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4. *Report of Heat Flow Measurements in Peru and Ecuador.*

By Seiya UYEDA, Teruhiko WATANABE,

Earthquake Research Institute,

Yoji OZASAYAMA,

C. Itoh and Company, Tokyo,

and K. IBARAGI,

Sumitomo Metal Mining Company, Tokyo.

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Abstract

Results of terrestrial heat flow measurements in Peru and Ecuador conducted in 1969, are reported. Eight different sites in Peru and one site in Ecuador were visited for underground temperature measurement. However, data from only five metal mines in Peru and the metal exploration site in Ecuador were usable. The geothermal gradient data on four oil fields in Peru and two in Ecuador were referenced. Although high heat flow has been indicated on the continent side of the Andes (the Casapalca and the Cuajone mines and the Ucayali oil field), low geothermal gradients were also found in mines in high Andes (the Raura and Cerro Verde mines). The latter are suspected to be the result of ground water circulation. The highly disturbed cases of the Morococha and San Vicente mines showed almost zero gradient. Much more work is needed to delineate the regional heat flow pattern of the area.

Introduction

Field work on heat flow measurement in Peru and Ecuador was conducted in 1969 by us, as 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 measurements on land by visiting boreholes in mines, while the US scientists made ship-borne measurements on Lake Titicaca (SCLATER *et al.*, 1970). References to existing temperature data in oil-wells have also been made, but, due to unavailability of rock samples for thermal conductivity measurement, heat flow values for oil-wells could not be obtained. 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 gradient were published (UYEDA and WATANABE, 1970). The present report is a part of series of papers describing the heat flow measurements at individual sites of different countries (UYEDA *et al.*, 1978a, b, WATANABE *et al.*, 1979).

Results

Heat Flow Values in Peru and Ecuador:

Figure 1 and Table 1 summarize the heat flow data in Peru and Ecuador. High heat flow values in the mines (4.68 HFU at Casapalca and 2.34 HFU at Cuajone) are based on fairly good data whereas subnormal values at Raura (0.71 HFU) and Cerro Verde (0.98 HFU) are considered

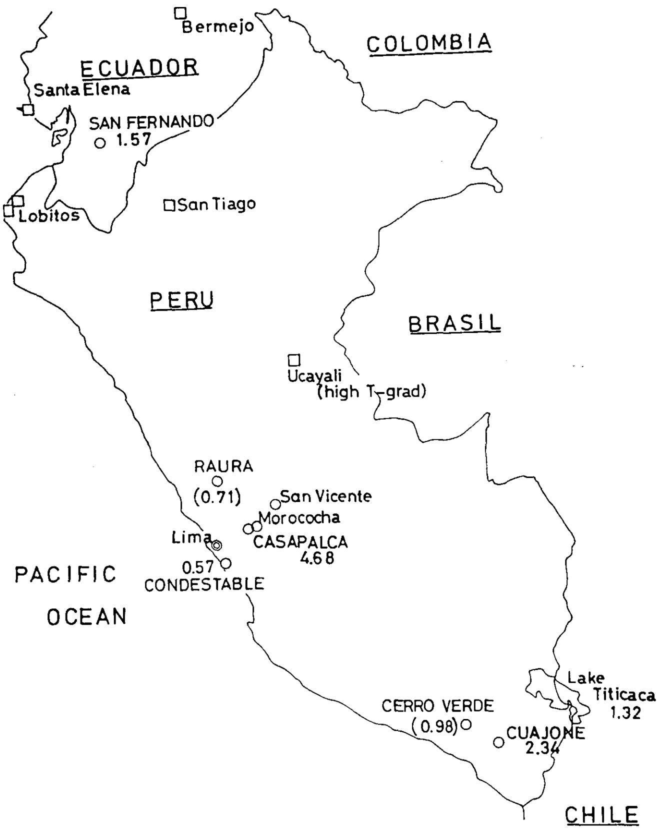

Fig. 1. Heat flow values in Peru and Ecuador.
open circles: this work; open squares: oil-field referenced; value at Lake Titicaca is due to Sclater et al. (1970). Values in paretheses are less reliable (see text).

Table 1. Summary of heat flow measurements in Peru and Ecuador.

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]
PERU									
Raura	Pb, Zn mine	10°29′S 76°45′W	4,800	146	0.71	9.34	0.71	30	V and H
Casapalca	Pb, Zn mine	11°39′S 76°14′W	4,700	654	4.68	6.32	4.68	196	H
Condestable	Cu mine	12°41′S 76°36′W	450	167	1.00	8.69	0.57	24	V and H
Cerro Verde	Cu mine	16°30′S 71°36′W	2,750	175	1.18	8.29	0.98	41	V
Cuajone	Cu mine	17°04′S 70°46′W	3,500	120	2.50	9.36	2.34	98	V
ECUADOR									
San Fernando	Cu prospect site	3°08′S 79°15′W	3,600	75	2.72	5.79	1.57	66	V

[1] *T*-gradient; 10^{-4}°C/cm (°C/100m)
[2] Conductivity; 10^{-3}cal/cm sec °C
[3] Heat flow; (HFU) 10^{-6}cal/cm^2 sec (=42SI)
[4] Heat flow; mWm^{-2}
[5] V......vertical hole
H......horizontal hole in mine

less reliable. In fact, it was found that the underground temperatures of the Andean mines appeared very heavily disturbed by moving undergound water. Especially, the limestone strata at the Morococha mine (high Andes) and the San Vicente mine (eastern foot of the Andes) were practically isothermal to the depth of 200–300m. The temperature data at these places were not usable for heat flow estimates. The subnormal value near the Pacific coast at the Condestable mine (0.57 HFU) is good data. At the Ucayali oil field a very high thermal gradient (5.99°C/100m) has been reported, suggesting a high heat flow value, whereas oil fields in the northwestern corner of Peru and western Ecuador indicate lower thermal gradients (2.91–0.74 °C/100m) (UYEDA and WATANABE, 1970).

