No. 42

THE REPUBLIC OF THE PHILIPPINES

REPORT ON ACUPAN-ITOGON GEOTHERMAL DEVELOPMENT

(SUMMARY)

SEPTEMBER 1985

JAPAN INTERNATIONAL COOPERATION AGENCY

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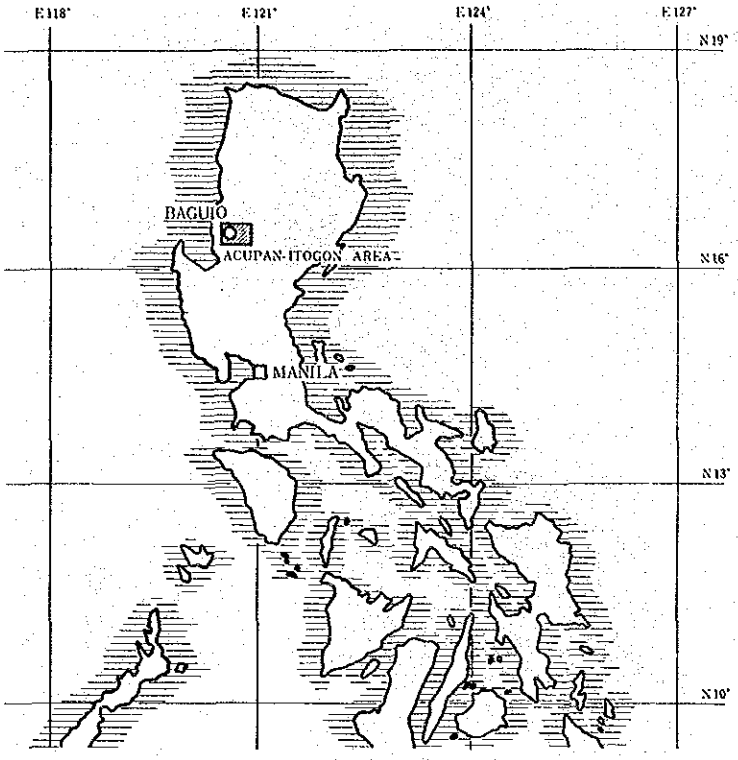

LOCATION MAP OF ACUPAN-ITOGON AREA

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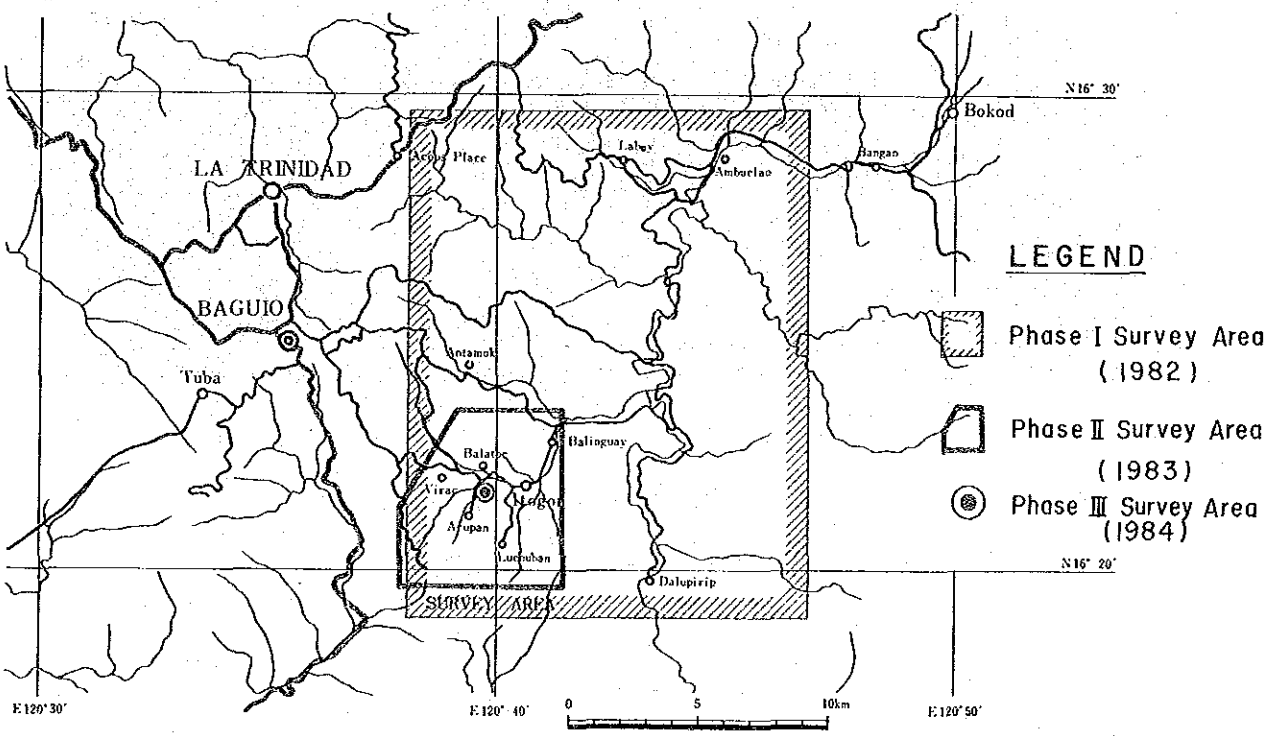

