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3. *Report of Heat Flow Measurements in Chile.*

By Seiya UYEDA, Teruhiko WATANABE,
Earthquake Research Institute,
Edgar KAUSEL,
Universidad de Chile, Santiago,
Masaaki KUBO* and Yoshio YASHIRO**,
Compañia Minera de Atacama.
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Abstract

Results of terrestrial heat flow measurements in Chile, conducted in 1969, are presented. Data from eight metal mines and one oil-field were used. It was found that the sites in the Pacific coastal zone have lower than normal heat flow, whereas moderately high heat flow values were obtained at inland sites and in Isla Tierra del Fuego. Since the coverage of sites (Table I, and Fig. 1) is still poor, it is not possible to determine whether or not the heat flow distribution in Chile is similar to that often found in trench-arc-back arc areas such as Japan.

Introduction

Heat flow features in the trench-arc-back arc areas are often represented by a zonal arrangement of low heat flow in the outer arc and high in the inner arcs (HORAI, 1964; UYEDA and HORAI, 1964; VACQUIER et al., 1967). Such a thermal state has been considered to be intrinsic to the tectonic process of subduction and various models have been put forward in the framework of plate tectonics (e.g. MCKENZIE and SCLATER, 1968; HASEBE et al., 1970; MINEAR and TOKSÖZ, 1970; OXBURGH and TURCOTTE, 1970; ANDREWS and SLEEP, 1974). However, in actuality, the heat flow distribution in those regions, where slab subduction is presumed, is not so simple. For instance, the heat flow distribution in the Izu-Bonin-Marianas and Tonga arcs and their back-arc regions is extremely complicated (WATANABE et al., 1970; SCLATER et al., 1972).

In 1969, we conducted a series of heat flow measurements in the continent of South America, the western part of which holds the charac-

* Now at Mitsubishi Mining and Cement Co. Ltd., No. 5-1, 1-chome, Marunouchi, Chiyoda-ku, Tokyo.
** Now at Mitsubishi Petroleum Development Co. Ltd., No. 2-6, 2-chome, Otemachi, Chiyoda-ku, Tokyo.

teristic features of active arcs. Until then there was only one heat flow determination (DIMENT et al., 1965) in the whole of South America. Our measurements were made in cooperation with a group of Scripps Institution of Oceanography, University of California at San Diego. The latter group made ship-borne measurements on Lake Titicaca (SCLATER et al., 1970) whereas we made measurements in mines and wells by the conventional land heat flow method with the close cooperation of colleagues in South American countries. Actual underground temperature measurements were conducted in western South America while existing temperature data were collected through kind cooperation of various oil companies and institutions throughout the continent.

The preliminary summary of only the geothermal gradient data obtained by this work was published earlier (UYEDA and WATANABE, 1970), since no thermal conductivity data was available at that time. We have now completed the measurement of the thermal conductivity of rock specimens for most of our sites. The thermal conductivity measurements were made by the newly developed apparatus (Quick Thermal Conductivity Meter, Showa Denko Company), which is a transient method, giving thermal conductivity in thirty seconds (SUZUKI et al., 1975). In the following series of papers we would like to report the results of measurements in more detail than the previous preliminary report. With regard to the oil well sites to which we did not visit, the state of affairs is essentially unchanged from that of the previous publication because we have not acquired rock samples from these sites, except the one in Isla Tierra del Fuego (see the last section of this paper). In the present report, results from Chile will be presented. We emphasize that the present data are grossly insufficient to draw any solid conclusions on the heat flow distribution of the vast continent of South America. It should be regarded as only the beginning of the work.

Results

Heat Flow Values in Chile:

Figure 1 and Table 1 summarize the heat flow data in Chile. As seen in the figure, at the latitude of 26°–29°S, the heat flow is consistently low (<1.0 HFU) at sites on the Pacific coast side of the Andes. Most of them are in the Atacama desert inland side of the Coast Range. This agrees with the previous determination (0.7–1.0 HFU) of DIMENT et al. (1965) at Vallenar. One can also notice that at about 23°S, there are two low values just oceanward of the Chile Trench (0.80 HFU at 23°28′S, 72°58′W and 0.89 HFU at 23°23′S, 72°10′W, VON HERZEN, 1959). But, El Salvador, which is almost in the mid-slope of the Andes, gave a high value of 1.8 HFU. Although high value has been obtained at only one

Table I. Summary of heat flow measurements in Chile

Station name	Station type	Location		Altitude (m)	Max depth (m)	T-gradient[1]	Conductivity[2]	Heat flow		Description
								(HFU)[3]	(SI)[4]	
El Salvador	Cu-mine	26°15′S	69°34′W	2,800	104	2.4−2.7	6.15−5.14	1.8*	75	Cu, V
Santa Clara	Fe-mine	26°32′S	70°18′W	980	100	0.21	11.02	0.24	10	Fex, V
Cerro Negro Norte	Fe-mine	27°06′S	70°21′W	1,250	325	0.85	10.2	0.87	36	Fex, V
Elisa	Fe-mine	27°16′S	70°23′W	480	87	1.08	7.90	0.85	36	Fex, V
Vallenar	Cu-mine	28°59′S	70°53′W	820	202	1.0	5.2	0.52	21	Cux, V
Boqueron Chanar	Fe-mine	28°05′S	70°43′W	355	490	0.97	5.57	0.54	23	Fex, V
La Africana	Cu-mine	33°20′S	70°45′W	510	280	2.89	6.52	1.88	79	Cu, H
Disputada	Cu-mine	33°28′S	70°10′W	3,700	198	1.60	9.06	1.45	61	Cu, V & H
Fuego	Oil-field	54°00′S	69°00′W		2,463	3.20	7.20	2.30	96	BPG

1. T-gradient; 10^{-4} °C/cm
2. Conductivity; 10^{-3}cal/cm sec °C
3. Heat flow; (HFU) 10^{-6}cal/cm^2 sec
4. Heat flow; (SI) 10^{-3}watts/m^2
5. x: prospecting borehole
   v: vertical hole
   H: horizontal hole
   BPG: bottom hole pressure gauge

* Topography corrected

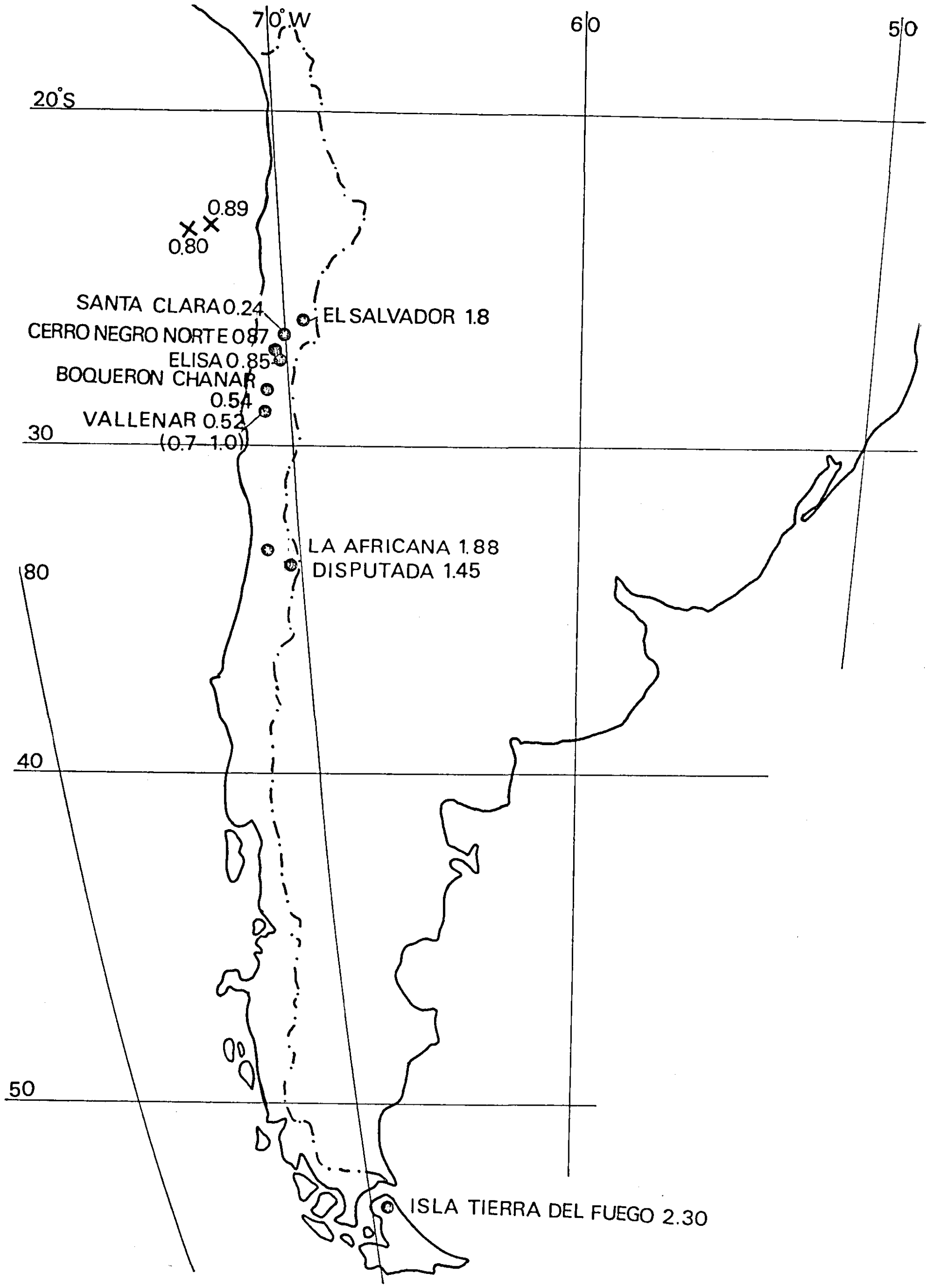

Fig. 1. Heat flow values in Chile. Two values in the Pacific are due to Von HERZEN (1959). Values in parenthesis at Vallenar are by DIEMENT et al. (1965).

locality at this latitude zone, it may be inferred that the heat flow distribution typical to active arcs may hold here. At the southern latitude, a high value (1.9 HFU) was found at one site (La Africana Mine) in the Coast Range near Santiago. This at least indicates that the low heat flow zone in the Coast Range is not consistent at this latitude. However, at a relatively near site (Disputada Mine) higher up in the Andes, only a normal value (1.45 HFU) was obtained. Therefore it is not certain whether this is a region of generally high heat flow.

From these observations, it may be inferred that low heat flow prevails in the coastal area but some higher values occur more to the inland. However, present data are not sufficient to preclude the possibility that the observed features represent the variation longitudinal rather than transverse to the arc axis. In this regard it appears worth noticing that the chain of active volcanoes in the Andes is missing at about the same latitude range as that of the consistent low heat flow. It has been noted that the longitudinal distribution of recent volcanism is strongly related to the longitudinal development of the Central Valley (e.g. KAUSEL and LOMNITZ, 1969). The El Salvador site is at about the southern limit of the volcanic zone in the north and the La Africana site is near the northern limit of the volcanic zone of South Chile. In addition, goethermal gradient data in Isla Tierra del Fuego oil field was made available (3.20×10^{-4} °C/cm) to us. This gives, with the measured value of $K=7.2\times10^{-3}$ cal/cm sec °C, heat flow of 2.3 HFU at the southern tip of the South American Continent. Obviously, much more data are needed to resolve these important problems.

In the following, some detailed descriptions will be presented from each of the heat flow stations taken in the present work. Stations are described from the north to the south. (No account on site will be given for Isla Tierra del Fuego because we did not visit there.)

EL SALVADOR Copper Mine: 26°15′S, 69°34′W

This site is a porphyry copper mine owned, until 1970, by the Andes Copper Mining Company but presently owned and operated by Corporacion Nacional del Cobre de Chile (CODELCO-CHILE). The mine is located at about 140 km NNE of the city of Copiapo at an altitude of 2800 m above sea level on the mid-slope of the Andes (GUSTAFSON and HUNT, 1975).

Two holes of the Andes Copper Mining Company were used for our study. The holes are Churn Drill Hole (CDH) 24A and Diamond Drill Hole (DDH) 501, the locations of which are shown in Fig. 2. CDH 24A was drilled in September, 1956 and DDH 501 in August, 1961. Thus both holes are sufficiently old to be completely free from the possible effects of drilling.