Judging from these observations and other information such as the occurrences of young volcanic rocks, it may be suspected that a zone of regionally high heat flow may exist in the Peruvian arc. However, the very distinct lack of presently active volcanoes in this part of the Andes and the non-high values on Lake Titicaca (SCLATER *et al.*, 1970) cast some serious doubt on its regional extent. Considering the well established heat flow-age relationship in continental regions (LEE and UYEDA, 1965; POLYAK and SMIRNOV, 1968; HAMZA and VERMA, 1969; SCLATER and FRANCHETEAU, 1970), it is expected that the Andean region has a high heat flow. On the other hand, whether this continental back-arc region has high heat flow as extensive as the actively spreading or recently formed back-arc regions is not clear and has an important bearing on the processes associated with subduction (UYEDA, 1979). Evidently, muchmore work is needed before a valid conclusion is derived.

RAURA Mine: 10°29'S, 76°45'W

Raura is a Pb-Zn mine located high in the Peruvian Andes (4,800-4,900m above sea level) about 150km north of the city of Lima. The mine is owned by the Compania Minera Raura, S. A., Cerro de Pasco Corporation. The authors visited this site on April 14th, 1969. The underground temperature measurements were conducted by utilizing vertical and horizontal boreholes drilled from drifts at Level 4,690m and Level 4,470m under the guidance of Superintendent Samuel Guia and Chief geologist Gregorio Reyes. The locations of the used boreholes are shown in Fig. 2. Unfortunately, most of the targeted holes were inadvertently plugged at a very shallow depth. Except for DDH No. 7 at Level 4690m that permitted insertion of the thermistor to the depth of 45m, measurements were possible only to about 10m of insertion. Moreover, the drifts as well as the holes were abundant with running water. The temperatures measured are plotted against the shortest distance to the surface as read from the topography map as shown in Fig. 3. The apparent thermal gradient is 0.76°C/100m.

The geology concerned is made of limestone strata. A representative sample of the limestone was given to us by Ing. G. Reyes. Its'

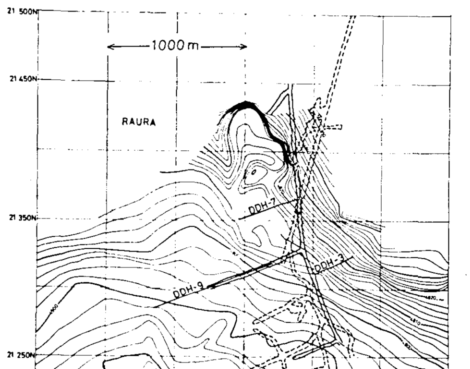

Fig. 2. Simplified map of the Raura mine in local coordinates in meters. DDH indicates the holes used for temperature measurements. Contours in meters above sea level.

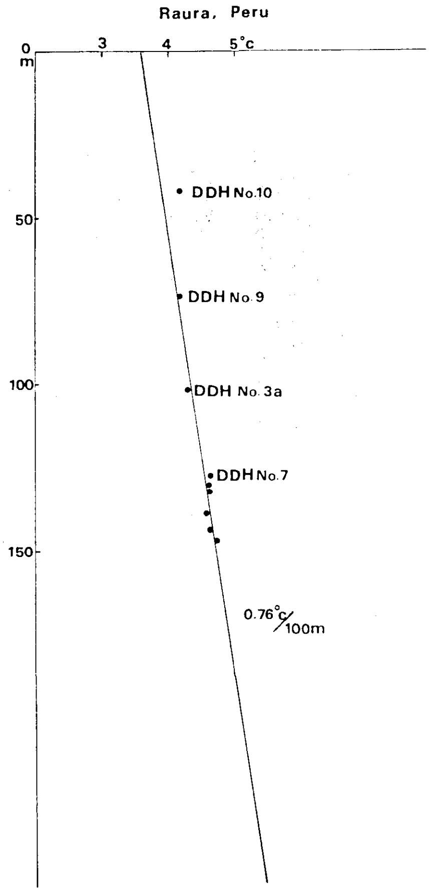

Fig. 3. Temperature versus shortest distance to the surface to the surface at the Raura mine.

thermal conductivity was measured as 9.34×10^{-3}cal. cm sec °C. From these values, the apparent heat flow may be calculated as 0.71 HFU. Because of the apparent active percolation of underground water throughout the mine, this measure is hardly a reliable heat flow value.

