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

By Teruhiko WATANABE, Seiya UYEDA,

Earthquake Research Institute,

Jaime A. GUZMAN ROA, Ramon CABRÉ,

Observatorió San Calixto, Casilla 283, La Paz, Bolivia,

and Hiroji KURONUMA*,

Nitto Bolivia Mining Company, Yaesu 2-5, Chuo-ku, Tokyo.

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Abstract

Results of terrestrial heat flow measurements in Bolivia, conducted in 1969, are reported. Nine different sites (all metal mines) were visited for underground temperature measurement. However, data from only five sites was usable. The geothermal gradient data from one oil field was referenced. The sites investigated were mostly in the area of the Altiplano and the western Cordillera Oriental. Heat flow in this area is found to be generally high: The average of the five values is 3.21±1.03HFU ($135\pm43 mWm^{-2}$).

Introduction

Field work on heat flow measurement in Bolivia was conducted by us as a part of a US-Japan Science Cooperation Program with a group of scientists of Scripps Institution of Oceanography, University of California at San Diego. We made the measurement on land by visiting various mines while US scientists conducted ship-borne measurements on Lake Titicaca (SCLATER *et al.*, 1970). We have also tried to make use of existing temperature data in oil-wells of the area, but, due to the unavailability of rock samples for thermal conductivity measurements, oil-well data is used only for reference. The thermal conductivity of rocks from mines visited was measured by the QTM (Quick Thermal Conductivity Meter, Showa Denko Company, SUZUKI *et al.*, 1975). In an earlier report, the results on the geothermal gradients were published (UYEDA and WATANABE, 1970). The present report is a part of series of papers describing the heat flow measure-

* Present affiliation: Dowa Kōei Company, Daiichi Tekko Building, 1-8-2, Marunouchi, Chiyoda-ku, Tokyo, Japan

Fig. 1. Heat flow values in Bolivia in HFU. Value at Lake Titcaca after SCLATER *et al.*, 1970, data at the Santa Cruz oil-field in gradient only.

Table 1. Summary of heat flow measurement in Bolivia

Station name	Station type	Location	Approx. Altitude (m)	Max. depth (m)	T-gradient[1]	Conductivity[2]	Heat flow (HFU)[3]	Heat flow (SI)[4]	Description[5]
Chojlla	W, Sn mine	16°25′S 67°44′W	2,000	600	1.95	8.31	1.62	68	H
Corocoro	Cu mine	17°11′S 68°30′W	3,900	485	5.75	7.60	4.37	183	H
Chacarilla	Cu mine	17°34′S 68°14′W	3,800	150	5.00	6.52	3.26	137	V and H
Santa Fe	Sn mine	18°10′S 66°49′W	4,350	213	3.71	8.11	3.01	126	H and I
Catavi	Sn mine	18°25′S 66°39′W	4,500	593	3.00	12.95	3.78	159	H and I

[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) mWm^{-2}
[5] V: vertical hole
H: horizontal hole
I: inclined hole

ments at individual sites of different South American countries visited (UYEDA *et al.*, 1978, a, b; 1980).

Results

Heat Flow Values in Bolivia:

Figure 1 and Table 1 summarize the heat flow data in Bolivia. Quite high heat flow values were obtained in four mines (Corocoro, Chacarilla, Santa Fe, and Catavi), while a value only slightly higher than the continental average was obtained in one mine (Chojlla). The average of the five sites is 3.21 ± 1.03HFU ($135 \pm 43 mWm^{-2}$). The sites studied are unevenly distributed in Bolivia. All are in the Altiplano and Cordillera Oriental zones, which are tectonically more active than the Brazilian shield part to the east. The higher four values were obtained in the Altiplano. Since the heat flow value at Chojlla is not so high, the Cordillera Oriental may not have regionally high heat flow. This point has to be checked by further measurements. Although we visited the Colquiri mine (Fig. 1) which is also in the Cordillera Oriental, the measurement was not successful. In the eastern part of the country, the heat flow appears to be lower, as inferred from