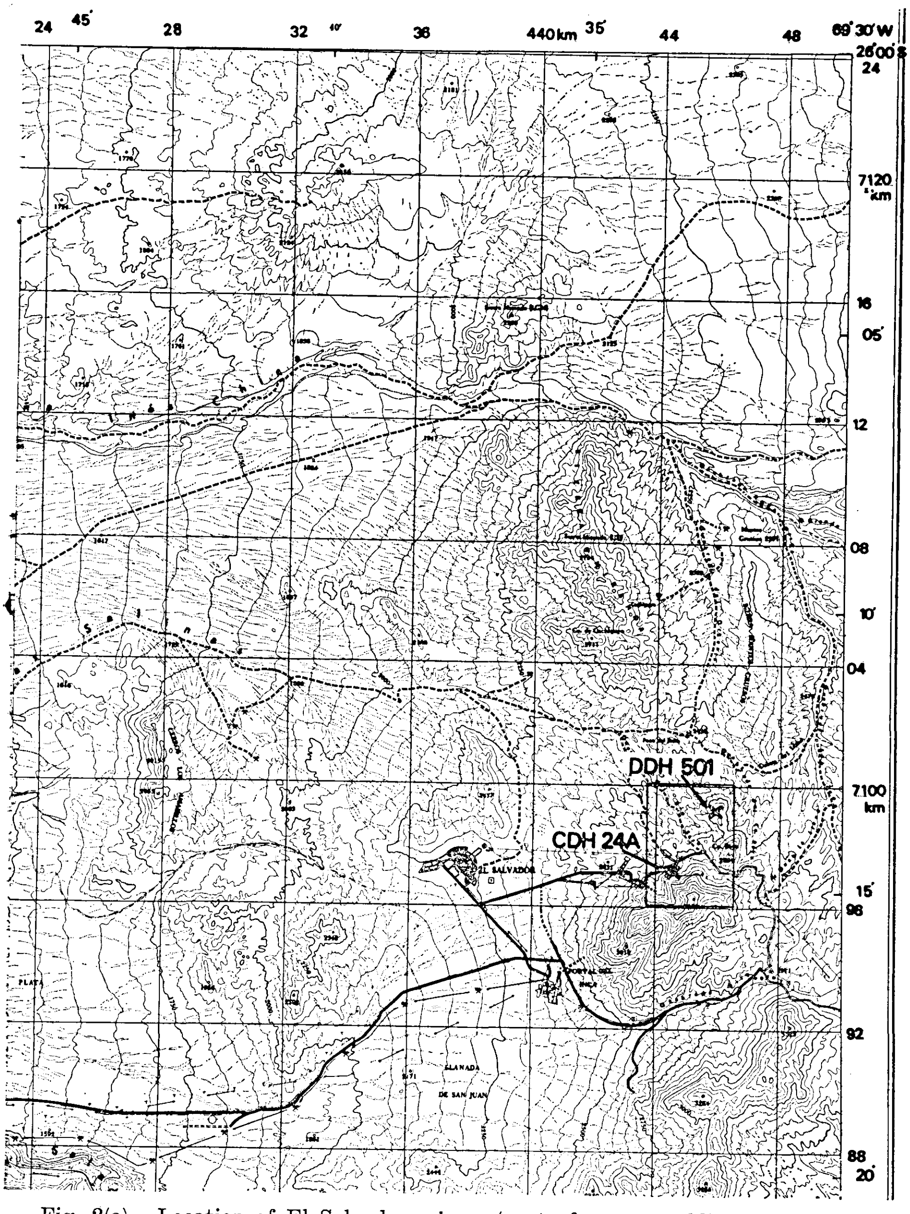

Fig. 2(a). Location of El Salvador mine. (part of a map published by Instituto Geografico Militar de Chile, EL SALVADOR, 2600-6930).

In Fig. 3, a and b are the vertical sections of the holes. Both holes are situated on a steep hill. CDH 24A is a vertical hole but DDH 501 is directed 30° from the vertical. The depth of the holes was 175.5 m and 120.9 m respectively, but, at the time of the temperature measurement the holes were found to be open only to 85.5 m (CDH 24A) and 119 m

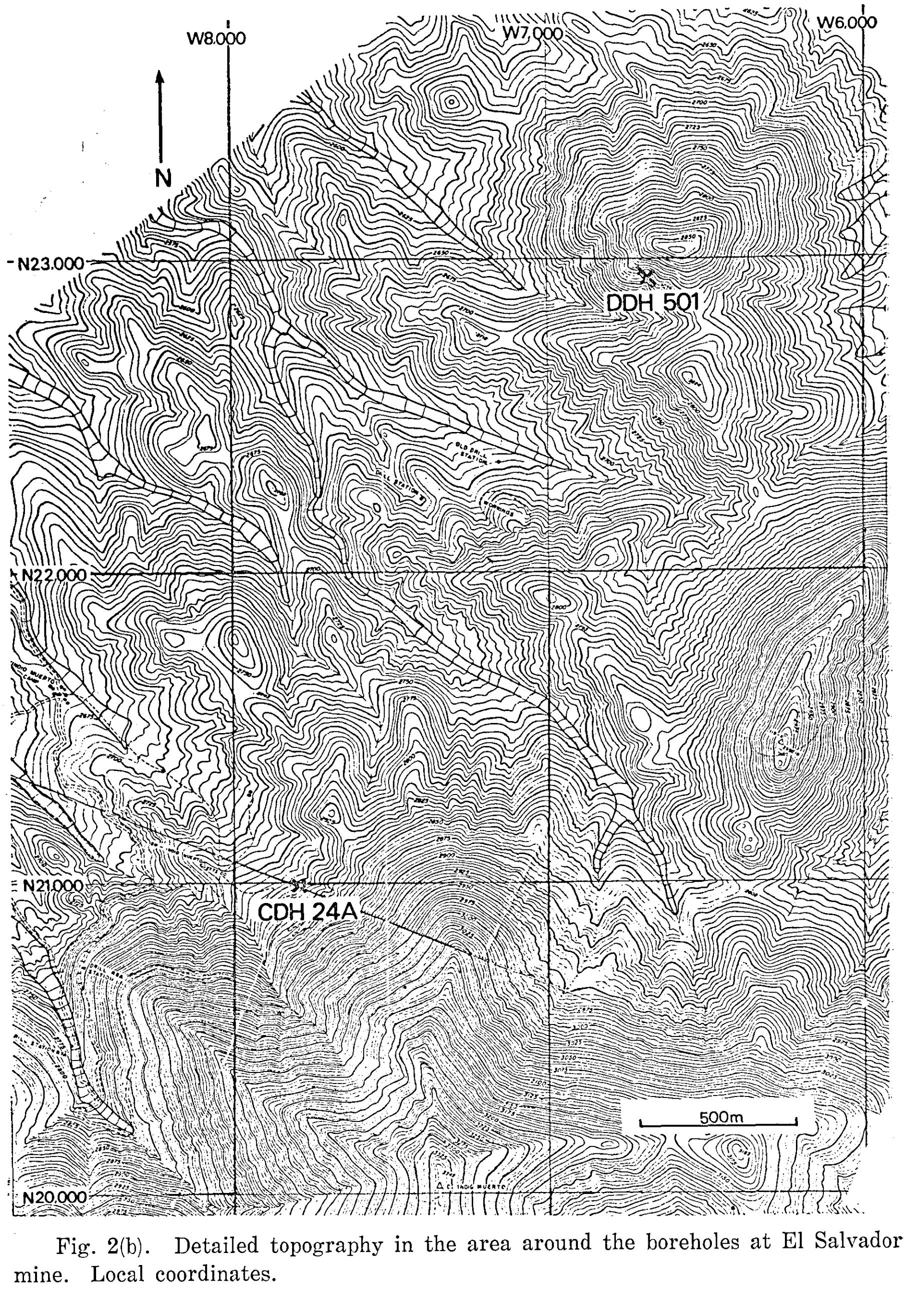

Fig. 2(b). Detailed topography in the area around the boreholes at El Salvador mine. Local coordinates.

(DDH 501). As the section indicates CDH 24A is in the mineralization zone where the rocks are feldspar porphyry of varying degree of alterations. DDH 501, on the other hand, is out of the mineralization zone and the rocks are andesite and rhyolite. The deeper portion of the hole

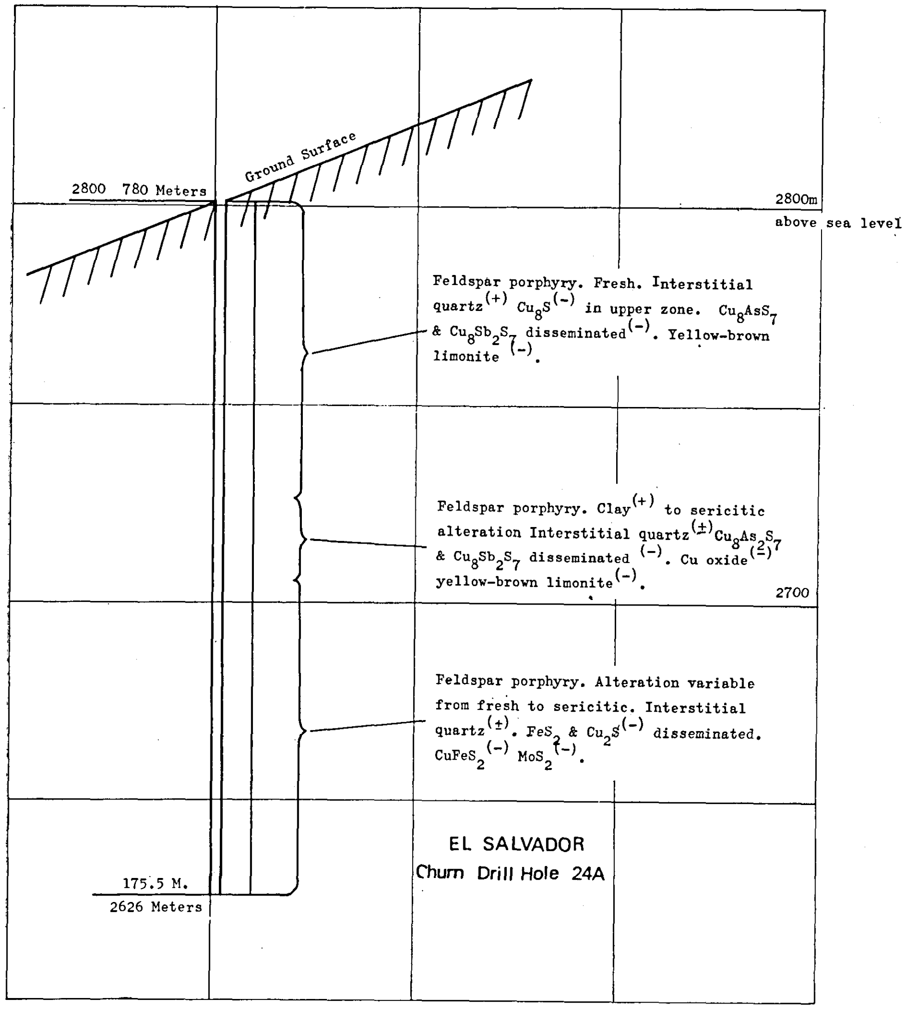

Fig. 3(a) Vertical section of borehole CDH 24A.

penetrated rhyolitic rocks.

Temperature measurements were made on March 24, 1969 with the assistance of Dr. L. B. Gustafson. Both holes were completely dry at the time of measurement. Fig. 4, a and b illustrate the relation between the temperature, T, and the length of penetration along the holes, L, and the relation between the temperature, T, and the minimum distance to the surface, R. For DDH 501 at the depth range greater than 55 m, the linearity is found to be superior for the T-R relation than for the T-L relation. Presumably above 55 m, surficial disturbances are large. In the case of CDH 24A, having smaller penetration, there are only two valid T-points, at 68 m and 82 m in R.