CASAPALCA Mine: 11°39′S, 76°14′W and *MOROCOCHA Mine*:

Casapalca is a Pb-Zn mine located in the high Andes (4,400-5,000m above sea level) at about 90km east-northeast of the city of Lima and owned by the Cerro de Pasco Corporation. Through the kind offices of Ing. P. Boswell of the Corporation, a heat flow survey in the Casapalca and the nearby Morococha mines was made. Mineralization at the Casapalca mine was due to vein intrusion accompanying the main Andes folding into Cretaceous-Tertiary red beds and Tertiary volcanics.

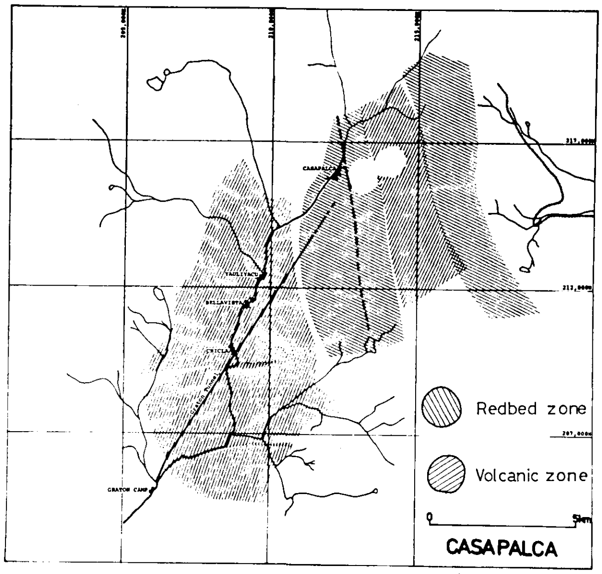

Fig. 4. Simplified map of the Casapalca mine. Local coordinates in meters. Lightly shaded circular areas show the areas of underground temperature measurements.

The site was visited by us on April 17th and 18th, 1969. Ing. Wilfredo Minez, Charles Kincaid, and R. E. Savage are especially acknowledged for assistance in the field work. They also provided us with the temperature data in the Graton Tunnel (Fig. 4) that was being drilled under the area at the time of our visit. The temperature data in the Graton Tunnel by R. E. Savage showed that at the level of the tunnel (3,200m above sea level), the temperature was highly variable, ranging from 30°-100°C. This data was, however, used only for reference in our study.

Fig. 4 is a generalized geological map of the Casapalca District after H. E. McKenstry, J. A. Noble, R. H. Kimball, A. R. Still and H. W. Kobe.

Temperature survey was made in two portions of the mine indicated in Fig. 4. One in the east is the portion occupied by Tertiary volcanics and the other in the west by Casapalca Red Beds of Cretaceous-Tertiary age.

In the volcanic zone, 3 short holes at the 200 foot level gave 7.9°C, 8.1°C and 10.5°C whereas 2 short holes at the 800 foot level gave 6.2°C and 7.5°C, indicating an apparent reversed gradient. The reason for the reversed gradient may be, inpart, that the 200 foot level is the out-let level and the 800 foot level is the in-take level of a ventilating drought. However, in most of the holes used, the effect

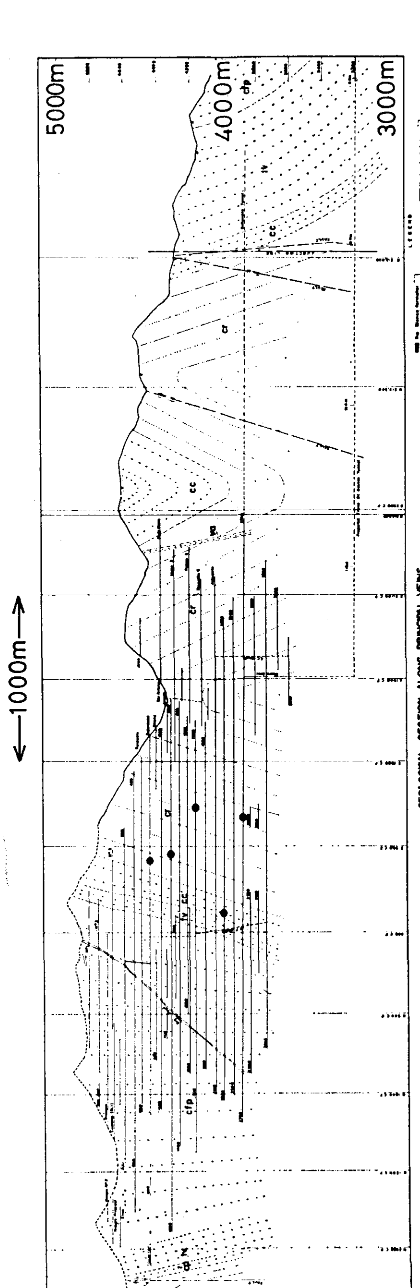

Fig. 5. Cross-section of the Casapalca mine. Black circles represent the locations of temperature measurements.