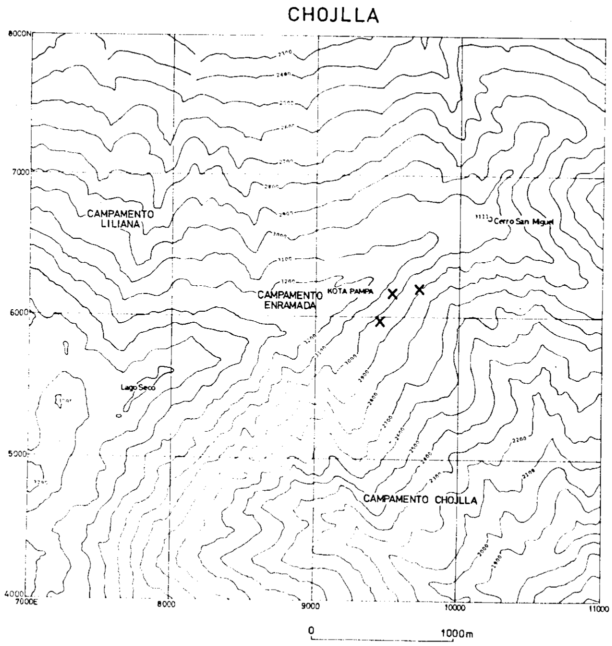

Fig. 2. Positions of temperature measurements in the Chojlla mine. (local coordinates).

the gradient data at an oil-well (2°C/100m at Santa Cruz, UYEDA and WATANABE, 1970).

CHOJLLA Mine: 16°25′S, 67°44′W

This is a tungsten-tin mine operated by the International Mining Company and located at about 40km east of the city of La Paz. Mineralization at this site took place in the Mesozoic time. A K-A data by AHLFELD and SCNNEIDER-SCHERBINA (1964) for muscovite in a tin-ore vein gives 183×10^6 years.

The mine was visited on May 10th, 1969 and Ing. A. Martinez and Ing. A. Bedoya kindly guided us into the mine in which temperature measurements were conducted through horizontal holes at four points on three levels. Thermistors were inserted 15 meters into the hole at each point. The locations of each point are shown in Fig. 2. The measured temperatures are plotted against the depth from the surface in Fig. 3: the temperature gradient is 1.95°C/100m. Two representative samples of slate gave the mean thermal conductivity of 8.31×10^{-3} cal/cm sec °C in wet state. These values gave 1.62 HFU ($68mWm^{-2}$) as the heat flow at Chojlla.

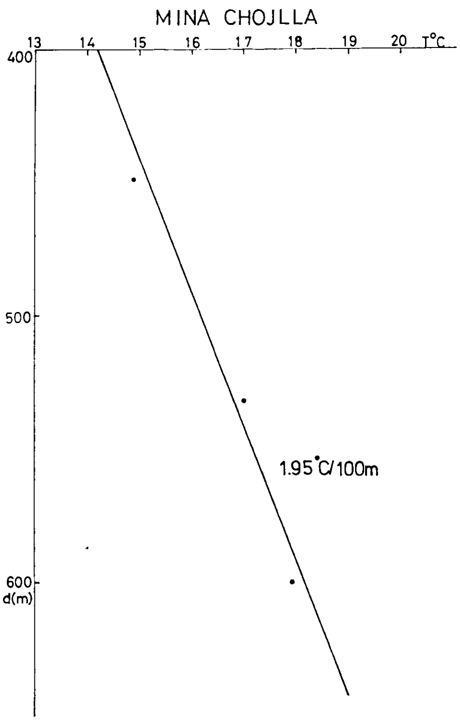

Fig. 3. Temperature-depth relation in the Chojlla mine.