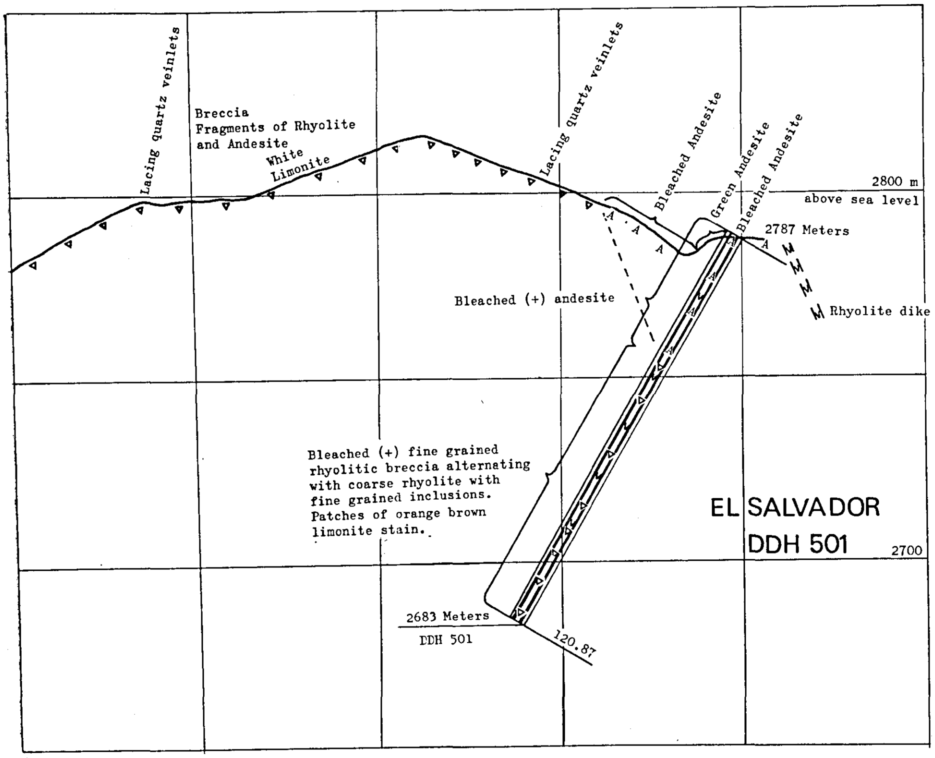

Fig. 3(b). Vertical section of DDH 501. Cross section: looking northeasterly.

We consider it quite reasonable that the T-R relation is more linear than the T-L relation (T-L relation can be converted to T-depth (Z) relation by multiplying cos 30° for DDH 501), because the length of time since the hills were formed must be long enough for the isotherms in the hills to attain the equilibrium state in which isotherms are more subparallel to the surface topography than horizontal (HORAI, 1964).

The estimated dT/dR for DDH 501 is 2.44×10^{-4} °C/cm, giving $dT/dZ = 2.38\times10^{-4}$ C°/cm. For CDH 24A, dT/dZ estimated from the deeper two points is 2.7×10^{-4} °C/cm.

Thermal conductivity was measured on the core specimens representing the column penetrated. The specimens taken at 69 m, 76 m, 119 m depths gave conductivities of 6.50, 5.04 and 6.05×10^{-3} cal/sec cm °C for DDH 501. According to Dr. Gustafson, specimens at 69 m and 119 m are similar in nature and comprize most of the strata, whereas the specimen at 76 m represents less than 10% of the strata. Accordingly, a weighted average was adopted to be the effective conductivity, i.e. $k=6.15\times10^{-3}$ cal/cm sec °C for DDH 501, giving a heat flow value of 1.46 HFU.

As to CDH 24A, three specimens presumably representing the depth

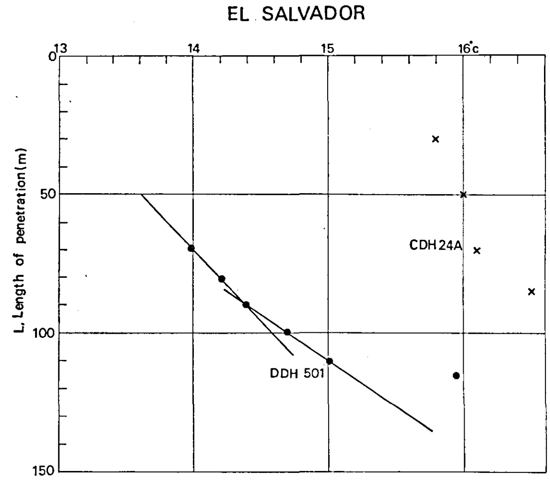

Fig. 4(a). Temperature vs. length of penetration in boreholes at El Salvador mine.

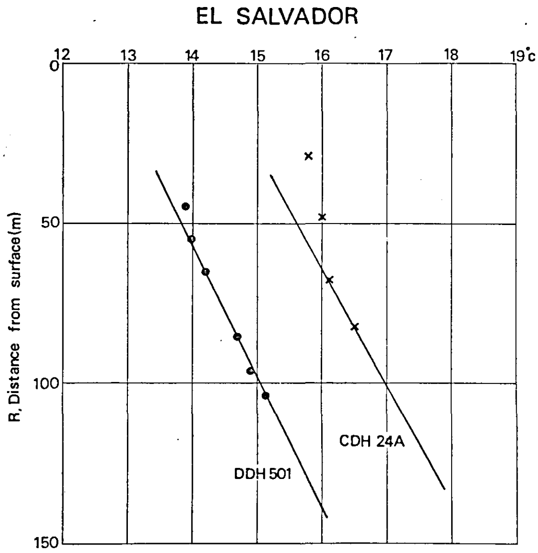

Fig. 4(b). Temperature vs. distance from the surface in boreholes at El Salvador mine.

ranges 60–75 m, 75–95 m and 95 m were provided by Gustafson from the nearby DDH hole. The conductivity of these specimens was measured as 5.14, 4.68 and 5.54×10^{-3} cal/cm sec °C. Considering the depth range used for estimating the gradient in CDH 24A, the value of $k=5.14\times10^{-3}$ was adopted, giving the heat flow value of 1.4 HFU. The average of the two heat flow value is 1.43 HFU. Since the topography is very steep, it was felt that a correction for it may be needed. The topography is in fact quite well fitted to apply Lees (1910) single hill correction. After the correction, the heat flow turned out to be

$$Q = 1.8\ \mathrm{HFU}$$

(Note: in our earlier publication (UYEDA and WATANABE, 1970) El Salvador was given a much smaller gradient value inadvertently.)

We thank Ing. Dr. Gustafson of the Andes Copper Mining Company for his kind cooperation.

SANTA CLARA Iron Mine: 26°32′S, 70°18′W

This site is one of the numerous iron mines in the Atacama Desert, where generally iron ores of varied degrees are found in andesites under-

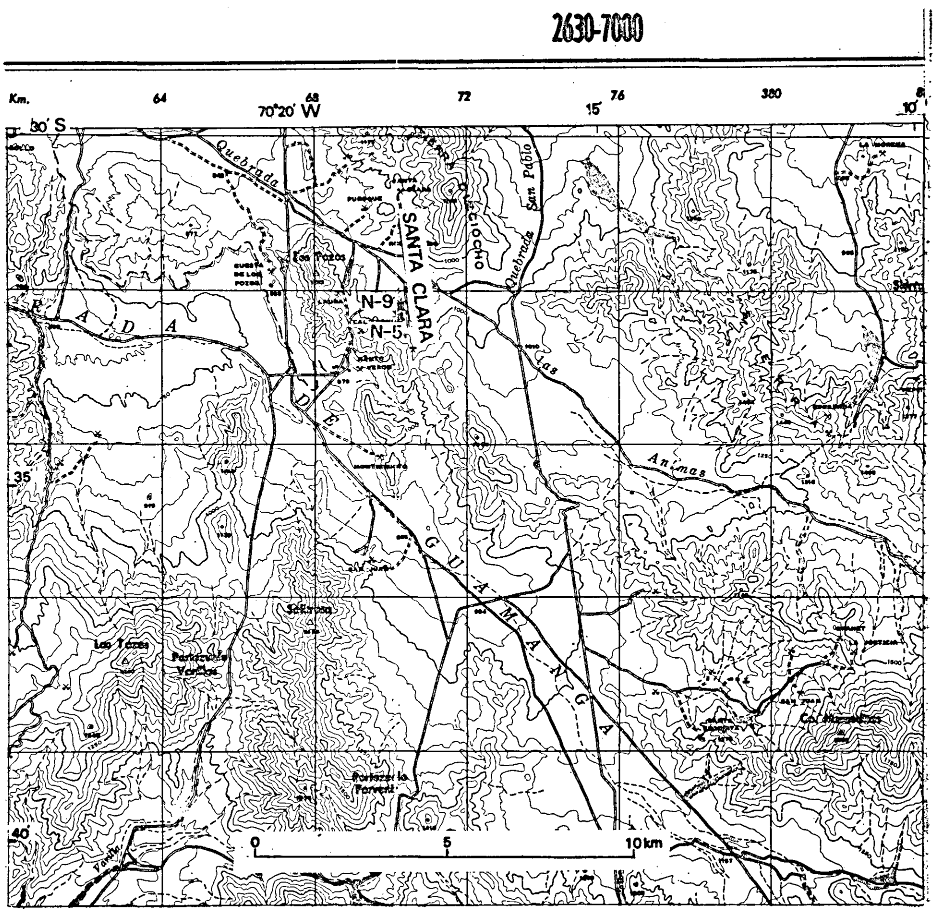

Fig. 5(a). Location of Santa Clara mine. (part of the map published by Instituto Geografico Militar de Chile, QUEBRADA SALITROSA, 2630-7000).

Fig. 5(b). Topography of the area of boreholes N-5 and N-9, at Santa Clara mine.

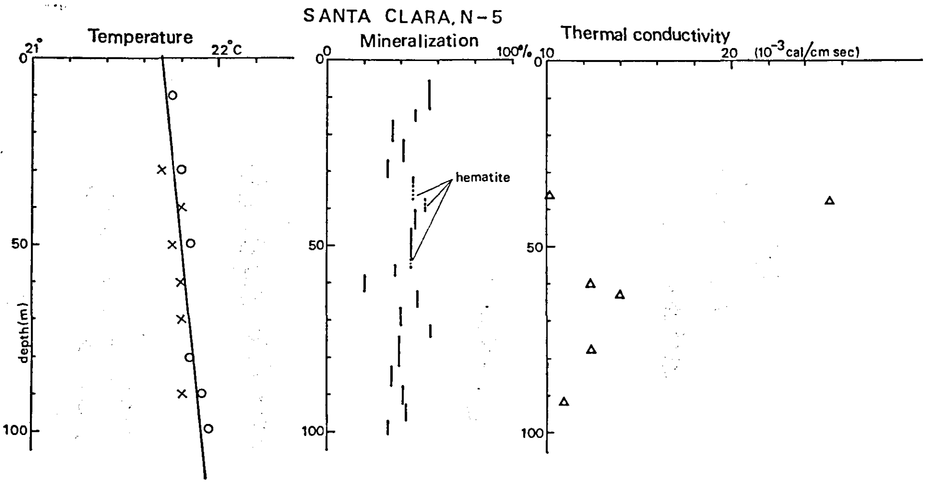

Fig. 6(a). Temperature, mineralization (%) and thermal conductivity vs. depth in borehole N-5, Santa Clara mine.

lying a thin cover of sand. Two prospecting boreholes, N-5, and N-9, at the Santa Clara Mine, presently owned by Compania Minera Santa Clara, were used for the present work. The locations of the holes are shown in Fig. 5, a and b. The temperature measurements were conducted on March 22, 1969 whereas the drilling of the Holes, N-5 and N-9, was made during Jan. 30–Feb. 13, 1969 and Feb. 1–Feb. 13, 1969 respectively. The holes were relatively shallow (160 m and 110 m deep). It was noted during

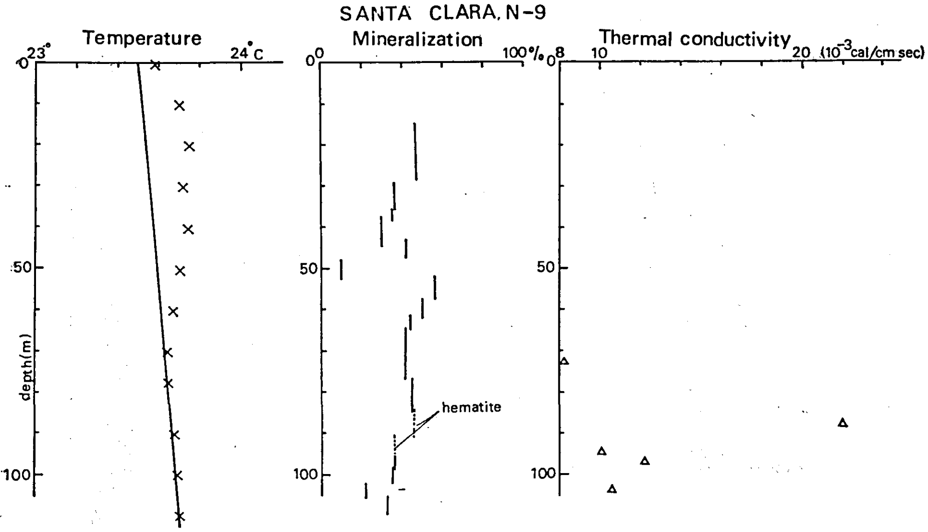

Fig. 6(b). Temperature, mineralization (%) and thermal conductivity vs. depth in borehole N-9, Santa Clara mine.