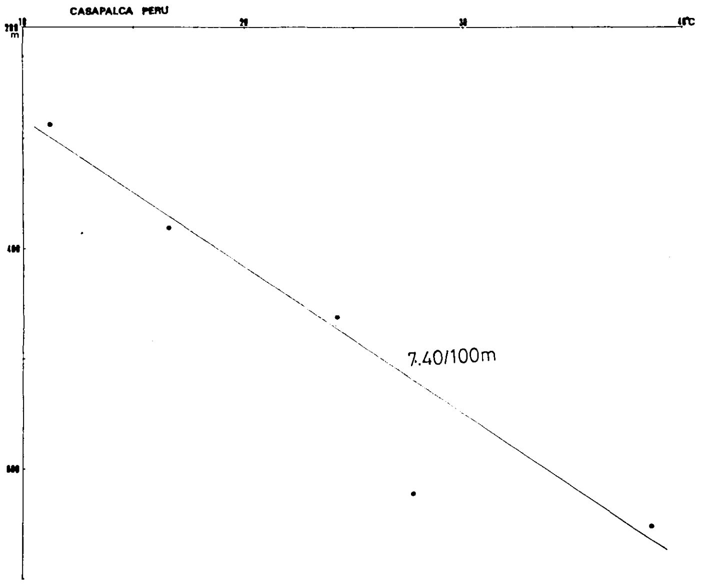

Fig. 6. Temperature-depth relation in the Casapalca Red bed zone. One point at 800m depth which is deviated from the general trend is in the volcanic zone.

of ventilation may not be the sole cause of the disturbed temperatures. In fact even at the 1700 foot level, the temperature of water in the drift was found to be only 8.7°C, 9.9°C and 14.5°C at three localities. It is obvious that the temperature field in the volcanic zone is too disturbed.

On the other hand, the temperature in the red bed zone was found to be more systematic. Fig. 5 shows the localities of the holes used in the cross-section. In each case, the thermistor was inserted into a horizontal hole to a distance of over 10m from the wall of the drift. Then the temperature variation, as a function of the distance from the wall-surface, was carefully taken. The rock temperature was estimated by smoothly extrapolating the measured temperatures. The results are shown in Fig. 6. The linearity is reasonably good except at one point. It may be worth noticing that this point alone is in the volcanic rock (Tablachaca volcanics, tv). The gradient is estimated as 7.40°C/100m.

Although nine rock samples representing the major rock units were kindly provided for thermal conductivity measurements only one, *i.e.* Casapalca Red Bed Sandstone, was considered to be relevant to the temperature data as seen in Figs. 4 and 5. Its thermal conductivity was found to be 6.32×10^{-3}cal/cm sec °C in wet condition. These values give the heat flow at Casapalca as $Q=4.68$ HFU.

This value is anomalously high. But in view of the fact that geothermal activities (hot water) were found in the Graton Tunnel, this high value may well be representative of the area. It is not known how wide an area this high heat flow covers. In fact, in the Morococha mine, which is only less than 20km apart from the Casapalca mine, no sign of high heat flow was observed. However, the measured temperature at Morococha may not be reliable, as briefly explained below.

The Morococha mine is also situated at high altitude (4,800m above sea level) in the Andes, where the Cretaceous Machay limestone that is believed to underlie the Casapalca area outcrops. This mine is also owned by the Cerro de Pasco Corporation and Ing. Miguel Carrizales (Superintendent) and Ing. Julio Pastor (Chief Geologist) kindly rendered assistance to us. The Morococha mine had numerous deep holes drilled from the surface so that it was considered a favorable locality for the present work. The mine was visited on the April 19th, 1969. It was found, however, that in both of the two holes that were only open (No. 28-43, 340m, deep; and No. 27-41, 313m deep), the temperature change is very small and erratic as shown in Fig. 7. Since the holes were dry, it took about one hour for the sensor to give stabilized

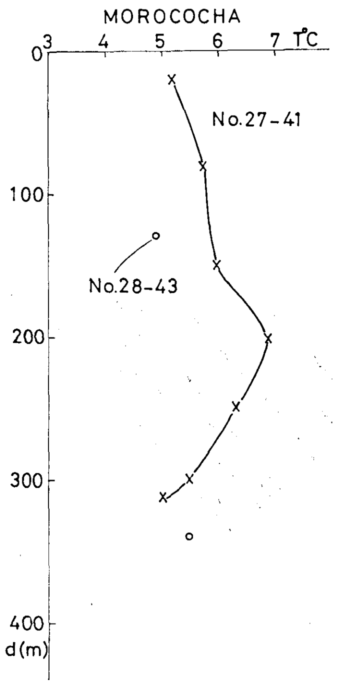

Fig. 7. Temperature-depth relation in the Morococha mine.

equilibrium temperatures. It was suspected that the limestone strata was practically transparent to water so that the ground has been thoroughly cooled by meteoric water. At any rate, there was no sign of high heat flow.

CONDESTABLE Mine: 12°41'S, 76°36'W

Condestable is a copper mine operated by The Nippon Mining

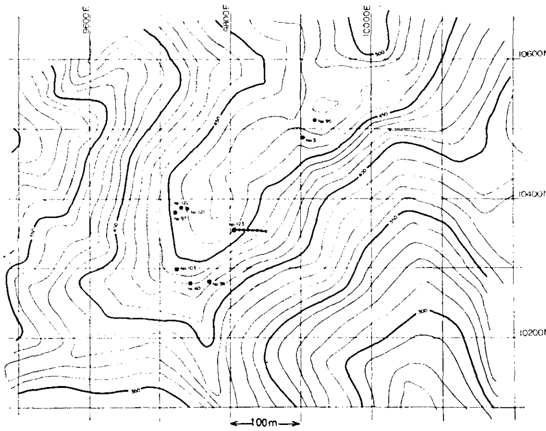

Fig. 8. Map of the Condestable mine showing the locations of temperature measurements. Local coordinates in meters. Contours in meters above sea level.