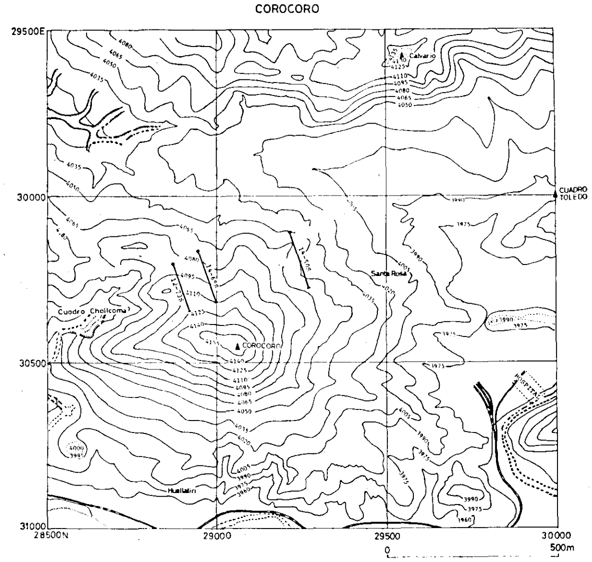

Fig. 4. Locations of temperature measurements in the Corocoro mine. (local coordinates).

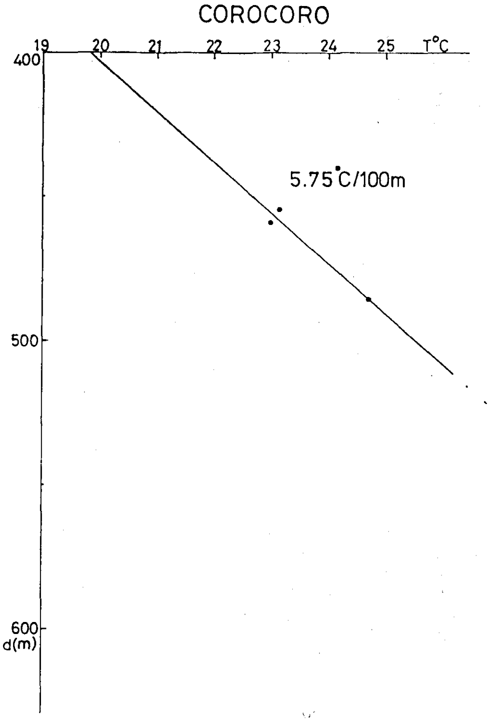

Fig. 5. Temperature-depth plot for the Corocoro mine.

COROCORO Mine: 17°11'S, 68°30'W

Corocoro is a copper mine situated at about 130km southwest of the city of La Paz. The mine is operated by COMIBOL (Corporacion Minera de Bolivia). The copper ore (either native copper or chalocite) is found in upper Tertiary red sandstone and conglomerates, forming a typical so called Corocoro type copper deposit. The ore deposits of this type are widely scattered in the Altiplano. The mine was visited on May 8th, 1969. Ing. Luis Ramos, Ing. Walter de La Fuente and Ing. Marwin Columba of COMIBOL kindly assisted the authors' work. Temperature measurements were made through horizontal holes drilled at two levels (level 12 and level 14) by inserting the thermistor about 15m into the holes. The locations of holes are indicated in Fig 4. The results plotted against the depth from the surface (Fig. 5), although there are only three points, indicate that the gradient may be 5.75°/100m. Two representative red sandstone samples yielded the mean wet thermal conductivty of 7.60×10^{-3}cal/cm sec °C. The heat flow at this site is estimated as 4.37 HFU (183mWm^{-2}). This value is extremely high for a continental heat flow apart from an active volcanic zone.

CHACARILLA Mine: 17°34'S, 68°14'W

This is also one of the Corocoro type copper mine situated about 60km south of the Corocoro mine, and was operated by the Nitto Bolivia Mining Company when the authors visited on April 27th, 1969.