Table II. Thermal Conductivity

Site: Santa Clara, Copiapo, Chile

Sample	Conductivity mcal/cm sec°C Dry	Wet	Description
N5			
36m	8.74	10.11	dark green skarn with micaceous hematite
40	(14.16)	(26.39)	actinolite
60	10.40	12.32	dark green skarn with very rare magnetite
63	10.01	14.00	magnetite (impregnation)
78	8.19	11.40	dark green grained impregnated skarn
92	8.56	10.98	dark green grained skarn with chalcopyrite
		K=11.76	
N9			
73	5.81	8.26	moderate-coarse grained magnetite
88	7.17	21.91	dark green skarn with magnetite impregnation
95	8.46	10.09	pyrite common partially with hematite spots
97	9.10	12.20	fine grained magnetite with actinolite
104	8.81	10.58	dark green skarn with very weak impregnation
		K=10.28	

drilling that drilling water escaped badly at levels above 50 m but much less at deeper levels. At the time of measurement, the holes appeared to have standing water in them.

The results of temperature measurement are shown in Fig. 6, a and

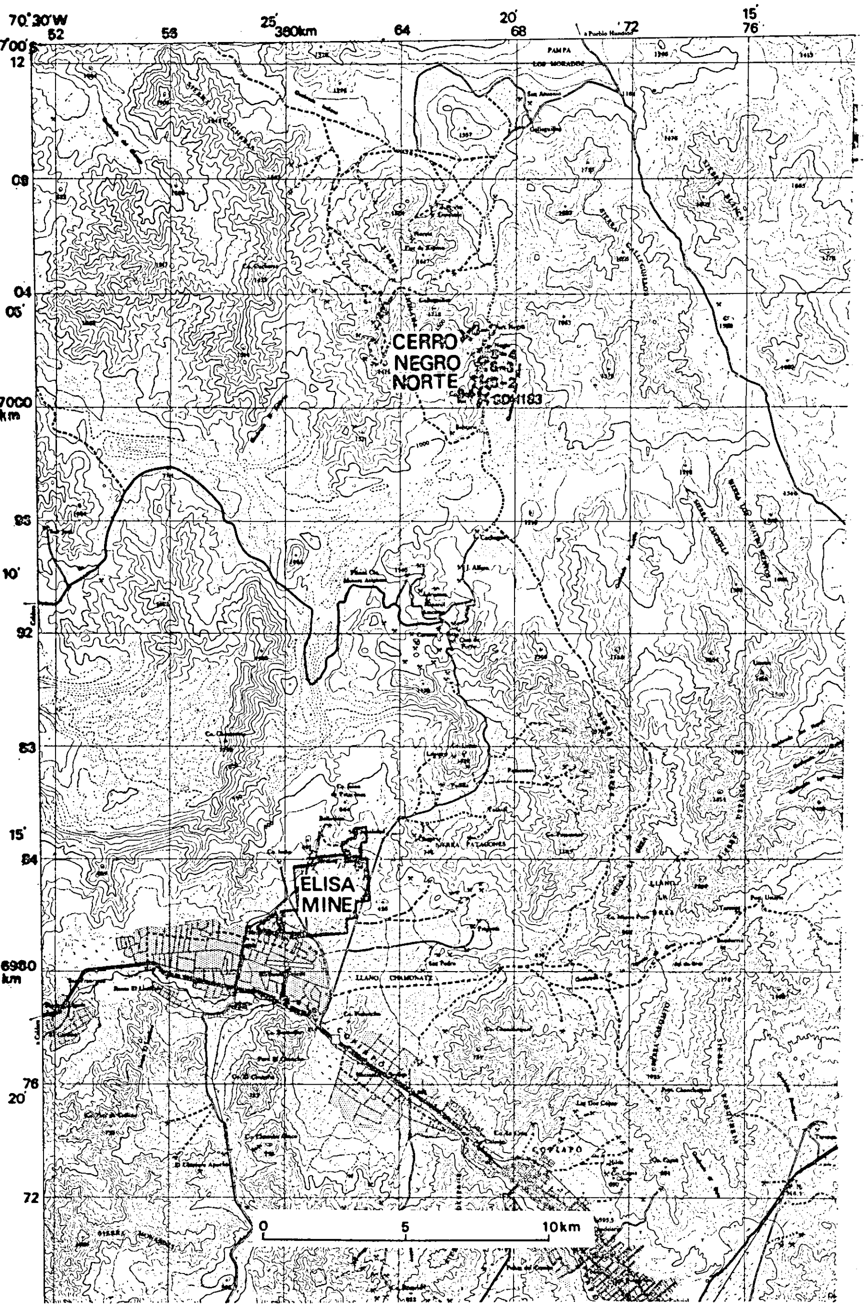

Fig. 7(a). Location of Cerro Negro Norte and Elisa mines. (part of the map published by Instituto Geografico Militar de Chile, COPIAPO, 2700-7000).

b, together with the columns showing the degree of mineralization in the weight percent of iron. The geothermal gradient was found to be very small in both holes (0.20×10^{-4} °C/cm for N-5 and 0.23×10^{-4} °C/cm for N-9).

Eleven selected core specimens, mostly magnetite ore, were used for the thermal conductivity measurements under both dry and wet conditions (Table II). In the real state, the wet condition was considered to prevail. The results are also shown in Fig. 6, a and b. Because of the high ore content, the conductivity is higher than the usual case of ore-free rocks. It was noticed that the conductivity was remarkably high for the ores described as hematite. This result agrees with the previous study (e.g. HORAI, 1971).* Since the layer described as hematite was very thin, the weighted mean of the observed conductivity values was taken to represent the effective conductivity which were 11.76×10^{-3} cal/sec cm °C for N-5 and 10.28×10^{-3} cal/cm sec °C for N-9. These values of geothermal gradient and thermal conductivity resulted in heat flow of 0.24 HFU for both holes. In view of the different values in the gradient and conductivity the agreement of heat flow values for the two holes is remarkably good.

CERRO NEGRO NORTE Iron Mine: 27°06′S, 70°20.6′W

The Cerro Negro Norte mine, owned by CAP-Santa Fé, is also one of the iron mines in Copiapo area. The altitude of the site was approxi-

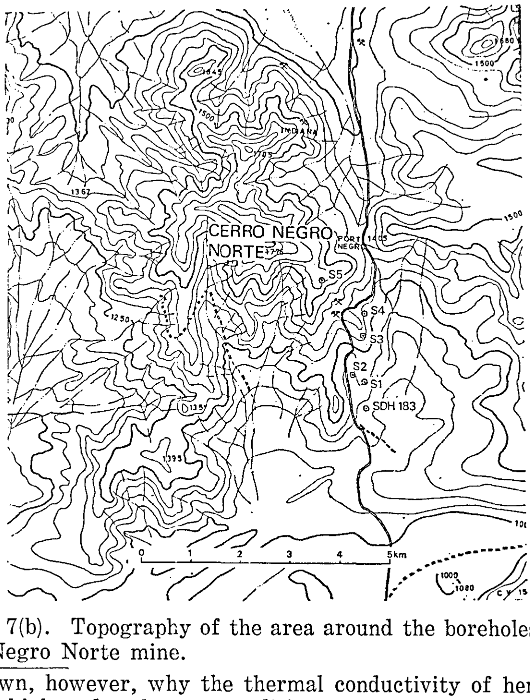

Fig. 7(b). Topography of the area around the boreholes studied in Cerro Negro Norte mine.

* It is not known, however, why the thermal conductivity of hematite bearing specimens is particularly high under the wet condition.

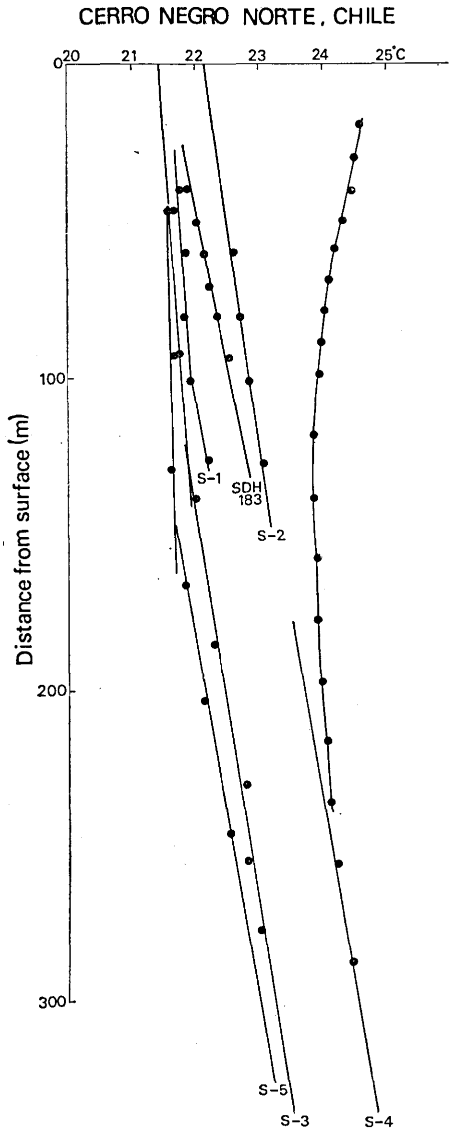

Fig. 8. Plots of temperature vs. distance from the surface in boreholes, Cerro Negro Norte mine.

mately 1250 m above sea level. The locations of the mine and the sites of six boreholes, used for the present study, are shown in Fig. 7, a and b. The results of temperature measurements, made on March 21, 1969, are plotted in Fig. 8 against the distance from the surface. All holes gave low geothermal gradient ranging from 0.3×10^{-4}°C/cm to 1.0×10^{-4}°C/cm. The deepest point in the holes was 354 m below the surface. Holes were all wet and the hole S4 indicated some anomalous features (Fig. 8) at depths shallower than 255 m. The reason for the anomalous feature (negative gradient) is unknown. Deeper parts of the holes, however, gave fairly uniform gradients. We adopted their average as the representative gradient; i.e. 0.85×10^{-4}°C/cm.

Neither geological column nor core specimens of the measured holes are available. But some specimens which were considered to be typical for the formations concerned were obtained. They were specimens CNN-1 and CNN-3 sampled from a nearby mine of Cia Minera de Atacama. The thermal conductivity of these specimens in the wet state was found to be: $K = 5.17 \times 10^{-3}$ cal/cm sec °C for NN-1 and $K = 15.24 \times 10^{-3}$ cal/cm sec °C for CNN-3. Having no more information, it was considered best to take the average of the two, i.e. $K = 10.2 \times 10^{-3}$ cal/cm sec °C.

From the above values for the gradient and the conductivity, heat flow was estimated to be 0.87 HFU at the Cerro Negro Norte mine.

ELISA Iron Mine: 27°15.8'S, 70°23'W

The Elisa mine is also one of the iron mines in Copiapo area, situated

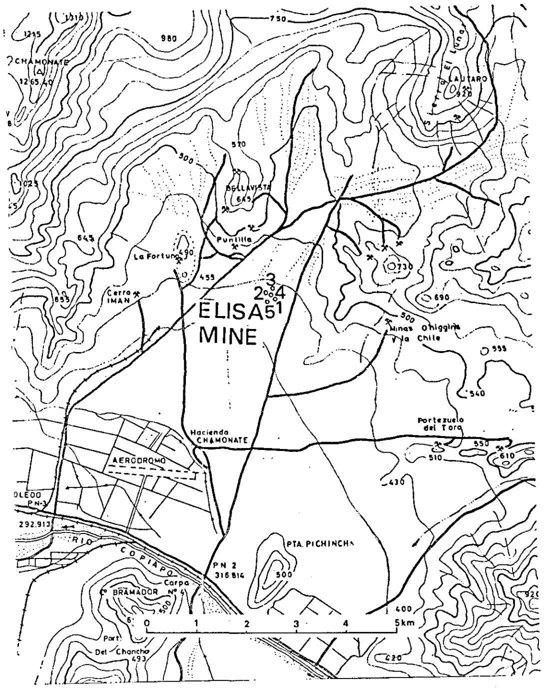

Fig. 9. Topography of the area around the boreholes studied in Elisa mine.