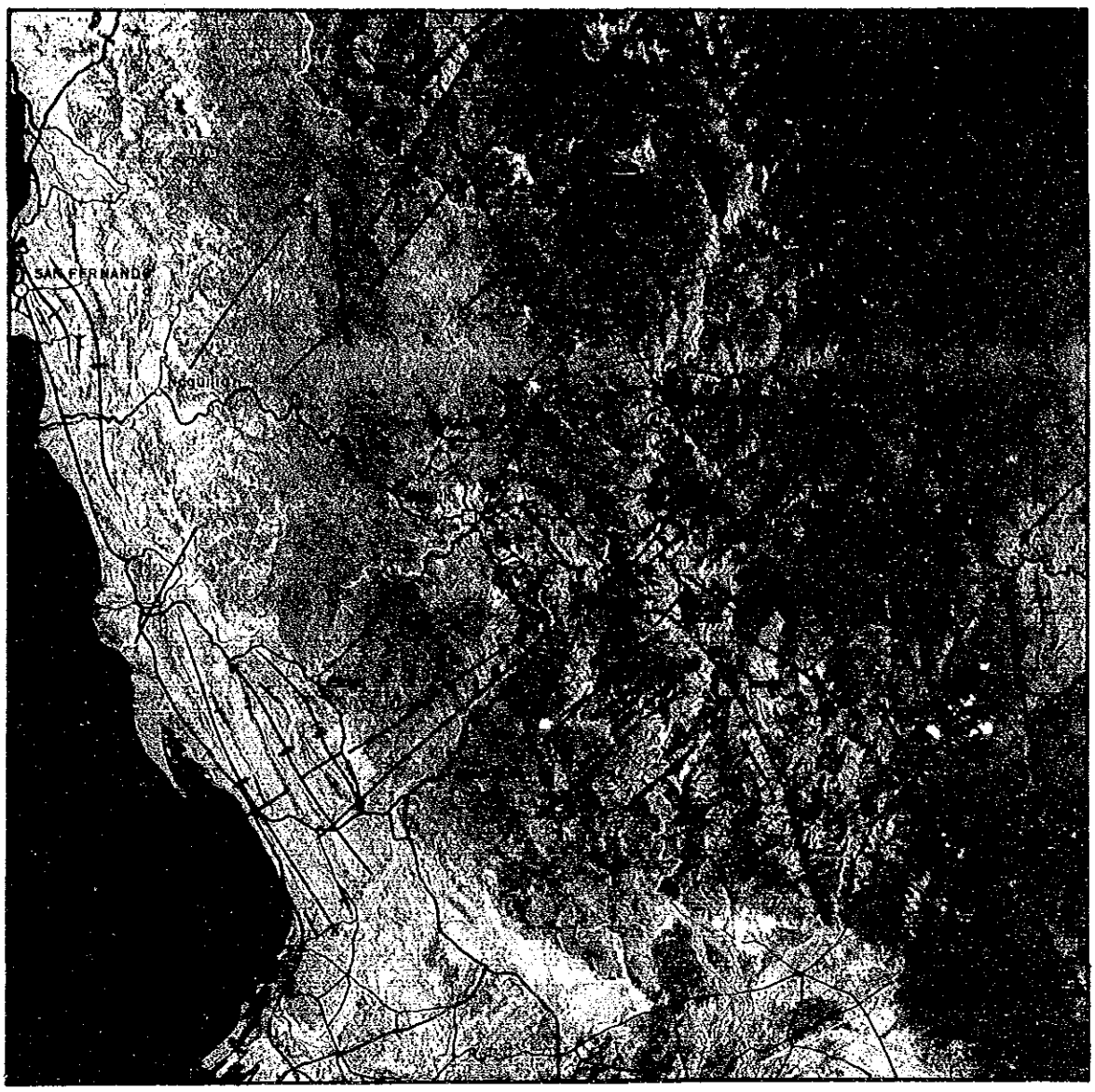

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