Two nearby vertical holes No. 96 and No. 97 (Fig. 6) were first

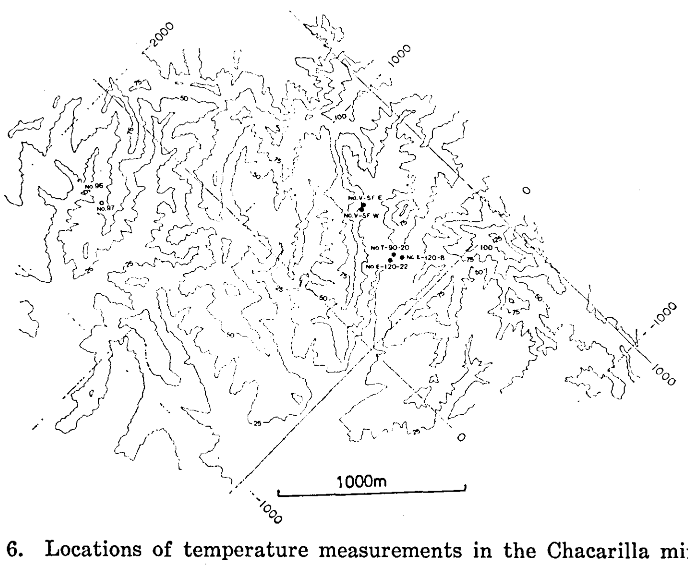

Fig. 6. Locations of temperature measurements in the Chacarilla mine.

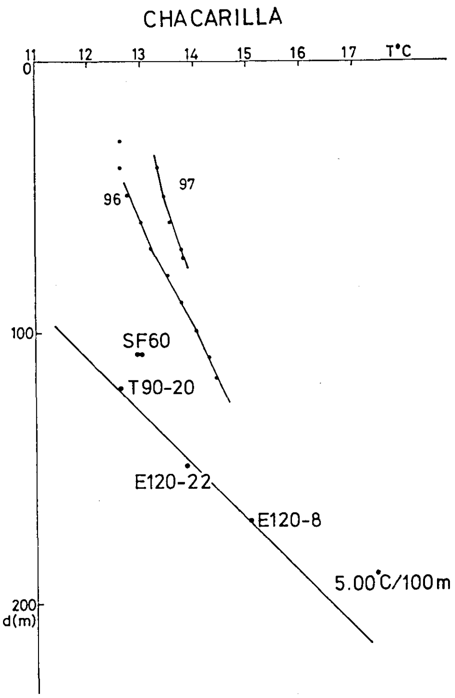

Fig. 7. Temperature-depth plots for the Chacarilla mine.

tried for temperature measurements. The results are shown in Fig. 7. Then, temperature measurements deeper in the mine were conducted at three levels (levels 60, 90 and 120) by using horizontal holes. The results are also plotted in Fig. 7 against the depth from the surface. Locations of measurements at level 60 are indicated by SF. These two points are separated from the sites at levels 90 and 120, which were close together in plan view. If we take the results from these latter points, the gradient turns out to be 5.00°C/100m whereas that from the vertical holes is about 2.4°C/100m. Because of the slight non-linearity of the $T-d$ relations in the vertical holes and their relative shallowness from the surface, here we take that the deeper values of 5.00°C/100m may be more reliable. We have measured the thermal conductivity of seven samples of typical sandstone. The mean value of the wet conductivity was $(6.52\pm1.95)\times10^{-3}$cal/cm sec°. Thus, the heat flow at the Chacarilla mine is estimated to be 3.26 HFU (137mWm^{-2}).

SANTA FE Mine: 18°10'S, 66°49'W

Santa Fe, operated by COMIBOL (Corporacion Minera de Bolivia) is a tin mine, located at about 40km southeast of the City of Oruro in the Altiplano. The tin mineralization at the Santa Fe mine, as in the cases of other nearby tin mines such as Catavi and Potosi, was associated with the upper Tertiary igneous activity. The mine was visited on May 2nd, 1969. Ing. Jorge Defilippis (Chief Geologist), Ing. Raul Arce (Superintendent) and Ing. Julian Vega of the mine have assisted the authors a great deal.

