,700)	0.92	0.92	18	0.74	0.63	18	2.4	1.2	5	14	18	17
Traverse N11,500:	DDH 539	(E4,090)	0.57	0.42	15	0.51	0.17	15	—	—	—	7	3	11
	DDH 559	(E3,695)	0.22	0.23	7	1.88	2.58	7	—	—	—	9	1	7
	DDH 552	(E4,295)	—	—	—	—	—	—	—	—	—	14	16	3
Traverse N12,000:	DDH 514	(E4,400)	0.89	1.95	19	1.10	0.98	19	3.4	2.0	10	18	9	10
	DDH 519-A	(E4,200)	0.78	1.00	20	1.25	1.31	20	2.8	0.8	11	13	7	18
	DDH 528	(E3,980)	0.34	0.43	9	1.82	1.06	9	1.8	0.3	5	—	—	—

n = number of samples.

number of samples (Table 8). From the results in Table 8 it is apparent that copper contents range relatively widely (0.22 to 2.44% Cu), reflecting the existence of the intensely leached capping rocks at Pampa Norte. Iron contents show a similar behaviour (they range from 0.31 to 1.88% Fe) and iron values are highest in the leached rocks, due to the abundance of limonite.

Uranium contents are higher than the average content for granodiorite (2.5 ppm; Rich *et al.*, 1977) in most diamond-drill holes and they range from 1.8 to 9.3 ppm. Mercury contents are low (they range from 2 to 18 ppb) as compared with the average abundance for intermediate intrusives (38 ppb; Jonasson and Boyle, 1972).

Furthermore, the sulphide ore minerals occurring at Pampa Norte (chalcopyrite, chalcocite,

bornite, covellite) generally have low mercury contents according to published data (Jonasson and Boyle, 1972); they range from 0.1 to 40 ppm, the highest value being the maximum mercury content of chalcopyrite; pyrite has a higher mercury content, but it is rarely found at Pampa Norte. No data are available on the mercury contents of oxidized copper minerals, but it is estimated from the results of this study, that they are not in any case higher than those of the sulphide minerals occurring at Pampa Norte. Olade (1977) reported fairly low Hg values (generally less than 100 ppb) in porphyry copper deposits in British Columbia.

A soil geochemical survey for Cu, As and Hg at Pampa Norte (Table 9) showed mean Cu contents ranging from 63 to 778 ppm, and generally the high means occurred nearest to the Chuquicamata

TABLE 9: COPPER, ARSENIC AND MERCURY IN SUB-SURFACE SOILS AT PAMPA NORTE+

Origin	Cu* $\overline{X}$	Range	No. of Samples	As* $\overline{X}$	Range	No. of Samples	Hg** $\overline{X}$	Range	No. of Samples
Traverse 1	778	304–1,220	26	26	16–50	27	75	<40–180	20
Traverse 6	581	150–1,168	18	33	16–40	18	–	–	–
Traverse 2	395	68–2,000	25	22	16–32	24	–	–	–
Traverse 4	274	96– 528	23	29	8–40	23	–	–	–
Traverse 5	351	60– 608	19	28	12–50	19	–	–	–
Traverse 10	312	125– 516	21	63	40–89	13	–	–	–
Traverse 7	196	54– 444	19	25	16–40	19	63	<40–120	15
Traverse 11	189	46– 468	20	–	–	–	–	–	–
Traverse 8	63	45– 284	23	–	–	–	–	–	–
Traverse 13	210	80– 378	26	–	–	–	–	–	–
Traverse 14	136	48– 243	17	–	–	–	–	–	–

+ All samples collected at 5 cm depth and −180 μm soil size fraction used for analysis.
* Results in ppm.
** Results in ppb.
   Traverse 14 is parallel to traverse 13 and located 1,100 m north of the latter; it spans 2,400 m from coordinate E2,750 to E5,150.

deposit reflecting contamination from the mineralization, mainly copper veins in the surrounding hills and to a smaller extent from copper mining activity in the distric (airborne particles contamination), and possibly from the smelter at Chuquicamata, some 7 km to the south. Arsenic contents ranged overall from 8 to 89 ppm (mean contents ranged from 22 to 63 ppm) and the distribution of results suggested that no contamination effects are responsible for it. Mercury analysis in a limited number of samples showed an overall range from 40 to 180 ppb and respective averages for the two traverses studied were 75 and 63 ppb.

A comparison between sub-surface soil analysis from four traverses shows no major variation in the mean contents of As and Hg with depth, whereas Cu contents decreased sharply with depth and increasing distance to natural contamination (mineralized) sources. This clearly indicates that mineralized source areas are responsible for increased copper contents in surface soil samples.

An extensive IP and ground magnetics survey was carried out at Pampa Norte in 1958 (Mc Allister and Powers). Data from both surveys indicated the occurrence of mineralization within the area now intensely drilled (Fig. 29). It must be noted that in order to overcome contact resistance by the caliche layer, 14 m² holes 0.6 to 0.9 m

deep were filled with 4,500 to 9,100 l of water. In spite of the measures taken many readings were missed due to contact resistance.