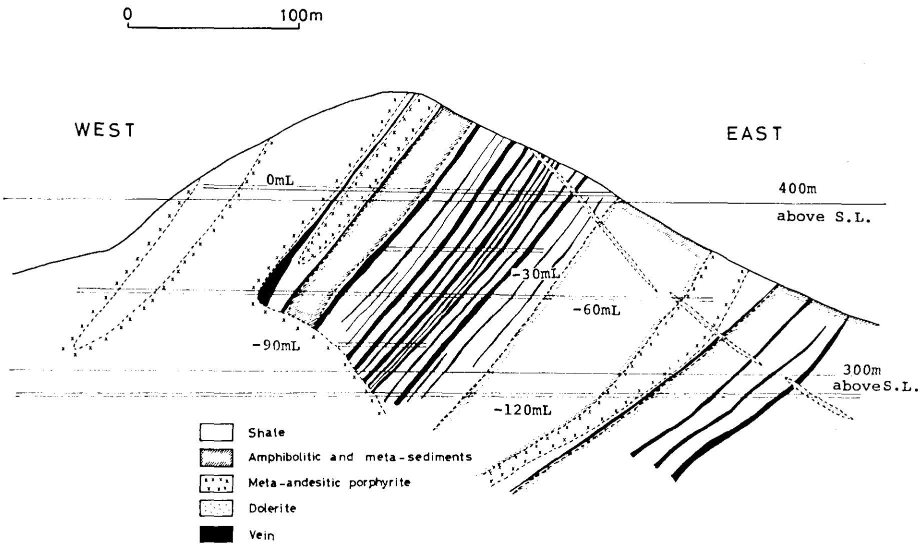

Fig. 9. East-west cross-section of the Condestable mine.

Company, and situated along the Pacific coast about 80km south of the city of Lima. The ore consists of three types; porphyry copper, so called mant-type copper along Cretaceous sedimentary strata and vein-type copper. Andesitic porphyrites intruding the sediments are of the Tertiary age. The mine extends in an area of approximately 3km×3km, and ore bodies are at 250–450m above sea level (see Fig. 8 and Fig. 9). At all levels there is not much ground water.

The mine was visited on April 10th, 1969 and the borehole temperature measurements were conducted with the guidance of Mr. K. Kakegawa of the Nippon Mining Company. All of the nine holes were more than one year old when the measurement was made, so were free from thermal disturbance due to drilling.

The results are plotted against the altitude, vertical depth from the surface and the distance from the nearest surface as shown in Figs. 10, 11 and 12.

Apparently, the points are grouped into two, and it is difficult to decipher which group is better data. However, it was noted that points giving lower temperature may be more problematical, *i.e.*, the

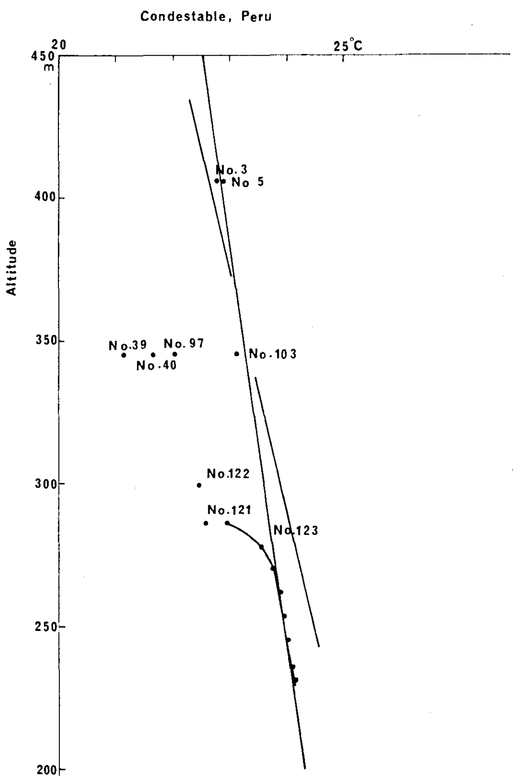

Fig. 10. Temperature-altitude relation in the Condestable mine.

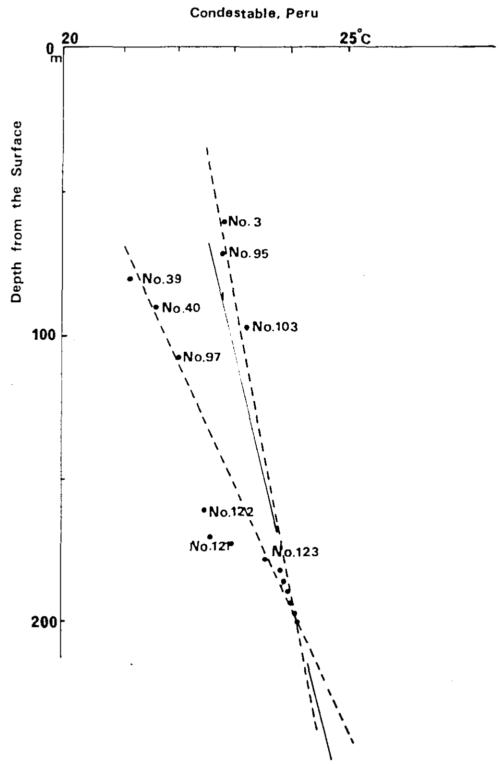

Fig. 11. Temperature-depth relation in Condestable mine.

holes No. 39, No. 40, No. 121, No. 122 are reaching within a few meters of nearby drifts and No. 97 even penetrated to another drift. So here we tentatively exclude these holes. Then, the apparent gradient in Figs. 10, 11 and 12 are 0.7°/100m, 1.00°/100m and 1.22°/100m respectively. There is no way to judge which of these is the closest to the true gradient, so that we tentatively take the middle value of 1.00°/100m. In any case, the gradient appears to be low.