In this mine, the temperature measurements were made at three

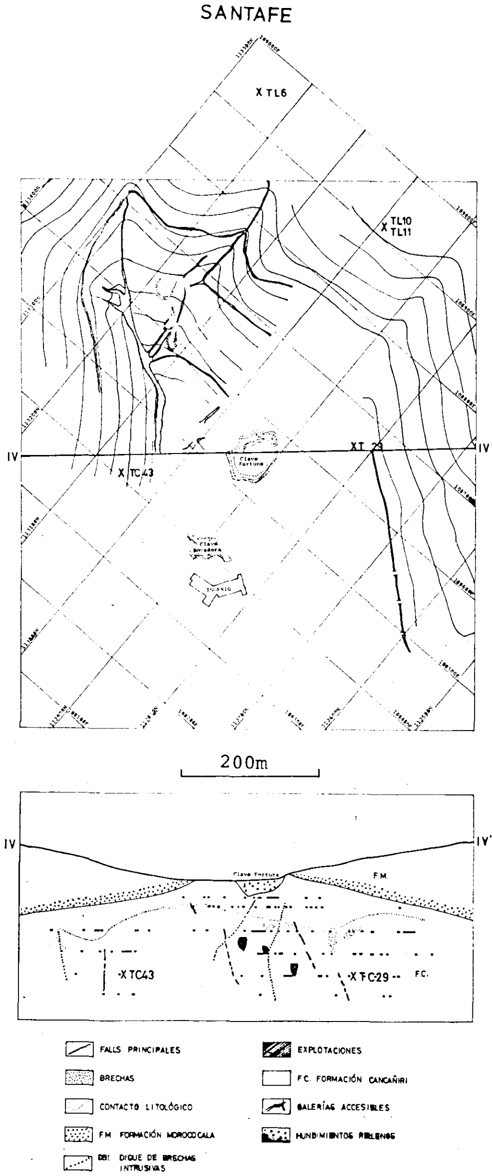

Fig. 8. Locations of temperature measurements in the Santa Fe mine. (local coordinates).

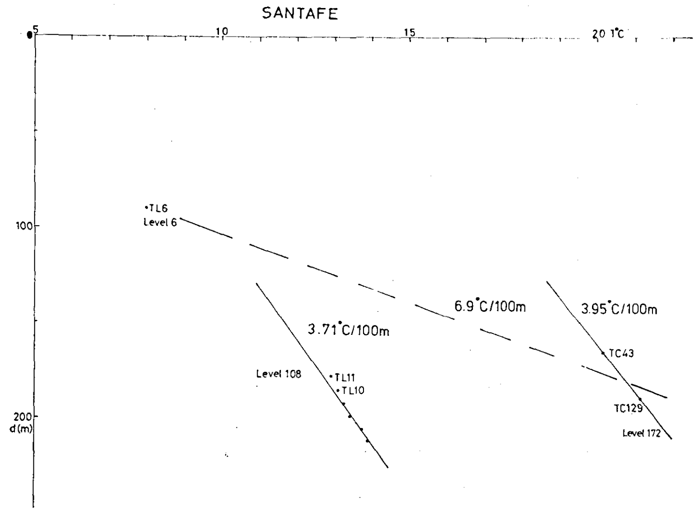

Fig. 9. Temperature-depth plots for the Santa Fe mine.

levels (levels 6, 108 and 172), utilizing horizontal and inclined holes. The locations of temperature measurements were widely scattered as shown in Fig. 8. The results of the measurement are plotted against the depth from the surface (Fig. 9). TL10 and TL11 are close to each other, giving the gradient of 3.71°C/100m. The other points (TL6, TC43 and TC29), if they are considered together, seem to give geothermal gradient of 6.9°C/100m. However, being different from the case in Chacarilla, these three points are so far apart that this value has little reliability. We, therefore, adopt the value from TL10. Although TL6 is too far away, TC43 and TC29 occupy more or less symmetric positions with respect to the valley as shown in the lower part of Fig. 8. Therefore, it may not be too unreasonable to assume that the isotherms may also be symmetric. With this assumption, the gradient from these two points is 3.95°C/100m, partially supporting the value from TL10.

The rocks concerned are mainly dolerite of which thermal conductivity (dry) was measured to be 8.11×10^{-3}cal/cm sec °C. Heat flow at this site is estimated to be 3.01 HFU (126mWm^{-2}). Again this value is high for a continental heat flow.