Abundant underground water is known to occur at a depth of 140 m through an exploratory shaft on section N 10,000 (Fig. 31) (O. Alvarez, pers. comm., 1978). The shaft is sited on coordinate E 4,000 and the water table level is 70 m below the bedrock gravel contact. This finding was confirmed by further exploration workings.
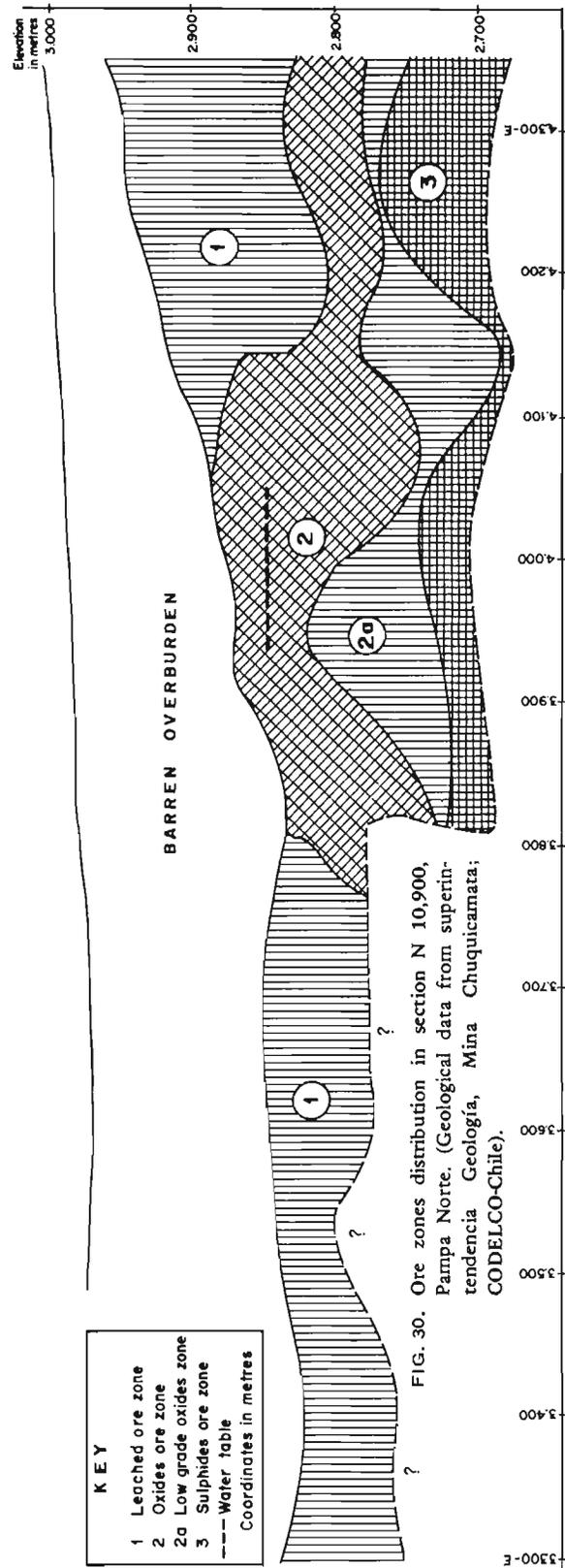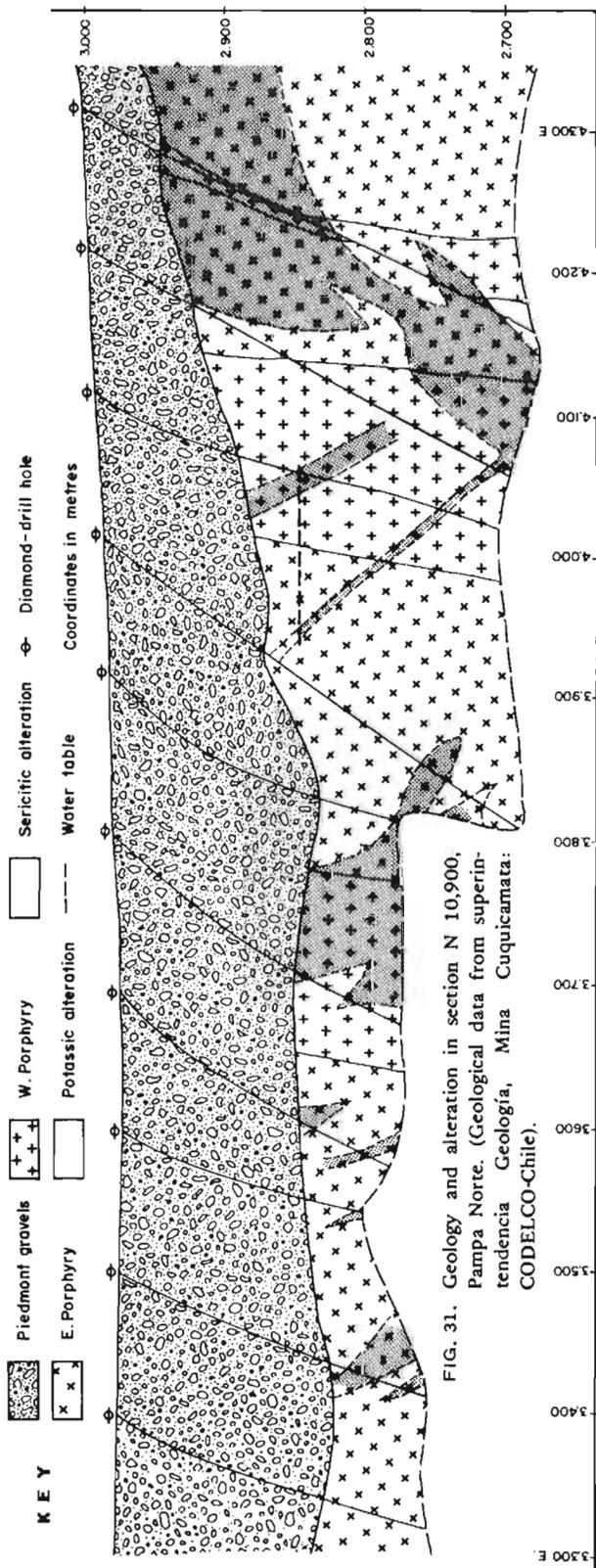
Mercury in Soil Gas

At Pampa Norte, down-hole soil gas samples from auger-drill holes from eight traverses (Fig. 29) were analyzed for Hg on-site; triplicate samples were taken at each station (Table 10). It was estimated that samples up to 1,400 m away from the area of presently known mineralization would contain local background levels of Hg. Results in Table 10 generally show that the first sub-sample had a lower Hg content than the other two samples, both for mineralized and unmineralized areas. The second and third sub-samples appear to have a good reproducibility as shown by their similar average Hg contents. However, it must be noted that these values are in the low ppb range. The lower Hg content of the first sub-samples indicates

dilution of the soil-gas in the immediate vicinity of the borehole and the higher values found in the second and third sub-samples probably represent the indiluted soil gas Hg content. Limited exhaustion tests were carried out in two different boreholes located on Lines N 10,400 and N 10,300. These showed that up to six sub-samples could be taken from a single borehole before the Hg content of the samples decreased noticeably, but without being exhausted. The pumping of 10 l of soil gas would affect an approximate volume of 0,05 m^3 (assuming a porosity of 20%). It is concluded that if measurable amounts of Hg are present in soil-gas, then the analysis of three consecutive sub-samples should provide sufficient information for exploration purposes. This is supported by the generally consistent results obtained for the second and third sub-samples.