Fig. 13 shows the geologic column of hole 123, which is mostly composed of amphibolitic rocks, porphyrite, and shale. The conductivity values measured on each of representative specimens were 7.39, 5.81 and 5.78×10^{-3}cal/cm sec °C under wet conditions. (6.15, 5.56 and 5.00×10^{-3}cal/cm sec °C under dry condition.) Taking simply the geometrical average of the wet value, the thermal conductivity relevant for the heat flow is estimated to be 5.71×10^{-3}cal/cm sec °C. The heat flow at the Condestable mine is then estimated to be $Q = 0.57$ HFU.

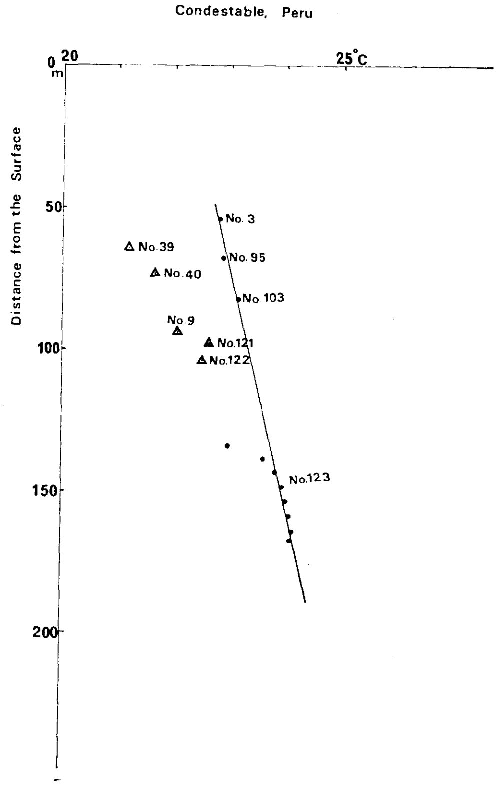

Fig. 12. Temperature-shortest distance to the surface relation in the Condestable mine.

CERRO VERDE Mine: 16°30'S, 71°36'W

The Cerro Verde mine, owned by the Andes del Peru, is a porphyry copper type mine situated at about 2,700–2,800m above sea level and about 10km southwest of the city of Arequipa in southern Peru. Ing. H. Robbins kindly gave us permission to work in this mine. When the mine was visited on the April 21st, 1979, Ing. Evic Bosc (Chief Geologist) assisted the authors in the field work. Two diamond drill holes from the surface as shown in Fig. 14 were utilized for temperature measurements. (Although two other holes were also tried, they were found blocked at shallow depths.) Fig. 14 is the generalized map of the area provided by Mr. Frank Trask Jr. of Chile Exploration Company through Dr. Bosc. Both holes were slanted (DDH 112, 55°; DDH 37, 60°) holes drilled into dioritic rocks. Temperature data is plotted against the depth from the surface (Fig. 15). In each hole temperatures above the water table were not taken as reliable. The temperatures below the water table were reliable and showed very small gradients, the mean being only 1.18°C/100m. The mean wet

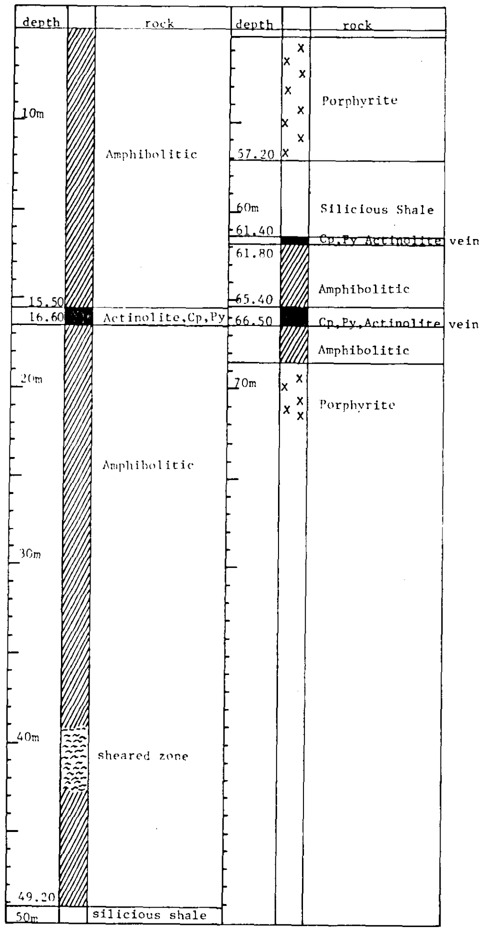

Fig. 13. Geologic column of hole 123.

thermal conductivity of seven representative dioritic rock samples was found to be 8.29×10^{-3}cal/cm sec °C, giving the heat flow value of 0.98 HFU. Considering the abundance of young volcanics in southern Peru, this value is quite low and it is considered that more work is needed before accepting this value as the representative of the area.