CATAVI Mine: 18°25′S, 66°39′W

The Catavi mine is the largest tin mine operated by COMIBOL. It is located at about 80km southeast of the city of Oruro. Ing. Feliz Lunario and Ing. Arnaldo Rivero of the mine rendered assistance to the authors' work, conducted on May 6th and 7th, 1969. The mineralization at the Catavi mine was associated with the late Tertiary intrusion of quartz porphyry (Salvadora stocks) into the Silurian formations.

The temperature measurements were made at levels 205, 481, 650 and 685 of the mine using horizontal and inclined drill holes. The locations of measurements are shown in Fig. 10 and the temperatures against the depth are in Fig. 11. The temperatures are somewhat scattered but this may be due to the scattered positions of measurements. If an average straight line is drawn through all the points, the apparent gradient comes out as 1.9°C/100m. However, it is noticed in the plan view of the points of measurement in Fig. 10 that, DDH593, DDH31, DDH383, DDH110 are relatively close together and DD234 and DDH612 form another group at a deeper level. If we treat these two groups separately and disregard other points that are isolated (DDH602, DDH623 and DDH432), the gradients are given as 3.0°C/100m and 4.1°C/100m respectively. Having no more information, here we tentatively take the middle of the above three estimates for the gradient of the area. This is given as 3.0°C/100m. Four representative rock samples were provided for the thermal conductivity measurements. Average of wet conductivity of these was obtained as $(12.59 \pm 2.11) \times 10^{-3}$

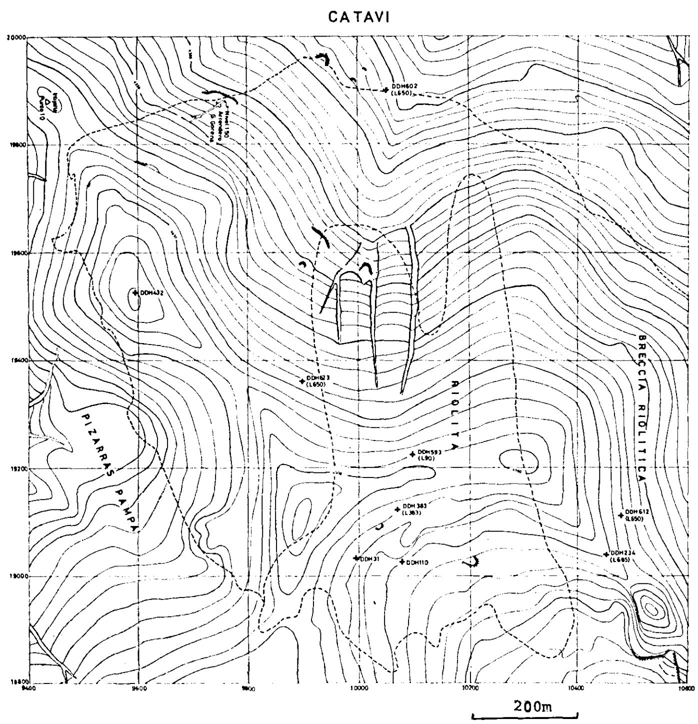

Fig. 10. Locations of temperature measurements in the Catavi mine. (local coordinates).