The averages for second sub-samples from the unmineralized areas range from 0.22 to 0.34 ng/l Hg and their overall range is 0.044 to 0.88 ng/l Hg (Table 10); variation within the unmineralized areas is relatively small and most samples have Hg contents of less than 0.50 ng/l Hg. Results of previous studies by Robbins (1975) at Almagrera and Sierrecilla (Huelva, Spain) and Arias (1975) at Cerro Colorado (Iquique, Chile) showed that the background Hg contents above unmineralized volcanic bedrock were always below the detection limit of the Scintrex HGG-3 Hg spectrometer employed (about 0.02 ng/l Hg); these areas occurred in semi-arid (Spain) and arid (Chile) terrains and were respectively covered by colluvial and thick piedmont gravel overburden. It is estimated that the relatively high Hg values measured over the unmineralized areas are due to regional Hg dispersion in the Chuquicamata district as a whole.

All the results of Hg determination in soil gas sub-samples from line N 10,400 were plotted on Fig. 32, in order to show variation between succesive sub-samples; it can be seen that generally the first sub-samples gave the lowest values, but this tendency is less well defined over the mineralization and the area east of it; mercury values of second and subsequent measurements are consistently higher over the mineralization than those found over the area located immediately west of the mineralized zone, shown at the bottom of Fig. 32. The relatively higher values occurring further west are possibly related to the presence of the West Fault, which occurs approximately in the

KEY
1 Leached ore zone
2 Oxides ore zone
2a Low grade oxides zone
3 Sulphides ore zone
—— Water table
    Coordinates in metres

FIG. 30. Ore zones distribution in section N 10,900, Pampa Norte. (Geological data from superintendencia Geología, Mina Chuquicamata; CODELCO-Chile).

FIG. 31. Geology and alteration in section N 10,900, Pampa Norte. (Geological data from superintendencia Geología, Mina Cuquicamata: CODELCO-Chile).

KEY

Piedmont gravels

E. Porphyry

W. Porphyry

Potassic alteration

Sericitic alteration

Water table

Diamond-drill hole

Coordinates in metres

vicinity of coordinate E 3,000. Repeat measurements of Hg contents in soil gas samples taken on line N 10,400 after a period of 1 year (Table 10; Fig. 32) showed a less well defined tendency of high values to occur over the ore zone, and relatively high values were found over the area west of the mineralization; the expression of the West Fault was not observed in the second series of measurements made one year after the first series. The N 10,400 traverse averages of second series measurements are lower than those of the unmineralized areas, as also are their ranges (Table 10). It was concluded that reproducibility on a longterm basis was not satisfactory. The results obtained for the remaining traverses, except N10,900 and N 10,010, are typified by those of traverse N 10,700 (Table 10 and Fig. 33). The measurements showed a range of 0.044 to 0.54 ng/l Hg and an average of only 0.12 ng/l Hg, close to the detection limit of the spectrometer. These Hg concentrations were lower than those measured over the unmineralized areas. The variation of the Hg values over line N 10,700 (Fig. 33) is small and no features were observed which could be related to the occurrence of buried mineralization. A similar picture was obtained for lines N 10,300; N 10,900 (A₂), N 11,100; N 11,500 and N 12,000 further details of which are not shown here (Table 10).

The occurrence of fairly low Hg contents in soil gas over the mineralized area at Pampa Norte and its surroundings, similar to those of unmineralized areas, can be explained by a series of factors, the most important of which are: 1) the low average Hg contents found in diamond-drill cores from the mineralized area; 2) the possibly reduced active sulphide ore oxidation; 3) the presence of a reactive water table, possibly with high Cl⁻ contents; 4) the presence of thick colluvial gravels which constitute the overburden of the area.

Fairly low Hg levels (range 2-18 ppb) were found in diamond-drill core samples from the mineralized area (Table 8); only exceptionally did Hg values in Pampa Norte cores reach 100 ppb or more, and this occurred only in some samples from the upper part of the sulphide ore zone; also, no differences were generally observed in the Hg contents of samples from the various ore zones. This is consistent with data reported by Olade (1977), who found low Hg contents in the periphery and mineralized areas of porphyry copper deposits at Highland Valley, British Columbia. For
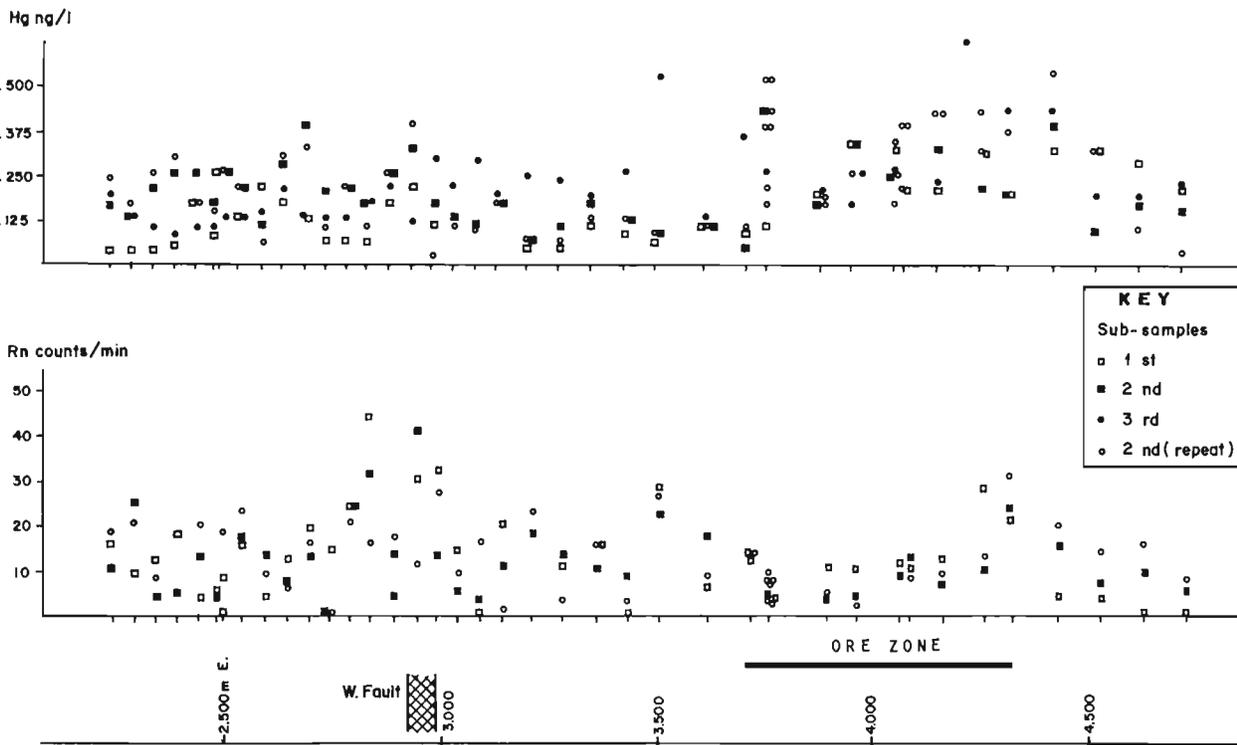
FIG. 32. Mercury and radon in soil gas on line N 10,400 at Pampa Norte.