CUAJONE Mine: 17°04′S, 70°46′W

This porphyry copper mine, owed by the Southern Peru Copper Corporation is situated at about 20km northwest of the city of Moquegua in southern Peru at about the altitude of 3,000–3,600m above sea level. Ing. S. P. Wimpfen, the president of the Corporation, kindly agreed to let the authors visit the mine to make the heat

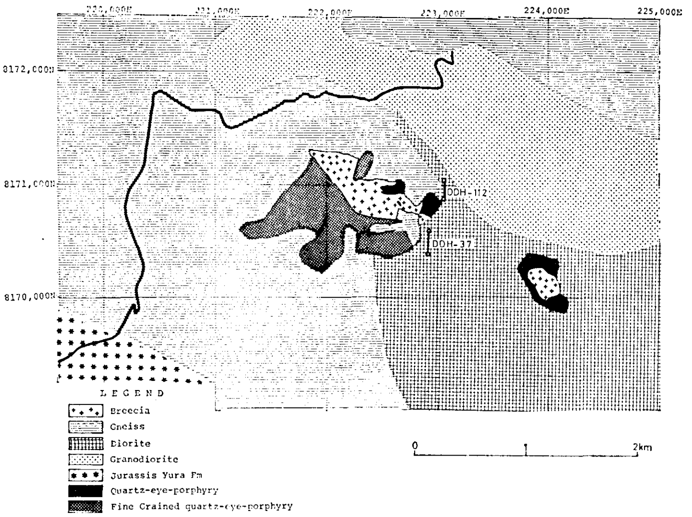

Fig. 14. Simplified geologic map of the Cerro Verde mine.

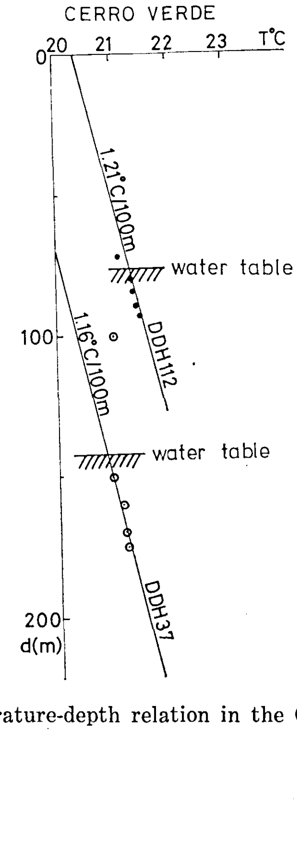

Fig. 15. Temperature-depth relation in the Cerro Verde mine.

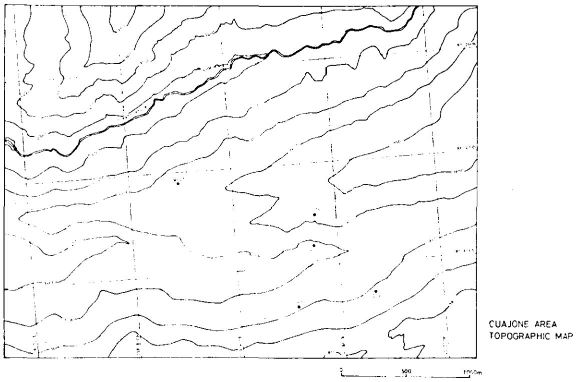

Fig. 16a. Simplified map of the Cuajone area. Local coordinates in meters. Contours in meters above sea level.

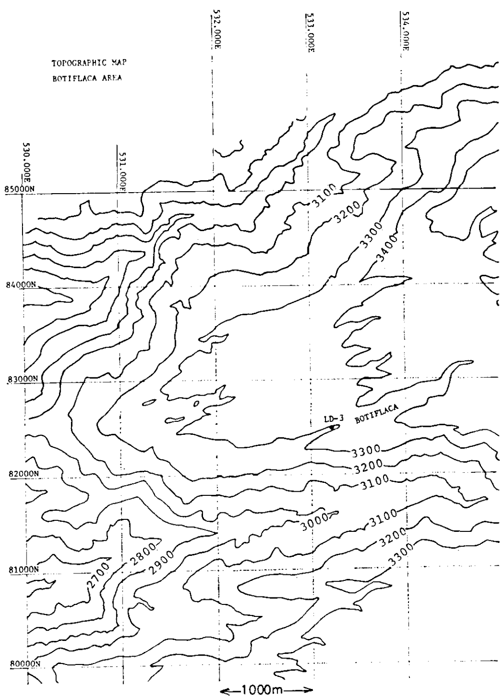

Fig. 16b. Simplified map of the Botiflaca area. Local coordinates in meters. Contours in meters above sea level.

flow study. Ing. F. B. Stevenson (Chief Geologist) and Ing. N. Socolich guided the authors to the field on the April 23rd and 24th, 1969. Five boreholes in the Cuajone area and one borehole in the nearby Botiflaca area (about 10km northeast of the Cuajone area), all vertically drilled from the surface (Fig. 16, a, b) were used. The temperature data is