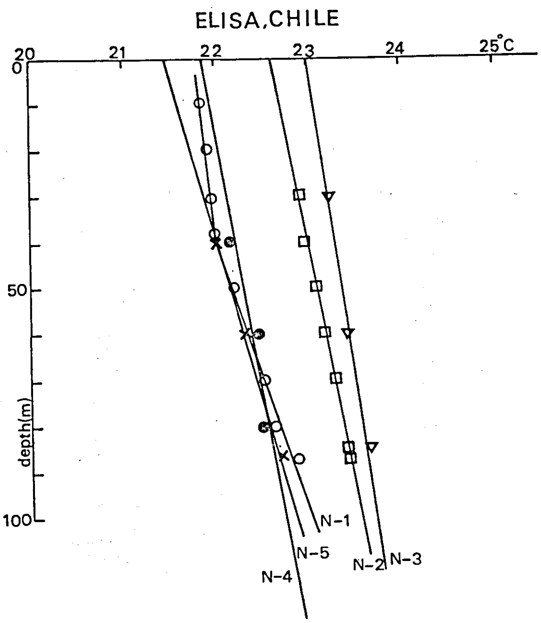

Fig. 10. Plots of temperature vs. depth in boreholes, Elisa mine.

about 14 km north-west of the City of Copiapo. The locations of the mine and boreholes are shown in Figs. 7, a and 9. The five boreholes used for the measurement on March 20, 1969 are located in the middle of a small alluvium plain as shown in Fig. 9 (altitude 48 m above sea level). The holes were drilled in 1967 and their maximum depth was only 85 m, but the temperature data was considered significant (see Fig. 10).

The upper 40 m of the formation was alluvium and below the 40 m level it was composed of andesite and ore (hematite and magnetite). The holes were all dry at the time of the measurements. The values of the gradient were found to be low ranging from $0.67–1.59\times10^{-4}$°C/cm, the average being 1.08×10^{-4}°C/cm.

Core specimens were unavailable. We, therefore, used rock specimens which correspond to the rocks in these holes. They are the specimens EL-1, EL-2 and EL-4. Their thermal conductivity in the dry condition was measured and is shown in Table III.

Table III.

specimen	K, dry, 10^{-3}cal/cm sec°C
EL-1	5.15
EL-2	7.37
EL-3	11.17
average	7.90

Again, without further information, the heat flow value was obtained, from the average of the gradient and conductivity, as $Q=0.85$ HFU at the Elisa Iron mine.

VALLENAR: 29°01'S, 70°53'W

This site was in a mining area where the Overseas Mineral Prospecting and Development Company of Japan made test drillings for porphyry copper. The area called Cachiyuyo was located in the Andes copper belt near the town of Domeyko about 50 km south of Vallenar city (Fig. 11(a)). Mr. K. Yatsuji of the Company gave us all the pertinent information about the mine and kindly accompanied us to the site. The site was visited by us on March 18, 1969 for the measurement.

Among eight boreholes drilled by the Company in the area, five holes were selected for the temperature measurements (Nos. 2, 4, 5, 6, 7 in Fig. 11(b)). But only holes No. 2 and 4 allowed for the lowering of the probe to the meaningful depth. Figure 12, a and b and Table IV show the geological column, temperature and the thermal conductivity of these two holes. Hole No. 2 and No. 4 were drilled in the period between Nov. 19–Dec. 9, 1968 and Jan. 28–March 4, 1969. Although the holes were only 3 months and 18 days old, the temperature in both holes indicated a good linear relationship with the depth. The original depths of the holes were 231 m and 198 m, but the depths to which the probe could attain were 210 m and 128 m (see Fig. 12, a and b).

As can be seen in Fig. 12, the temperature data below about 80 m is probably meaningful for both holes, giving the geothermal gradient 0.99×10^{-4}°C/cm for No. 2 hole and 1.02×10^{-4}°C/cm for No. 4 hole.

Hole No. 2 penetrated the rock composed largely by dacites with a varying degree of chrolitization. Above about 100 m depth (50–105 m), considerable amount of hornblende quartz porphyry with pyrite mineralization is found. 11 representative specimens of dacites and quartz porphyry (all from deeper than 100 m) were used for the thermal conductivity measurement, the results of which are illustrated in Fig. 12(a). The mean value of the 11 conductivity values is 5.40×10^{-3} cal/cm sec °C. This gives the heat flow for the hole No. 2 as 0.53 HFU.

Hole No. 4, as shown in Fig. 12(b), has microdiorite at a depth less than 50 m. But the deeper column is largely dacite with varying degree of chrolitization. 14 representative rock specimens were used for the

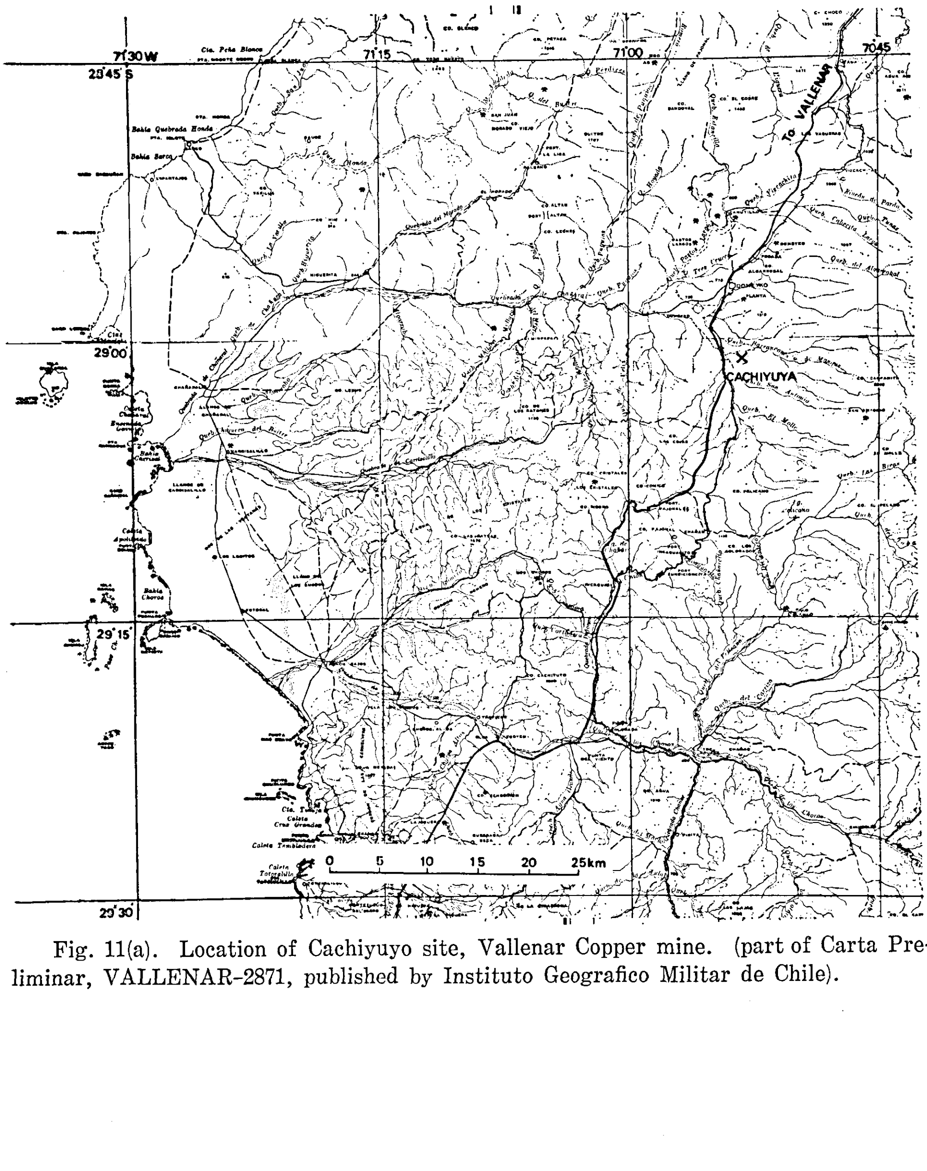

Fig. 11(a). Location of Cachiyuyo site, Vallenar Copper mine. (part of Carta Preliminar, VALLENAR-2871, published by Instituto Geografico Militar de Chile).

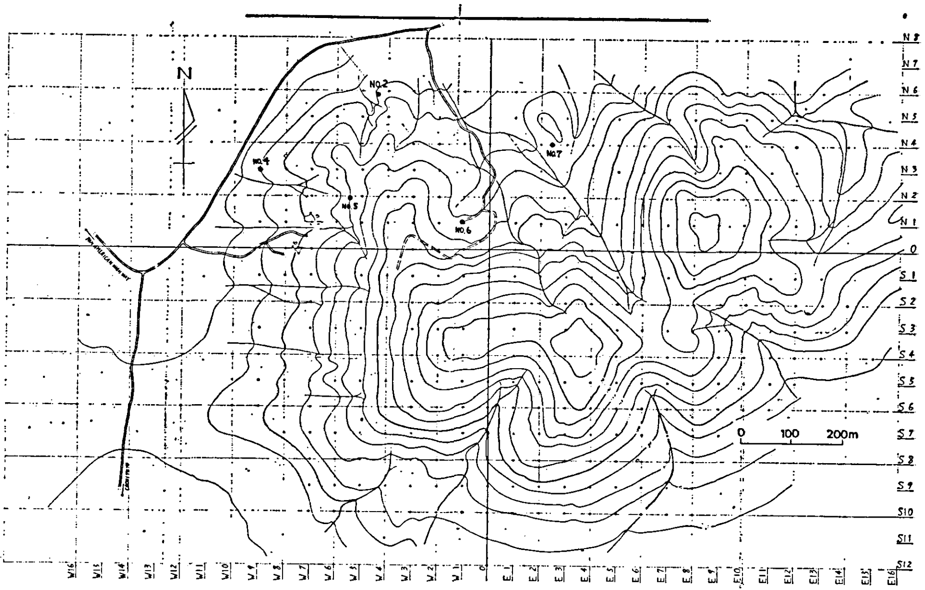

Fig. 11(b). Topography of the area around the boreholes studied in Vallenar area.

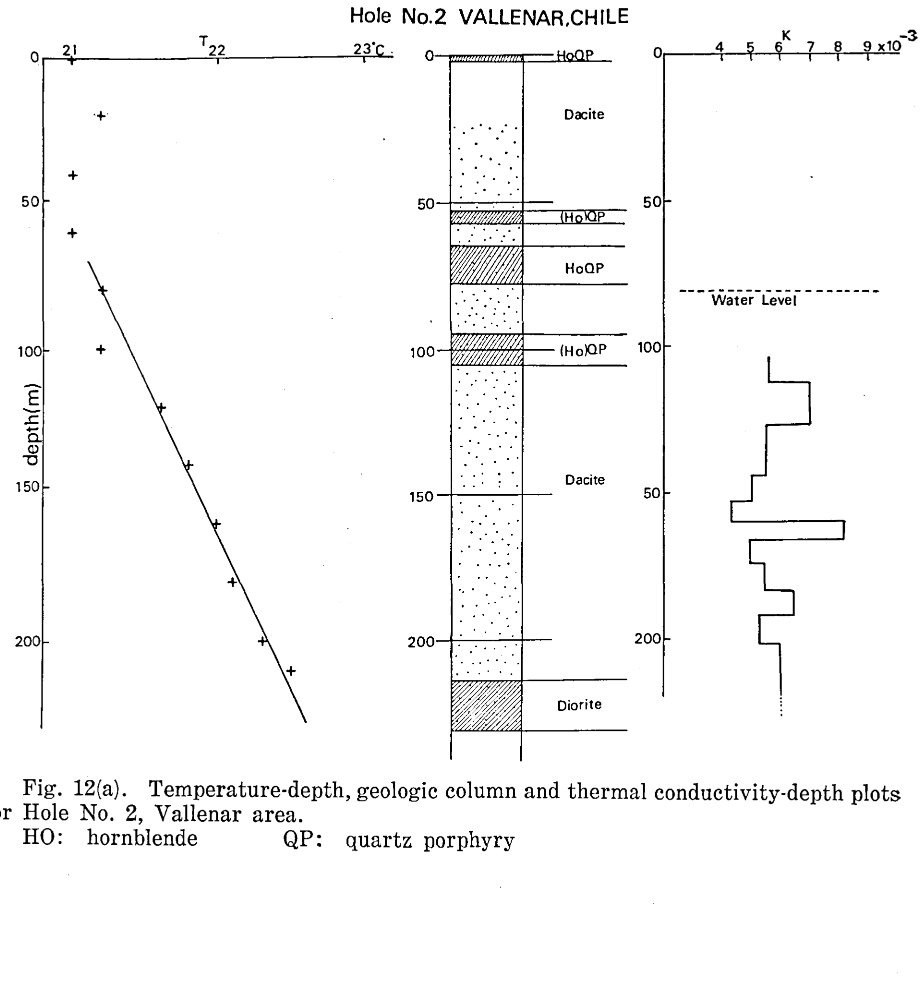

Fig. 12(a). Temperature-depth, geologic column and thermal conductivity-depth plots for Hole No. 2, Vallenar area.