example at the Bethlehem-JA deposit, values of less than 10 ppb Hg occur at the periphery which increase to more than 40 ppb Hg in a central zone, where well mineralized areas showed Hg values exceeding 100 ppb. At the Valley Copper deposit this same author found low Hg values ranging from 1 to 52 ppb and only six out of 61 values were greater than 7 ppb. Olade (1977) further reported that at the Highmont porphyry Cu deposit very low Hg values were found (<5 ppb) and concluded from the study of his own data and data from McCarthy (1972) that the behaviour of Hg in porphyry copper deposits was inconsistent. Gott and McCarthy (1966) reported that at the Ely porphyry deposits, Nevada, Hg was enriched in the rocks surrounding the ore deposits and depleted in the central ore-bearing intrusive rocks. The low Hg values found by Olade (1977) in porphyry Cu deposits were attributed by this author to loss of Hg due to relatively high temperatures of ore formation, of about 350°C, as deduced from fluid inclusion studies; conversely, the higher Hg values found at the Bethlehem deposit could be explained by its lower temperature of formation.

Although oxidation of sulphides can be taking place at Pampa Norte at present, it is likely that a reactive water table and adsorption of migrating Hg vapour significantly reduce the gas amount reaching the surface; Jonasson (1972) reported that irreversible adsorption of mercury occurs onto sulphide surfaces. Futhermore, the water table can act as a barrier to migrating Hg vapour if chloride (Cl⁻) ions are dissolved in it; the occurrence of a reactive water table at Pampa Norte is supported by the finding by Jarrel (1944) of fairly high Cl⁻ ion concentrations which ranged from 280 to 2,130 ppm in underground water at Chuquicamata. The thick overburden gravels might be yet another barrier for Hg vapour migration, but it is estimated that if a sufficiently large and constant Hg vapour supply exists, a secular equilibrium might be attained wich would allow part of the mercury vapour to pass through the overburden. Geophysical data (McAllister and Powers, 1958) indicated that mineralization should at least span the whidth, of approximately 800 m, of the Chuquicamata porphyries occurring in the Pampa Norte area. However, the results of

TABLE 10: MERCURY CONTENT IN SUCCESSIVE SOIL GAS SUB-SAMPLES AT PAMPA NORTE

			$\overline{X}$	Hg ng/l Range	No. of Sample Sites
PAMPA NORTE					
Traverse	N10,010:	1st Measurement	0.17	0.044−0.44	19 (12)
		2nd Measurement	0.34	0.11 −0.77	31
		3rd Measurement	0.36	0.11 −0.70	31
Traverse	N10,400 (1976 Survey)				
		1st Measurement	0.17	0.044−0.64	39
		2nd Measurement	0.20	0.044−0.43	38
		3rd Measurement	0.21	0.044−0.54	39
Traverse	N10,400 (1977 Survey)				
		1st Measurement	0.12	0.044−0.308	15 (24)
		2nd Measurement	0.19	0.044−0.55	38
		3rd Measurement	0.20	0.088−0.616	39
UNMINERALIZED AREAS					
Pampa Calama		1st Measurement	0.13	0.044−0.22	16 (5)
		2nd Measurement	0.26	0.11 −0.68	21
		3rd Measurement	0.31	0.17 −0.88	21
Pampa Cere	N16,000:	1st Measurement	0.25	0.044−0.88	8 (4)
		2nd Measurement	0.31	0.044−0.88	11 (1)
		3rd Measurement	0.22	0.044−0.66	12
	N16,500:	1st Measurement	0.09	0.044−0.15	8 (6)
		2nd Measurement	0.22	0.044−0.40	14 (1)
		3rd Measurement	0.22	0.044−0.35	14 (1)
Norte Barren		1st Measurement	0.15	0.044−0.33	12 (4)
		2nd Measurement	0.34	0.22 −0.66	16
		3rd Measurement	0.36	0.19 −0.66	16

Note: Numbers is parenthesis represent number of measurements below detection limit of 0.044 ng/l Hg.

Hg vapour measurements in soil gas failed to show the presence of the mineralization established by diamond drilling.

It is concluded therefore that, in general, the application of Hg vapour in soil gas techniques to the prospecting of the Pampa Norte deposit showed no indication of the presence of mineralization. Some limited indication of doubtful significance was obtained on some traverses but little support for these results was obtained in adjacent traverses and with repeat measurements. Very limited indications of the presence of the West

TABLE 11: MEAN CONTENTS AND RANGE OF MERCURY IN SOILS FROM THE PAMPA NORTE AREA

	Sample Depth		$\overline{X}$	Hg ppb Range	No. of Sample Sites
PAMPA NORTE AREA					
Line 7	Sub-surface	1 to 5 cm	23	2−75	19
Line 11	Sub-surface	1 to 5 cm	29	10−63	19
Line 4	Sub-surface	1 to 5 cm	13	2−47	22
Line 5	Sub-surface	1 to 5 cm	19	2−42	19
Line 10	Sub-surface	1 to 5 cm	24	2−56	26
N10,010:	Surface	0 to 5 mm	75	56−89	12
	Sub-surface	5 mm to 5 cm	41	2−55	17
N10,300:	Top Caliche	5 cm to 0.4 m	12	1−76	34
N10,700:	Top Caliche	5 cm to 0.5 m*	2	1− 4	33
	Sub-caliche soil	2 m*	2	1− 8	34
UNMINERALIZED AREAS					
Pampa Calama:					
	Surface	0 − 5 mm	15	1−56	9
	Sub-surface	5 mm − 5 cm	24	5−51	5
	Deep soils	3 m	19	5−53	9
Barren Norte:					
	Surface	0 − 5 mm	40	26−55	9
	Sub-surface	5 mm − 5 cm	12	4−31	13
Pampa Cere:					
N16,000	Sub-surface	5 mm to 5 cm	27	9−46	9
N16,500	Sub-surface	5 mm to 5 cm	24	6−61	14

Note: All samples analyzed are from the −75 μm size fraction except those marked *which were from the −180 μm fraction.