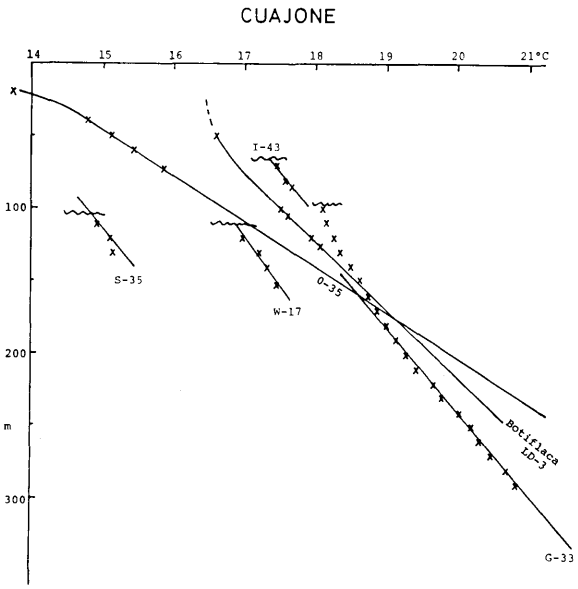

Fig. 17. Temperature-depth relations in boreholes in the Cuajone mine.

summarized in Fig. 17 as plotted against the depth from the surface. Only temperatures below the water table are shown in the figure, because those above the water table were not reliable. Among these, LD-3 in Botiflaca gives 2.2°C/100m of gradient whereas all but O-35 in Cuajone give about 1.7°C/100m. Hole O-35 alone, giving 3.3°C/100m, is drilled at the bottom of valley (Fig. 16a). It may therefore be suspected that the different gradient values in Cuajone was caused by the topographic effect. A simple estimate on the topographic effect suggests that the real gradient there may be 2.75°C/100m. On the other hand, hole G-33 was in drilling operation, at a rate of about 40m a day, and the measurement was made at midnight when drilling was in recess. Therefore, the temperature in G-33 might have been subject to the disturbance due to drilling, although the agreement with those in other short holes suggests that the drilling effect may be small. With little information, here we tentatively take the mean of the Cuajone and Botiflaca areas, *i.e.* 2.5°C/100m as the area value.

Eleven rock-samples (rhyolite porphyry, quartz latite porphyry, quartz monzonite, andesite) were provided for thermal conductivity measurements. The average wet thermal conductivity of these samples was $9.36 \pm 1.99 \times 10^{-3}$cal/cm sec °C. From these heat flow may be obtained as $Q = 2.34$ HFU.

SAN FERNANDO: 3.08°S, 79°15′W

This is the only site studied in Ecuador. It is high in the Andes at about 40km southwest of the city of Quenca. A surface borehole drilled for copper exploration had been used for the temperature measurement on May 17th, 1969 with the help of Ing. R. Enlla. The arrangement for the work was made through the kind offices of Mr. Peter Fozzard, UN Mining Project. The location of the hole (DDH No. 16) and the temperature-depth relation in the hole are shown in Figs. 18 and 19. Although the hole was shallow, the gradient (2.72°C/100m) seems to be reasonably reliable. A representative rock sample gave the wet conductivity of 5.79×10^{-3}cal/cm sec °C. Thus, the heat flow of this site was assessed as 1.57 HFU.

Fig. 18. Simplified map of San Fernando area, Ecuador. Double circle indicates the location of the borehole used (DDH No. 16). Contours in meters above sea level.

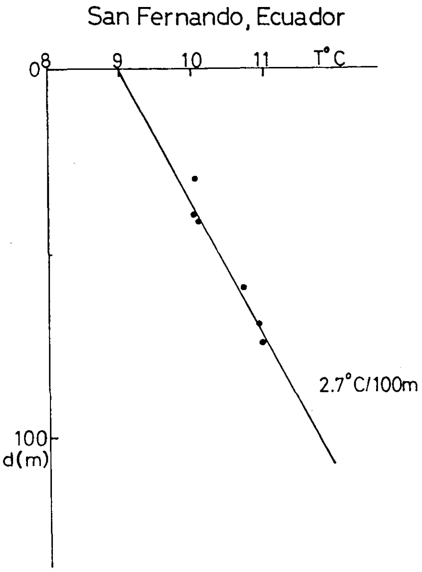

Fig. 19. Temperature-depth relation in DDH No. 16, San Fernando.

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4. ペルー，エクアドールにおける地殻熱流量測定結果

地震研究所 {上田誠也 / 渡部暉彦

伊藤忠商事株式会社 小笹山洋治

住友金属鉱業株式会社 茨木謙三

1969年，日米科学協力事業の一環として，地殻熱流量測定を実施した．この結果，ペルー国内に5点，エクアードル国内に1点の熱流量値が得られた他，油田地帯の温度検層データを用いて，ペルー国内に4点，エクアドール国内に2点の地中温度勾配が求められた．

アンデス山系中およびその内陸部においては，明瞭に高熱流量を示す点が分布すると同時に，低熱流量点も多く分布し複雑な様相を呈している．測定値への各種温度擾乱の影響も無視出来ない場合が多く，今後の調査を必要とするところが大きい．