HO: hornblende QP: quartz porphyry

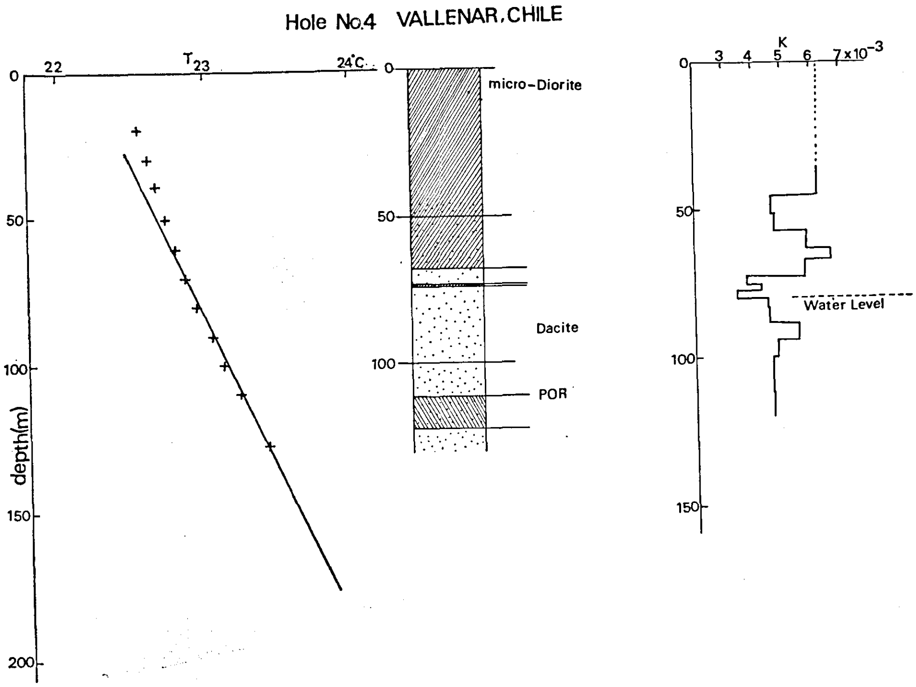

Fig. 12(b). Temperature-depth, geologic column, and thermal conductivity-depth plots for Hole No. 4, Vallenar area.
POR: porphyry

Table IV. Thermal Conductivity

Site: Vallenar, Chile

Sample	Conductivity mcal/cm sec°C Dry	Wet
Hole No. 2		
102.0m	6.49	5.92
102.9	5.88	6.98
130.5	5.13	5.49
138.0	5.15	4.98
147.6	3.91	4.28
153.0	6.50	8.12
158.7	5.29	4.85
168.3	4.18	5.40
179.4	4.65	6.43
180.9	5.14	5.13
209.4	6.31	5.89

Sample	Conductivity mcal/cm sec°C Dry	Wet
Hole No. 4		
43.8m	6.24	4.47
46.5	4.62	5.70
54.3	4.75	7.52
60.0	5.88	6.35
66.0	6.63	6.65
68.1	5.78	5.79
75.0	3.79	4.29
75.9	4.29	4.91
79.2	3.48	4.54
86.4	4.37	4.56
90.3	4.47	5.52
98.7	3.52	4.84
103.5	5.70	4.61
120.9	4.43	4.68

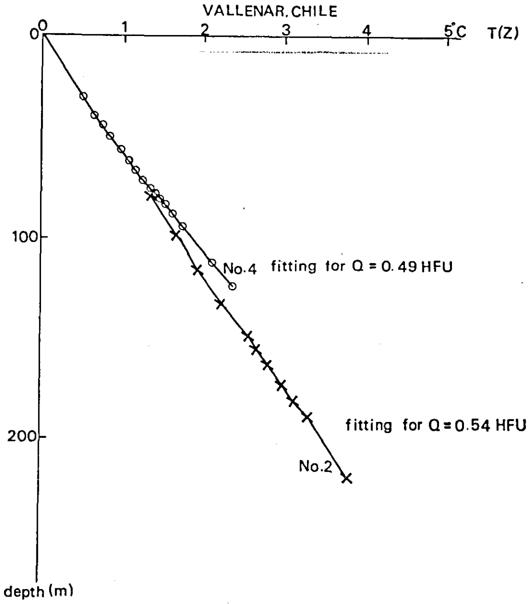

Fig. 13. Fitting of $T(Z)$, vs. Z, where $T_0=0$.

thermal conductivity measurement. The results are also shown in Fig. 12(b). Since the hole had a water table at about 80 m, conductivity under dry and wet conditions are shown in the figure for rocks at a depth less than 80 m and more than 80 m respectively. The average K for a depth greater than 80 m is 4.81×10^{-3} cal/cm sec °C. Therefore, the heat flow would be 0.49 HFU for the hole No. 4.

When a sufficient number of conductivity measurements are available, the heat flow could be obtained by fitting the relation

$$T(Z)=Q\int_0^z \frac{dz}{k(z)}+T_0$$

The fitting for the hole No. 2 rendered the heat flow 0.54 HFU. When we applied this method for the hole No. 4 with the assumption that the conductivity above 45 m is the same as that of the sample measured (6.24×10^{-3} cal/cm sec °C), heat flow value was found to be 0.49 HFU, agreeing very well with the value obtained by the mean value (see Fig. 13). Thus, the gradient of 1.0×10^{-4} °C/cm and the conductivity of 5.2×10^{-3} cal/cm sec °C would be the reasonable values at Vallenar, giving a heat flow of 0.52 HFU.

BOQUERON CHANAR Iron Mine: 28°05.0S, 70°43.0′W

Boqueron Chanar, presently owned by Compania de Acero del Pacific (CAP), is an iron prospecting site about 100 km north of Vallenar (Fig. 14).

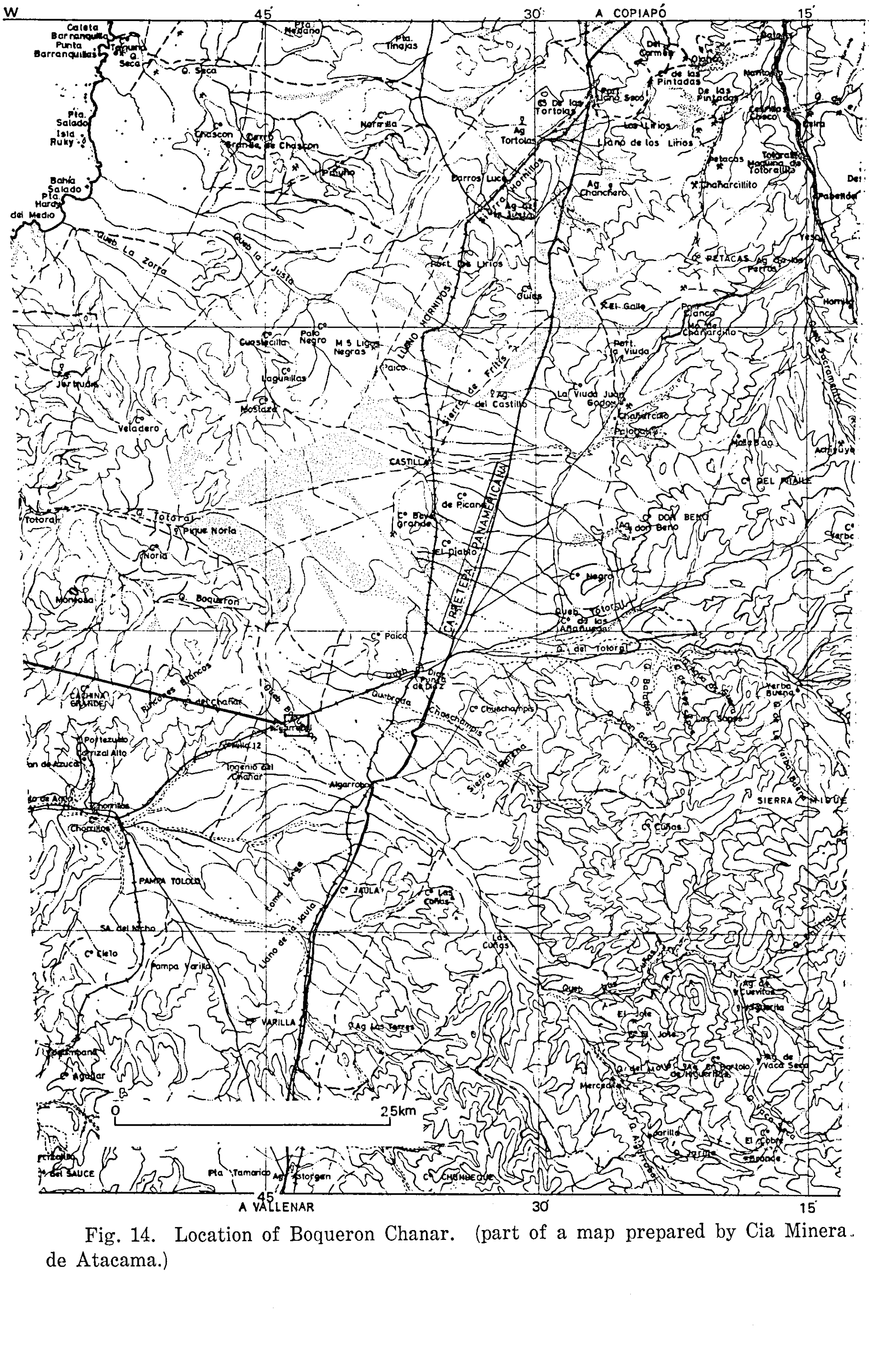

Fig. 14. Location of Boqueron Chanar. (part of a map prepared by Cia Minera de Atacama.)

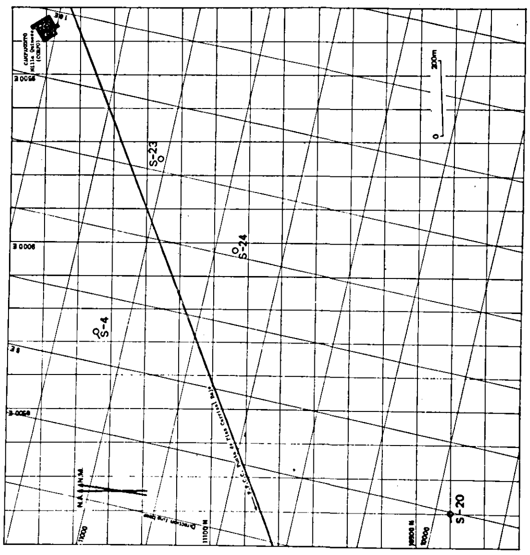

Fig. 15. Locations of boreholes studied in Boqueron Chanar. Short lines attached to sites S-4, S-20 are horizontal projection of slanted holes. Local magnetic and astronomic coordinates. (By courtesy of CORFO).

A number of deep vertical test boreholes had been drilled in a flat plain at the altitude of 355 m above sea level. The prospecting was made by the Proyecto Boqueron Chanar of Corporacion de Fomento de Production (CORFO) de Chile. Ing. M. Rivadeneira of the Proyecto kindly supplied us with pertinent information about the site.