Fault, a major structure closely associated to the occurrence of mineralization at Pampa Norte, was obtained from the Hg in soil gas survey. Furthermore, from the results of analysis of Hg adsorbed on soils (Table 11) it was concluded that no surface expression of the mineralization in depth is seen on the Hg contents of surface soils, caliches and sub-caliche soils. The relatively higher Hg contents found in surface soils appear to result from contamination of the surface layers of the soil by mineralized particles from the mines occurring in the hills around Pampa Norte, as well as from mining and, possibly, smelting operations at Chuquicamata. The first conclusion is consistent with the results of measurement of Hg vapour in soil-gas over the Pampa Norte area, which showed

very low amounts of Hg to occur in approximately similar concentrations in both unmineralized and mineralized areas.

Radon in Soil Gas

The results of Rn measurements in soil gas showed no distinct features related to the mineralization but, nevertheless, the West Fault was clearly observed in most traverses. The fault zone usually had associated the highest Rn values measured in any given section, and only occassionally were high Rn contents found above mineralization; a typical section is shown in Fig. 33. The highest Rn content measured was 122 counts/min (above the West Fault) compared to maximum contents
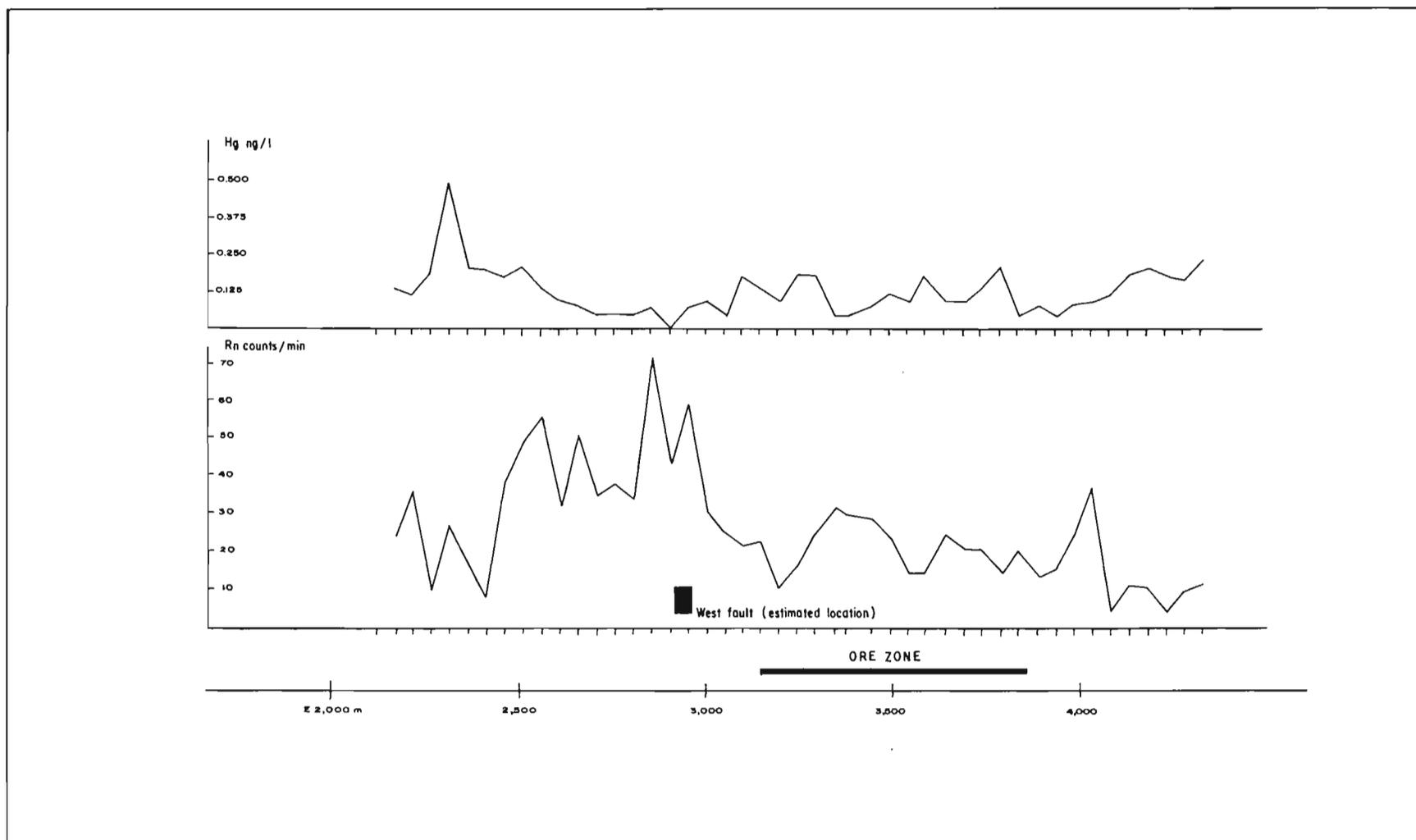
FIG. 33. Mercury and radon in soil gas on line N 10,700 at Pampa Norte.