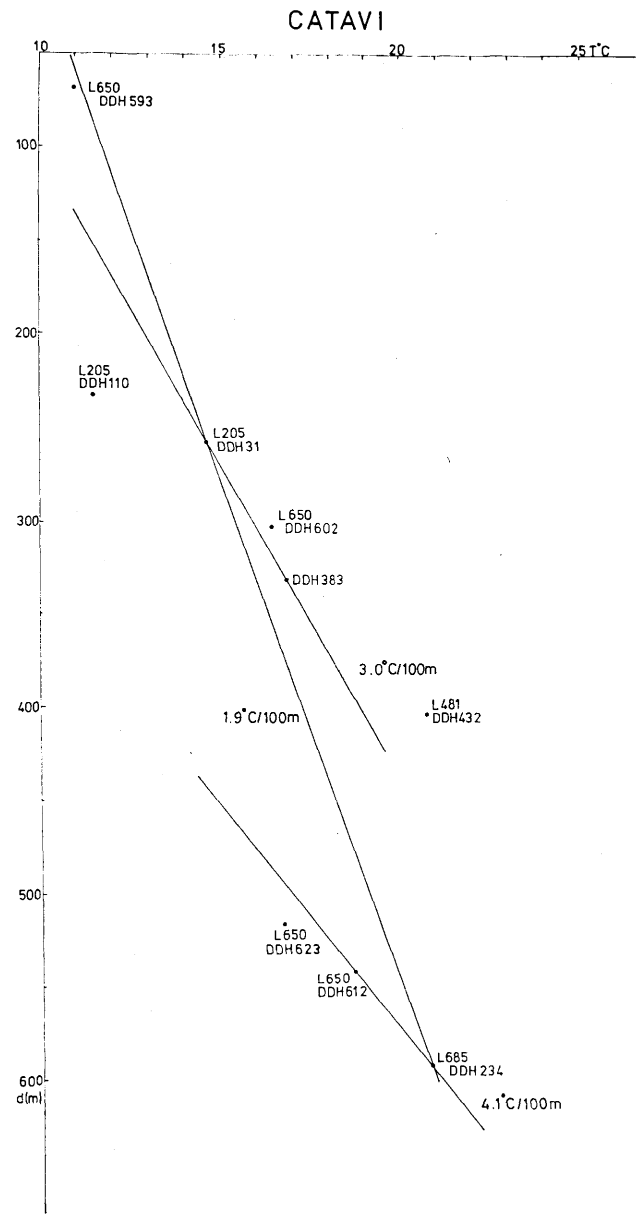

Fig. 11. Temperature-depth plots for the Catavi mine.

cal/cm sec °C. These values of gradient and thermal conductivity yielded heat flow at Catavi as 3.78 HFU ($159mWm^{-2}$).

Acknowledgments

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References

AHLFELD, F. and A. SCHNEIDER-SCHERBINA, 1964. Yacimientos minerales y de hidrocarburos de Bolivia, Ministerio de Minas y Petroleo, *Depto. Nal. de Georogia*, Bol., No. 5 (Especial), 78-79.

SCLATER, J. G., V. VACQUIER and J. H. ROHRHIRSH, 1970. Terrestrial heat flow measurements on Lake Titicaca, Peru, *Earth Planet. Sci., Lett.*, **8**, 45-54.

SUZUKI, S., S. SUMIKAMA, S. MATSUMOTO, J. ITO and Y. ARAKAWA, 1975. Study on the application of a new rapid instrument for determination of thermal conductivity, (paper read at 1975 Pittsburgh Conf. on Analytical Chemistry and Appl. Spectroscopy).

UYEDA, S., and T. WATANABE, 1970. Preliminary report of terrestrial heat flow study in the South American continent; distribution of geothermal gradients, *Techtonophys.*, **10**, 235-242.

UYEDA, S., T. WATANABE, E. KAUSEL, M. KUBO and Y. YASHIRO, 1978, a. Report of heat flow measurements in Chile, *Bull. Earthq. Res., Inst.*, **53**, 131-163.

UYEDA, S., T. WATANABE and F. VOLPONI, 1978, b. Report of heat flow measurements in San Juan and Mendoza, Argentine, *Bull. Earthq. Res. Inst.*, **53**, 165-172.

UYEDA, S., T. WATANABE, Y. OZASAYAMA and I. IBARAGI, 1980. Report of heat flow measurements in Peru and Ecuador, *Bull. Earthq. Res., Inst.*, **55**, 55-74.

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3. ボリビアにおける地殻熱流量測定結果

地震研究所 渡部暉彦
上田誠也
San Calixto 観測所 J. GUZMAN ROA,
Ramon CABRÉ
日東ボリビア鉱山会社 黒沼広治
(現: 同和工営株式会社)

1969年，日米科学協力事業の一環として実施されたボリビアにおける地殻熱流量測定結果は，この国の西部（特にアルテイプラーノ地域）において高熱流量を示した．5ケの測定値の平均は 3.21±1.03 HFU であった．