The temperature measurements were made on March 25, 1969 in four boreholes; S-4, S-20, S-23, and S-24 (Fig. 15). Here the state of the holes was generally good and the depth of measurements in one of them (S-20) was limited by the length of the available cable. Figure 16 a, b, c, d shows the results of measurements together with the lithological column. In all the holes the temperature gradient at deeper levels were close to 1.0×10^{-4}°C/cm. In the upper levels where the strata are sediments, gradients were larger as seen in the figures, although the depths of changing gradient do not correspond to the lithological changes exactly. None of the measurements penetrated into the mineralized zone. For each hole, two core specimens considered representative for deeper levels were selected for the K-measurement. The depths of the cores are also indicated in Fig. 16, a, b, c, d. Their conductivity values under dry and wet conditions are shown in Table V. Since the holes were filled with water, wet-values were used to compute heat flow values.

The average value of heat flow in Boqueron Chanar is obtained, thus, as 0.54 HFU. This value appears to be in an agreement, though not

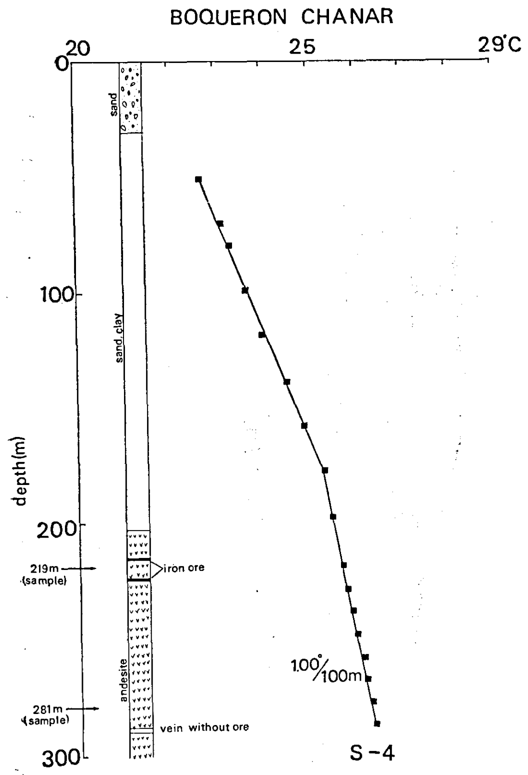

Fig. 16(a). Temperature vs. depth plot and geologic column for Hole S-4, Boqueron Chanar. Samples for K measurement are indicated by arrows.

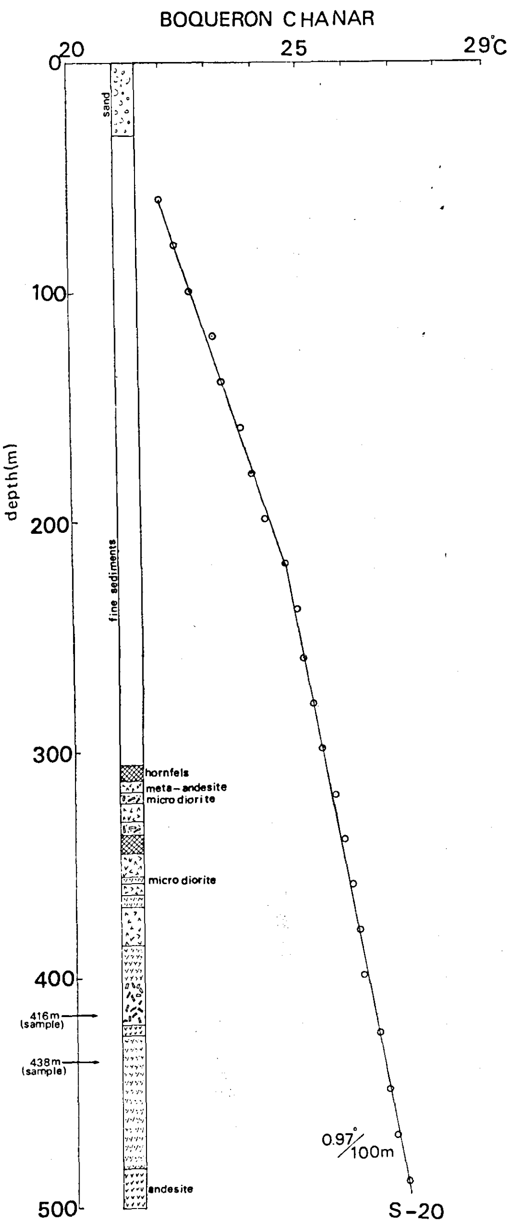

Fig. 16(b). Temperature vs. depth plot and geologic column for Hole S-20, Boqueron Charnar. Samples for K measurement are indicated by arrows.

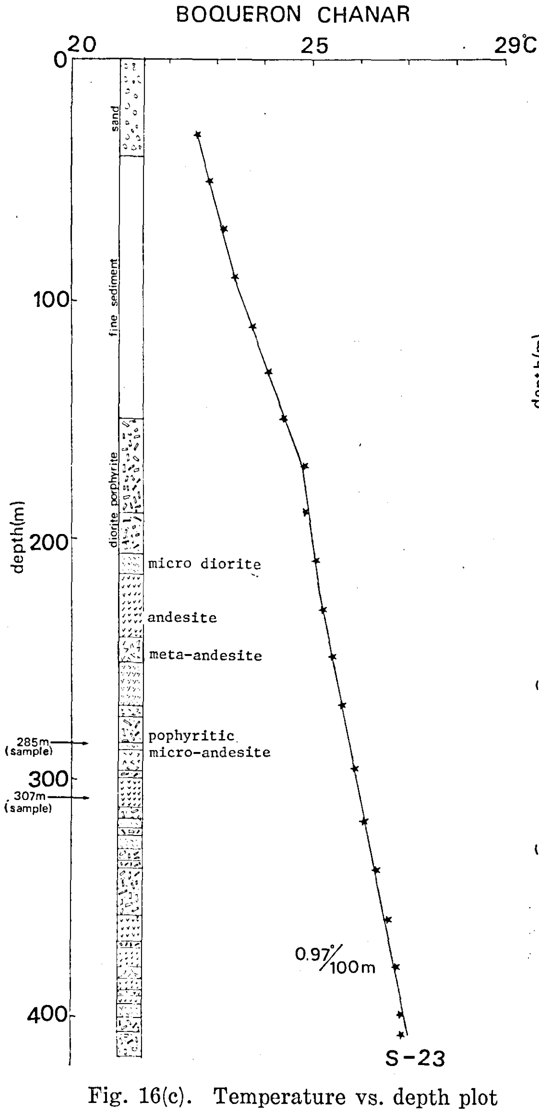

Fig. 16(c). Temperature vs. depth plot and geologic column for Hole S-23, Boqueron Chanar. Samples for K measurement are indicated by arrows.

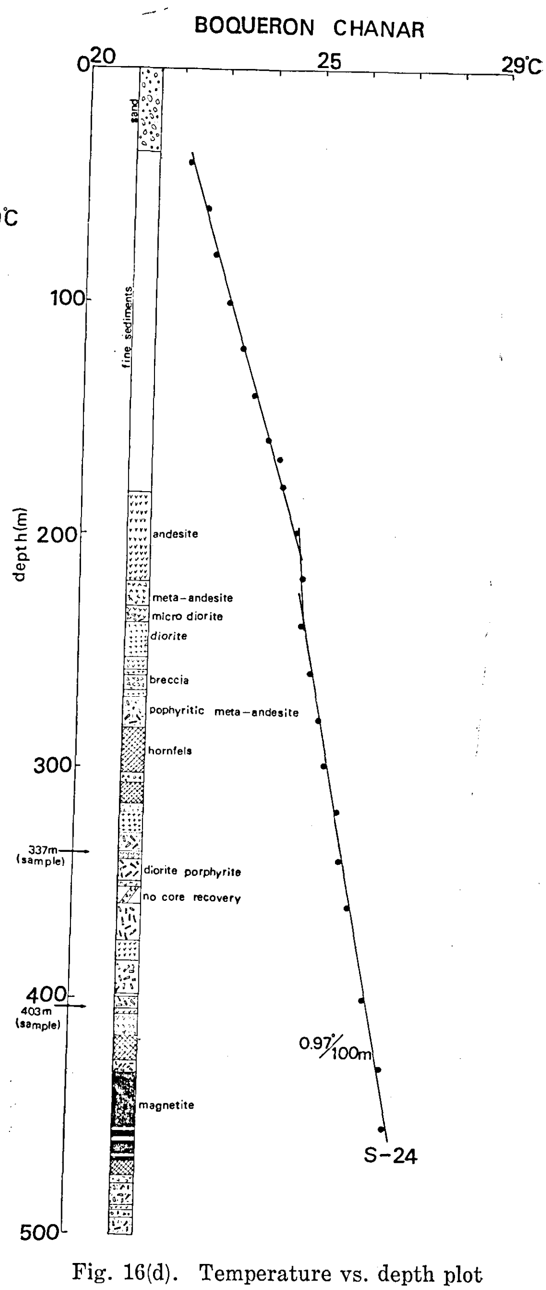

Fig. 16(d). Temperature vs. depth plot and geologic column for Hole S-24, Boqueron Chanar. Samples for K measurement are indicated by arrows.

Table V. Thermal Conductivity

Site: Boqueron Chanar, Chile

Sample	Conductivity mcal/cm sec°C Dry	Wet	Average K (wet)	T-Gradient 10^{-4}°C/cm	Heat Flow HFU
BH4 219m	6.13	6.66			
			6.25		
281m	5.52	5.74		1.00	0.62
BH20 416m	4.80	5.08			
			5.14		
438m	4.49	5.19		0.97	0.50
BH23 285m	5.03	6.36			
			5.59		
307m	4.58	4.83		0.97	0.54
BH24 337m	6.03	6.01			
			5.33		
403.7m	4.09	4.64		0.94	0.50
		Average	5.57	0.97	0.54

exactly, with the previous value (0.7–1.0 HFU) obtained by DIMENT et al. (1965) for the same site.

LA AFRICANA Copper Mine: 33°20'S, 70°45'W

The La Africana copper mine of Santiago Mining Company of the Anaconda Company, presently owned by Compania Minera Pudahuel, is

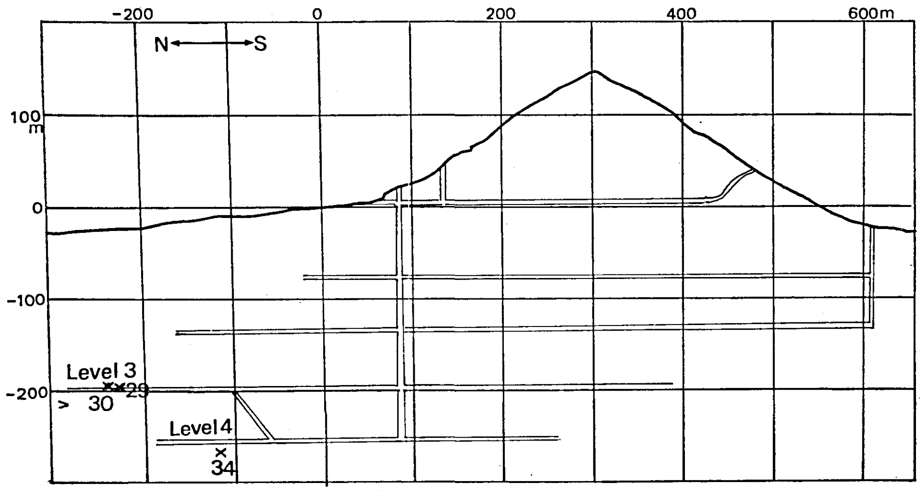

Fig. 17. Cross section of La Africana mine (Sylvester, 1964).