TABLE 12: RELATIVE TOTAL HYDROCARBON YIELD OF VARIOUS SOIL SIZE FRACTIONS

| | Soil Size Fraction | Total Hydrocarbon | | No. of Samples |
		$\overline{X}$	Range	
Traverse 2	$-180 + 150\,\mu m$	2.5	1.5— 9	25
	$-150 +\ 75\,\mu m$	5.0	1.5—19	25
	$-\ 75\,\mu m$	9.5	4—21	26
Traverse 8	$-180 + 150\,\mu m$	2.9	1.6— 5.8	23
	$-150 +\ 75\,\mu m$	5.8	2.0—17.6	23
	$-\ 75\,\mu m$	7.4	3.9—18.4	23

of up to 35 counts/min for unmineralized areas. Uranium contents in Pampa Norte diamond-drill cores range from 2 to 9 ppm. It is considered that the high Rn values over the West Fault are a result of the increased permeability in the bedrock and overburden above the fault, and that Rn is derived from the U associated to the mineralization. It is concluded that Rn can be most useful in detecting large faults associated to overburden covered porphyry copper mineralization. However, it has no application as a direct indicator to concealed sulphide mineralization unless faults act as channelways for the Rn-gas. The amounts of thoron found in soil gas were relatively small (up to 10 counts/min) and since they are discernible, do not reduce the usefulness of the Rn-technique.

Soil-Adsorbed Hydrocarbons

Soils and caliche samples collected from various traverses over unmineralized areas and over the area of the Pampa Norte deposit (Fig. 29) were analized for their total adsorbed hydrocarbon·gas contents. Desorption tests using various soil size fractions (Table 12) showed that the fine soil fraction ($-75\ \mu m$) gave the highest hydrocarbon'gas yields; therefore, this soil size-fraction was used in all the analyses.

The analytical results are shown in Table 13. Results are given in peak area counts (PAC) and peak height units (PHU). The integrated results (PAC) are much more precise than those obtained as PHU.

It is apparent from Table 13 that the results for the area over mineralization are generally lower

than those from unmineralized areas, except 'for traverse N 10,010 which has contents about three times higher. However, patterns of measured hydrocarbon gases in soils are observed which are somewhat related to the presence of mineralization (Fig. 34). It is not understood why the hydrocarbon gas contents measured in the samples from unmineralized areas are comparatively high but two possible explanations are suggested: 1) different sources of hydrocarbon-gases could contribute to the total amounts observed in both areas; 2) there is no emission of hydrocarbons from the buried mineralization and the variation observed is the random variation within the sample population. The evidence available is inconclusive. However, the presence of the West Fault was generally shown by distinct peaks (Fig. 34).

The results suggest that the dispersion of hydrocarbon-gases in a porphyry copper environment is wide. It must be remembered that little is known about the possible sources of hydrocarbons in this type of environment and that an origin related to mineralization cannot be proven without further research. Analysis of diamond-drill cores showed hydrocarbon-gas contents of 16 to 450 PHU. This suggests that at least part of the hydrocarbon-gases could originate in the bedrock of the deposit. Nevertheless some contamination from industrial lubricants used in drill-tooling is suspected.

It is concluded that hydrocarbon-gases which may have originated in the mineralized bedrock at Pampa Norte can migrate and reach the surface. Incomplete understanding of the occurrence, generation and migration of hydrocarbon-gases in
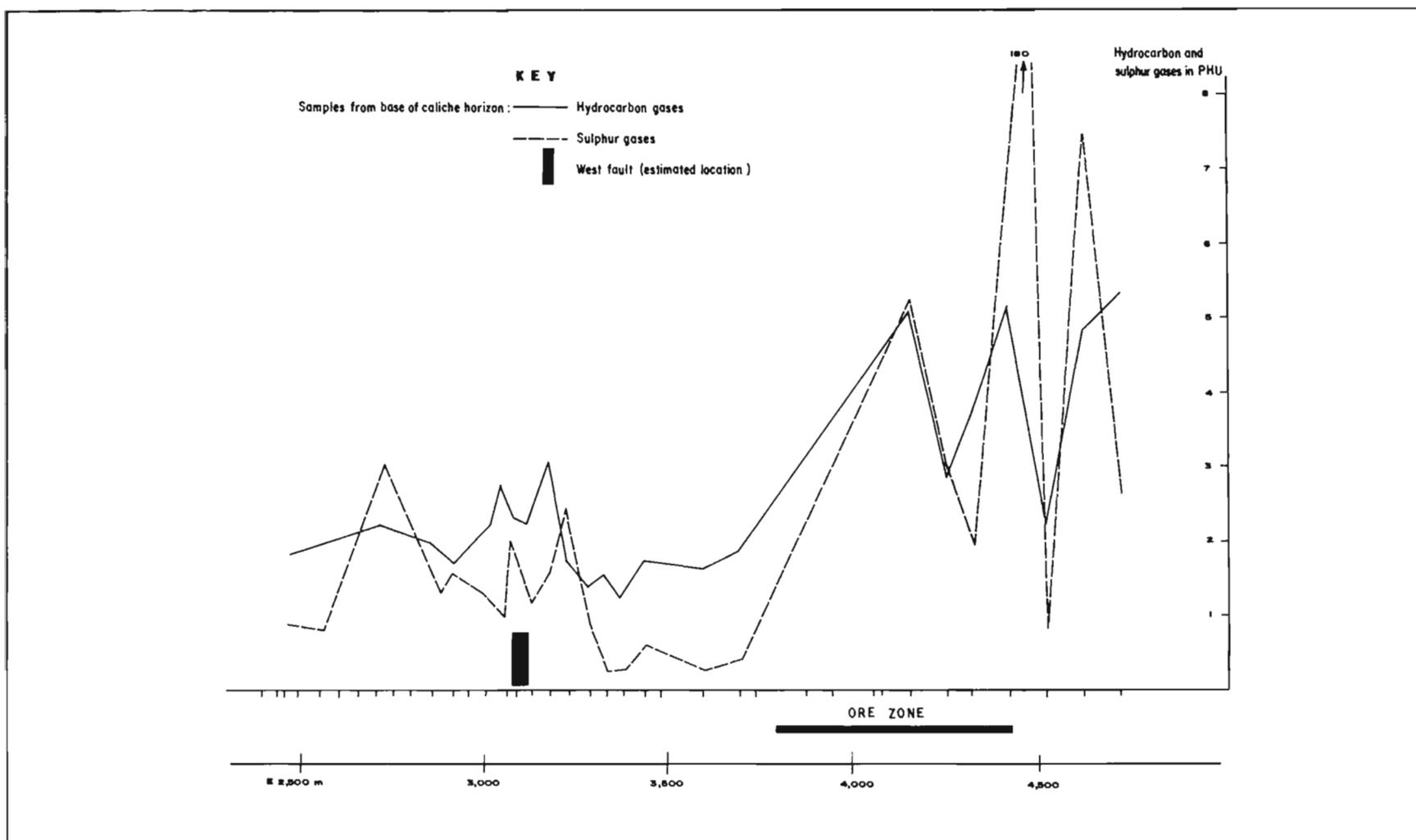
KEY

Samples from base of caliche horizon : ———————— Hydrocarbon gases

— — — — — Sulphur gases

▮ West fault (estimated location)

Hydrocarbon and
sulphur gases in PHU

ORE ZONE

E 2,500 m   3,000   3,500   4,000   4,500

FIG. 34. Hydrocarbon and sulphur gases in soils from line N 10,400 at Pampa Norte.