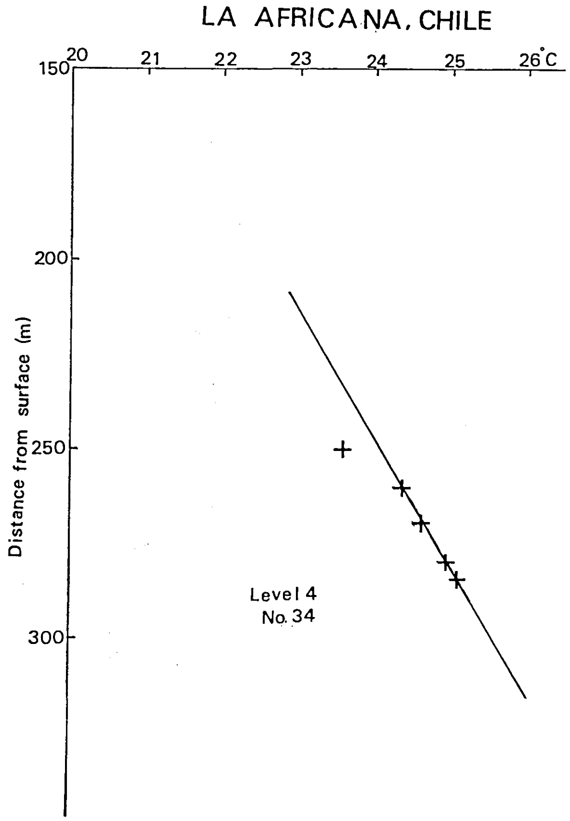

Fig. 18. Temperature vs. depth plot of borehole No. 34, La Africana mine.

Table VI. Thermal Conductivity

Site: La Africana, Chile

Sample	Conductivity mcal/cm sec°C Dry	Wet	Average K (wet)
DDH34			
10.3m	6.88	6.69	
15	7.28	7.94	
20	6.08	6.61	6.52
25	5.57	5.69	
30	5.61	5.86	

located in the coast range near Santiago, at the altitude of 510 m above sea level. Ing. C. P. Sylvester of the mine kindly gave us pertinent information and led us to the sites of the mines on March 28, 1969. The rocks are almost entirely granodiorite (SYLVESTER, 1964). A short inclined hole (DDH No. 34) drilled from the deepest level (Level 4) of the mine was available for the measurement (Fig. 17, SYLVESTER, 1964). The inclination of the hole was $-75°$. The hole was filled with water. The temperature-depth relation obtained is shown in Fig. 18. Although the hole was short, the depth from the surface of Level 4 is already 250 m, so that the gradient (2.89×10^{-4} °C/cm) was considered to be meaningful.

In addition, two wall rock temperature measurements were made using short bore holes (No. 29 and 30) drilled horizontally from Level 3

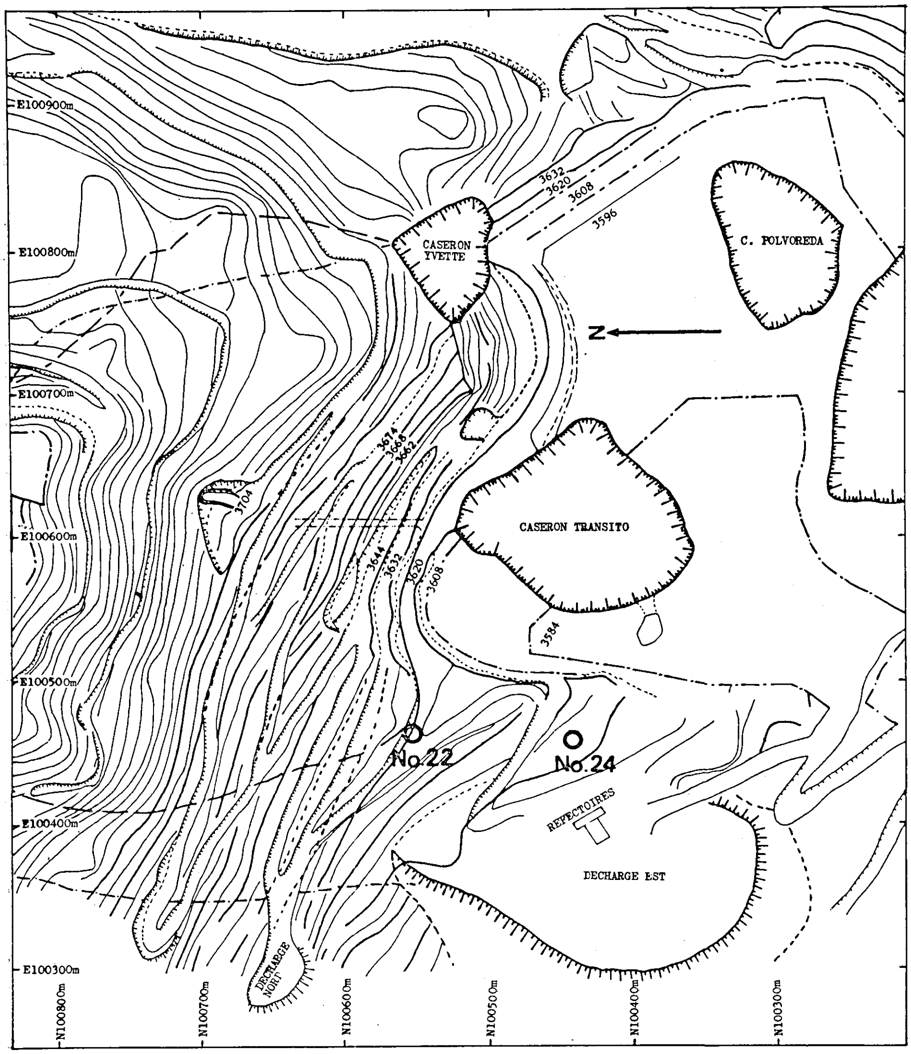

Fig. 19. Locations of boreholes at Disputada mine. (part of a map prepared by Compania Minera Disputada de Las Condes.) Numbers attached to contour lines are altitudes in m. above sea level.

(Fig. 17). However, the penetration of the probe was less than 2 m in each case. The temperatures were 23.05°C (No. 29) and 23.30°C (No. 30). The temperature of the running water at the site and the air temperature were 23.06°C and 22.0°C respectively. Considering the shallowness of the hole and the horizontal distance from the hole No. 34 at Level 4, temperature data at Level 3 were discarded.

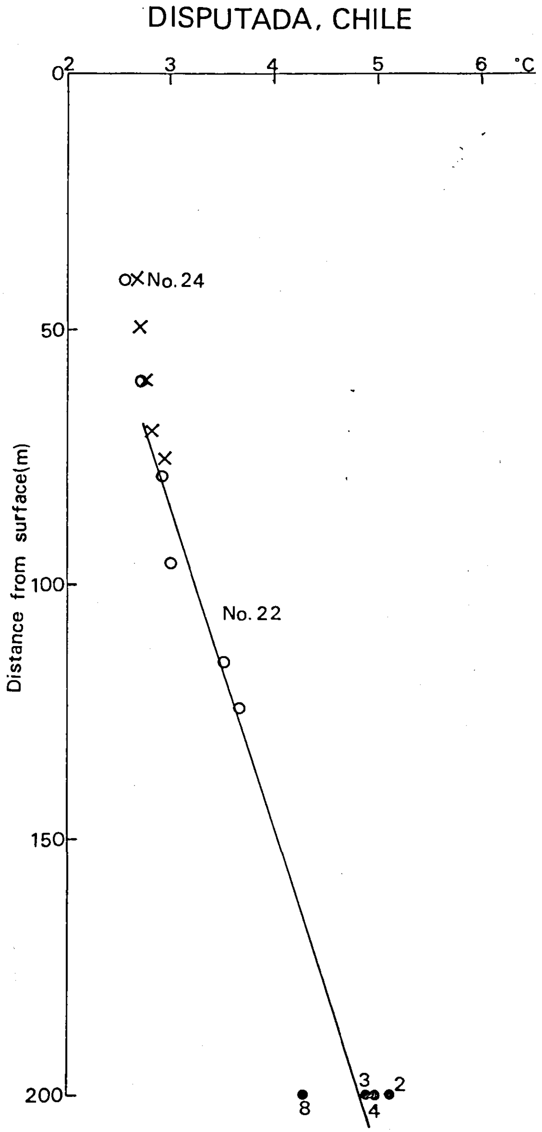

Fig. 20. Temperature vs. distance from the surface plot for Disputada mine.

Five granodiorite sample from the hole No. 34 were used for thermal conductivity measurement. Table VI shows the results. Excluding the one at a 10.3 m depth, the average of four wet conductivity values is 6.52×10^{-3} cal/cm sec °C, giving the heat flow 1.88 HFU.

DISPUTADA Copper Mine: 33°28'S, 70°10'W

A copper mine of Cia Minera Disputada de Las Condes, located at about 65 km to the east of Santiago on the western slope of the Andes. The altitude of the mine is 3,700 m above sea level. Ing. M. Richert of the mine kindly rendered assistance to us in providing information and locating boreholes on March 30, 1969. Two dry surface boreholes (Nos. 24 and 22), (Fig. 19) and one dry horizontal short hole drilled into the wall of the drift at the level 200 m below the surface were used for the temperature measurement. The results of the measurement are shown in Fig. 20.

Borehole No. 24 was measured only to the depth of 75 m. The data are not sufficient to give a reliable gradient by itself, but if we take the lowest two points only, the gradient is 2.4×10^{-4} °C/cm. Two rock samples were available for conductivity assessment (see Table VII). Taking the mean of the two measurements under a dry condition, (6.01×10^{-3} cal/cm sec °C), the heat flow was assessed as 1.45 HFU.

Borehole No. 22 was open to the depth of 124 m and the gradient was estimated as 1.60×10^{-4} °C/cm. Again two core samples (Table VII) were used for the conductivity measurement, the average of the measured values being 9.06×10^{-3} cal/cm sec °C. The heat flow is obtained, thus, as 1.45 HFU. The rocks above 130 m level were almost entirely granodiorite with a low degree (10%) of mineralization.

In addition to these, one locality at a 200 m level was chosen for a wall rock temperature measurement. The 15 m long dry horizontal hole gave a temperature of 4.25°C (No. 8 in Fig. 20). This and three other temperatures of running water at the same localities are also shown in

Table VII. Thermal Conductivity

Site: Disputada, Chile

Sample	Conductivity mcal/cm sec°C Dry	Wet	Average K Dry
BH24			
75m	5.98	6.55	6.01
86m	6.05	7.16	
BH22			
100m	11.28	12.04	9.06
206	6.84	7.88	

Fig. 20. Although these results show some scatter, heat flow at this mine may be taken as about 1.45 HFU.

ISLA TRIERRA DEL FUEGO Oil field: 54°S, 69°W

Previously available information for this oil field was the thermal gradient value of 3.20×10^{-4} °C/cm estimated from the bottom hole pressure gauge log data down to 2,463 m depth. Five core specimens from the oil field were made available for thermal conductivity measurement. The result, as shown in Table VIII, gave the average conductivity of 7.20×10^{-3} cal/cm sec °C. The estimated heat flow value turned out to be 2.30 HFU.

Table VIII. Thermal Conductivity

Specimen	Depth (m)	Conductivity mcal/cm sec°C Wet
Daniel 1 No. 2	1781-1787	3.68
Lautaro 4 No. 3	2520-2523	6.71
Cullen 32 No. 1	1770-1776	6.08
Chanarcillo 24 No. 2	2264-2270	10.25
Calofate 22 No. 2	1868-1874	9.29
		7.20

Acknowledgment

The authors would like to thank a great number of colleagues who kindly rendered their assistance in our field work in Chile. Acknowledgment has been made in the text at pertinent parts to just a few of them.

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3. チリーにおける地殻熱流量測定

地震研究所 上田誠也, 渡部暉彦
チリ大学 E. KAUSEL
アタカマ鉱山会社 久保正明, 屋代好男

1969 年, 日米科学協力事業の一環として, 南米西部の地殻熱流量測定が行われた. 本報告は, そのうちチリー国に関する部分である. 地温勾配の実測は, 9 地点において行なわれ, 他のもう一地点(油田) については既存のデータを利用させていただいた. 測定結果によると, 太平洋海岸ではほゞ一貫して低熱流量が得られた. しかし, アンデス山中 (El Salvador 鉱山) 及び, サンチアゴ付近(La Africana 鉱山), 並びにチリ南端フエゴ島 (油田) では高熱流量が得られた. 日本列島にみられるような海溝側の低熱流量帯, 内陸, 背弧側の高熱流量帯という明瞭なパターンが存在するか, 否かは, 測点不足のため, 未だはっきりしない. ただ, 高熱流量を示す 2 地点がそれぞれチリの 2 つの活火山帯に位置するのは興味深い.