TABLE 13: TOTAL HYDROCARBON GAS CONTENTS IN SOILS FROM THE PAMPA NORTE REGION

	Soil Depth	$\overline{X}$*		Total Hydrocarbon	No. of Samples
			$\overline{X}$**	Range	
PAMPA NORTE					
Traverse N10,010	5 mm to 5 cm	26	—	14– 36	18
N10,010	3 m	20	—	8– 31	17
N10,400	0 to 0.5 m	—	23	13– 51	32
N10,400	1 to 2 m	—	25	12– 56	24
N10,700	0.3 to 0.8 m	—	15	6– 37	23
N10,700	1 to 1.5 m	—	18	9– 39	26
N10,700	2.5 to 4 m	—	20	10– 38	16
N10,700+	2.5 to 4 m	—	60	8–176	29
N10,900	0 to 5 cm	—	13	4– 19	26
N10,900	0.3 to 0.5 m	—	9	5– 19	11
UNMINERALIZED AREAS					
Pampa Calama					
E–W Traverse	0 to 5 mm	8	33***	2– 12(23–50)	10
	5 mm to 5 cm	3	16	3– 9(4–29)	9
	3 m	2	10	3– 10(7–15)	10
N–S Traverse	0 to 5 mm	7	32	3– 9(12–46)	10
	5 mm to 5 cm	6	27	0– 6(15–41)	11
	3 m	5	23	2– 3(19–28)++	11
Norte Barren	0 to 5 mm	5	20	2– 8(11–30)	12
	5 mm to 5 cm	5	22	4– 7(8–34)	9
Pampa Cere					
N16,000	5 mm to 5 cm	10	50****	5– 14(21–97)	7
N16,500	5 mm to 5 cm	9	51	3– 33(23–97)	14

* PAC
** PHU
*** All ranges for unmineralized areas in PAC;
  Ranges in PHU in parenthesis;
  All samples analyzed were from the −75 μm fraction except **** (150 μm).
+ Gases desorbed at 250° C;
++ One erratic high sample excluded had 126 PHU;
  Depth ranges (e.g. 2.5 to 4 m), indicate minimum and maximum depths at which samples were collected.

TABLE 14: RELATIVE TOTAL S GAS YIELD OF VARIOUS SOIL SIZE FRACTIONS+

	Soil Size Fraction	Total S Gas		No. of Samples
		$\overline{X}$	Range	
Traverse 2	$-180 + 150 \, \mu m$	15*	12–27	24
	$-150 + 75 \, \mu m$	19*	13–29	24
	$- 74 \, \mu m$	27*	19–46	24
Traverse 8	$-180 + 150 \, \mu m$	10	8–14	23
	$-150 + 75 \, \mu m$	10	8–14	23
	$- 75 \, \mu m$	15	12–27	23

Note: + Results in PHU;
     * Erratic high values excluded (respectively: 800, 150 and 100 PHU).

ore deposits conspires against its use in minerals exploration.

Soil-Adsorbed S Gases

Soil and caliche samples collected from various traverses over unmineralized areas and over the area of the Pampa Norte deposit (Fig. 29) were analyzed for their total adsorbed S gas content. Desorption tests using various soil size fractions were conducted to measure their relative gas yields; results are shown in Table 14. These results show that the highest S gas yield is obtained from the $-75 \, \mu m$ soils and therefore all analyses were carried out in that soil size-fraction.

The results of the determination of total S gas contents in soils and caliches are shown in Table 15. Soils collected from various depths at the unmineralized areas generally showed low mean S gas contents (up to 9 PHU) and values ranged from 2 to 18 PHU; the deep soils (3 m) showed slightly lower mean S gas values (up to 4 PHU) than surface soils (up to 9 PHU). Since the differences between these soils are relatively small it is estimated that little or no contamination of surface soils by S gases effluents from the sulphide ore smelter at Chuqicamata has taken place.

By comparison, mean S gas values over the mineralized area at Pampa Norte range from 10 to 106 PHU (Table 15); soils from different depths collected on traverse N 10,010 showed high S gas values to occur; sub-surface soils (5 mm to 5 cm)

showed a much smaller mean S value (22 PHU) as compared to surface soils (0 to 5 mm; 90 PHU); deep soils collected at 0.5, 1.0, 2.0 and 3.0 m showed high mean S gas values (58 to 106 PHU). Tipically, (Fig. 34) most high S values occurred over the mineralized area, but several high values occur to the west, including the area above the West Fault. The considerable variation observed between adjacent samples suggests that S gas migration could be strongly controlled by faults and other structures, such as intrusive contacts.

The results discussed above suggest that the S-gases could originate at depth and be related to the occurrence of mineralization and deep faults. It is estimated that no S gases are derived from the gypsum found as the main constituent of caliches. It is important to consider that the random fluctuation of S gas contents could also be explained by varying adsorptive characteristics of the soil which could be related to the relative abundance of clays and other strongly adsorbent minerals.

From the results of Pampa Norte area, the following conclusions can be drawn: 1) increased amounts of S gas adsorbed by soils were found to occur generally above the known mineralized area, geophysical IP anomalies, and the West Fault; 2) unmineralized areas showed consistently low concentrations of S gases in soils, and 3) deep caliches and soils appear to give the best results.

Concerning point 1) it is believed that sulphur gases are generated by active oxidation of sulphide mineralization, including relic sulphide minerali-

TABLE 15: TOTAL SULPHUR GAS CONTENT IN SOILS AND CALICHES FROM THE PAMPA NORTE AREA

		Samples Depth	Total S Gas*		No. of Samples
			$\overline{X}$	Range	
PAMPA NORTE					
N10,010	Surface Soils	0 to 5 mm	90	32—252	12
	Sub-surface Soils	5 mm to 5 cm	22	12— 36	17
	Deep Soils	0.5 m	75	20—236	18
	Deep Soil	1.0 m	101	34—248	18
	Deep Soil	2.0 m	106	10—320	16
	Deep Soil	3.0 m	58	16—128	17
N10,400	Top of Caliche	1 to 0.5 m	16	3—200	29
	Base of Caliche	1 to 2 m	22	2—180	26
N10,700	Top of Caliche	0.1 to 0.5 m	15	8—100	28
	Base of Caliche	2.5 to 4 m	19	8— 48**	27
	Sub-caliche Soils	3 to 4 m	23	10— 37	27
N10,700	+Sub-caliche Soils	3 to 4 m	19	4— 51	31
N10,900	Surface Soils	0 to 5 cm	15	5— 34	27
N10,900	Top of Caliche	0.3 to 0.5 m	10	3— 20	11
UNMINERALIZED AREAS					
Pampa Calama					
EW Traverse:					
Surface Soils		0 to 5 mm	6	4— 7	10
Sub-surface Soils		5 mm to 5 cm	3	2— 4	11
Deep Soils		3 m	4	3— 7	10
N-S Traverse:					
Surface Soils		0 to 5 mm	9	3— 18	10
Sub-surface Soils		5 mm to 5 cm	6	3— 10	11
Deep Soils		3 m	4	3— 16	11
Norte Barren:					
Surface Soils		0 to 5 mm	3	2— 5	9
Sub-surface Soils		5 mm to 5 cm	4	3— 5	11
Pampa Cere:					
N16,000	Surface Soils	5 mm to 5 cm	7	4— 13	7
N16,500	Surface Soils	5 mm to 5 cm	6	4— 11	14

Note: *   All results in PHU; + Samples heated to 250° C for gas desorption.
  **   Two erratic high values excluded (184 and 144 PHU).

zation. Some support comes from the fact that only diamond-drill core samples from the sulphide ore zone showed comparatively high S gas values (up to 78 PHU) whereas all other rock samples, including oxide and leached ore zone samples, had S gas values of less than 10 PHU. Nevertheless, the water table can be a potential obstacle to S gases migration. Concerning the S gases found in soils from above the West Fault it is estimated that they could be generated by the oxidation of pyrite possibly occurring in the fault zone, since pyrite has been found to occur in the rocks adjacent to the West Fault at the Chuquicamata deposit.

The thickness of the gravel overburden (up to 150 m) at Pampa Norte appears to cause no hindrance to the migration of S gases from depth. Although the effect of soil moisture upon S-gas migration and its subsequent accumulation in soils is not known, the results suggest that no interference on S gas migration is caused by the presence of soil moisture. It is estimated that it could have a beneficial effect by dissolving S gases, thereby facilitating their retention in the soils.

CONCLUSIONS

From the results and discussions concerning the application of selected vapour geochemistry techniques to the exploration for concealed porphyry Cu and vein-type Ag mineralization, the following general conclusions can be obtained:

a) Active oxidation of the sulphide mineralization appears to be an essential condition for the generation and dispersion of gases.

b) The migration of gases appears to be strongly controlled by faults and possibly other structures; under favourable conditions, vapour geochemistry can indicate the presence of structurally controlled mineralization or faults concealed beneath transported overburden.

c) The collection of three consecutive soil-gas subsamples from boreholes 2 to 4 m deep provides sufficient information for prospecting purposes.

d) The nature and age of the overburden materials as well as the supergene history of the deposits studied are important in the interpretation of vapour geochemical prospecting data.

It would appear that porphyry Cu mineralization which is not undergoing active oxidation is a difficult exploration target, when it is concealed beneath dry exotic overburden, however thick. The usefulness of mercury vapour for porphyry copper prospecting is debatable as shown by the mixed results obtained. It appears that mercury contents in such deposits are generally low, but more data are required to support this preliminary conclusion.

a) The detection of concealed mineralization at the Cachinal Ag vein-type deposit as well as at the Cerro Colorado and Pampa Norte porphyry Cu deposits is considered to be successful.

b) The application of the measurement of S gas contents in soils to prospecting for deeply buried porphyry Cu mineralization is considered to be successful, since distinct indication of the occurrence of mineralization was generally obtained.

c) The detection of the mineralization at the unoxidizing disseminated Cu deposit at Quebrada M was not possible; the prospecting of concealed porphyry Cu sulphide mineralization not undergoing active oxidation is not feasible by the adsorbed S gas in soils method.

d) The thickness of the unconsolidated overburden of up to 150 m at Pampa Norte appears to cause no hindrance to the dispersion of S gases through it; the detection of overburden covered faults associated to concealed mineralization is also feasible. However, the existence of thick, compact, saline horizons (caliches) in the overburden can present a major obstacle preventing migrating gases from reaching the surface. The detection of concealed mineralization by means of analysis of the S gas content of overburden materials (e.g. soils and caliches) is considered to be feasible. The application of S gas measurements to exploration appears to be the most promising of the techniques studied, since it is, apart from mercury vapour in mercury and silver prospecting, the only method that is able to specifically indicate the occurrence of concealed sulphides.

It is interesting to note that near-surface soils may provide useful prospecting applications as compared to deep soil sampling. It is considered that in view of the variations in soil composition

and content of fine fractions found in different areas, which may be responsible for some of the high variability of results, the choice of sample material (i.e., depth of soils, soil size fractions) as well as the use of caliche should be thoroughly investigated.

With most methods of soil-gas sampling the entrainment of atmospheric air and subsequent dilution of the sample is an ever-present danger. However, the collection of consecutive samples during on-site soil gas surveys from boreholes minimized this risk, since in the case of Hg vapour for example, dilution is evident in a decrease of measured contents. Furthermore, this sampling method makes it possible, during Rn surveys, to determine the contribution of thoron derived from the overburden to the total α activity, and hence to measure the true Rn level in soil gas. In addition, there is more confidence in the results of multiple soil gas measurements of, for example, Hg and Rn, than in those from a single determination.

As with other forms of geochemistry, an understanding of the nature of the overburden as well as the basic geology and the supergene history of the prospective areas is important. It is otherwise difficult to usefully interpret dispersion patterns of gases from basic vapour geochemical data.

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