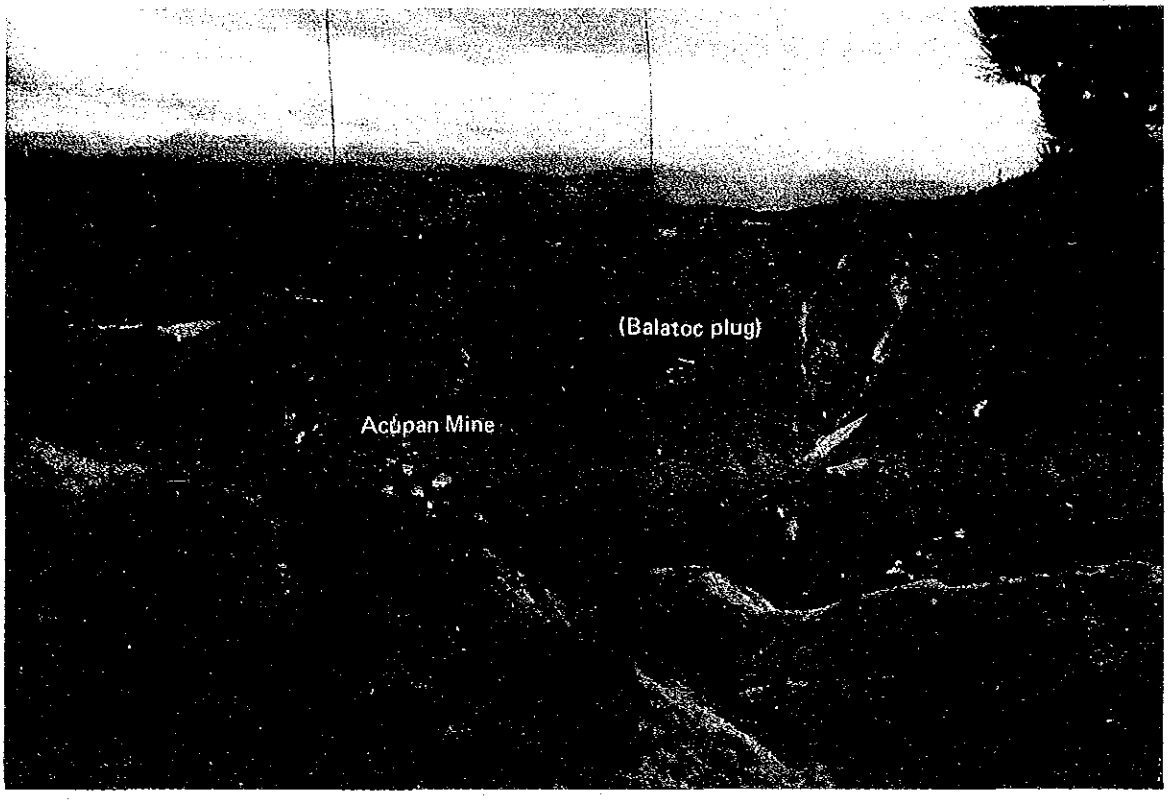
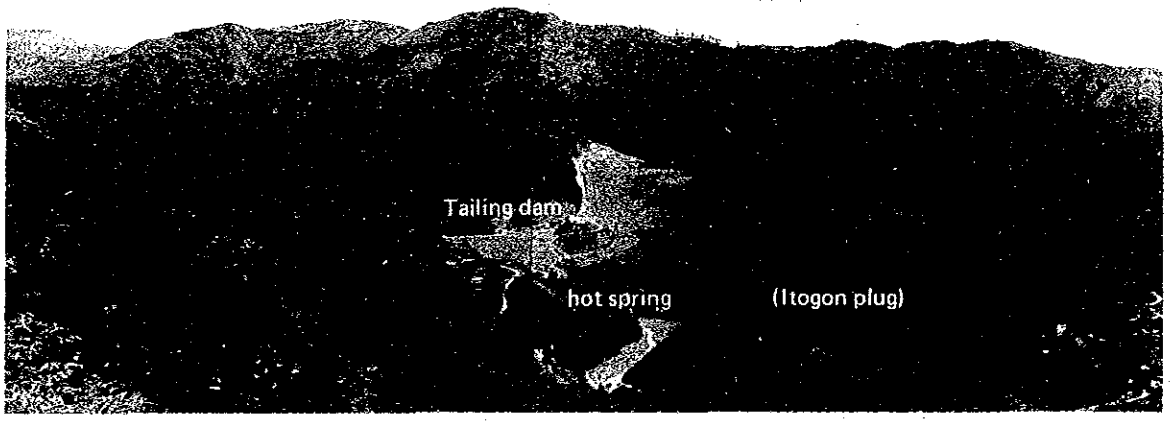
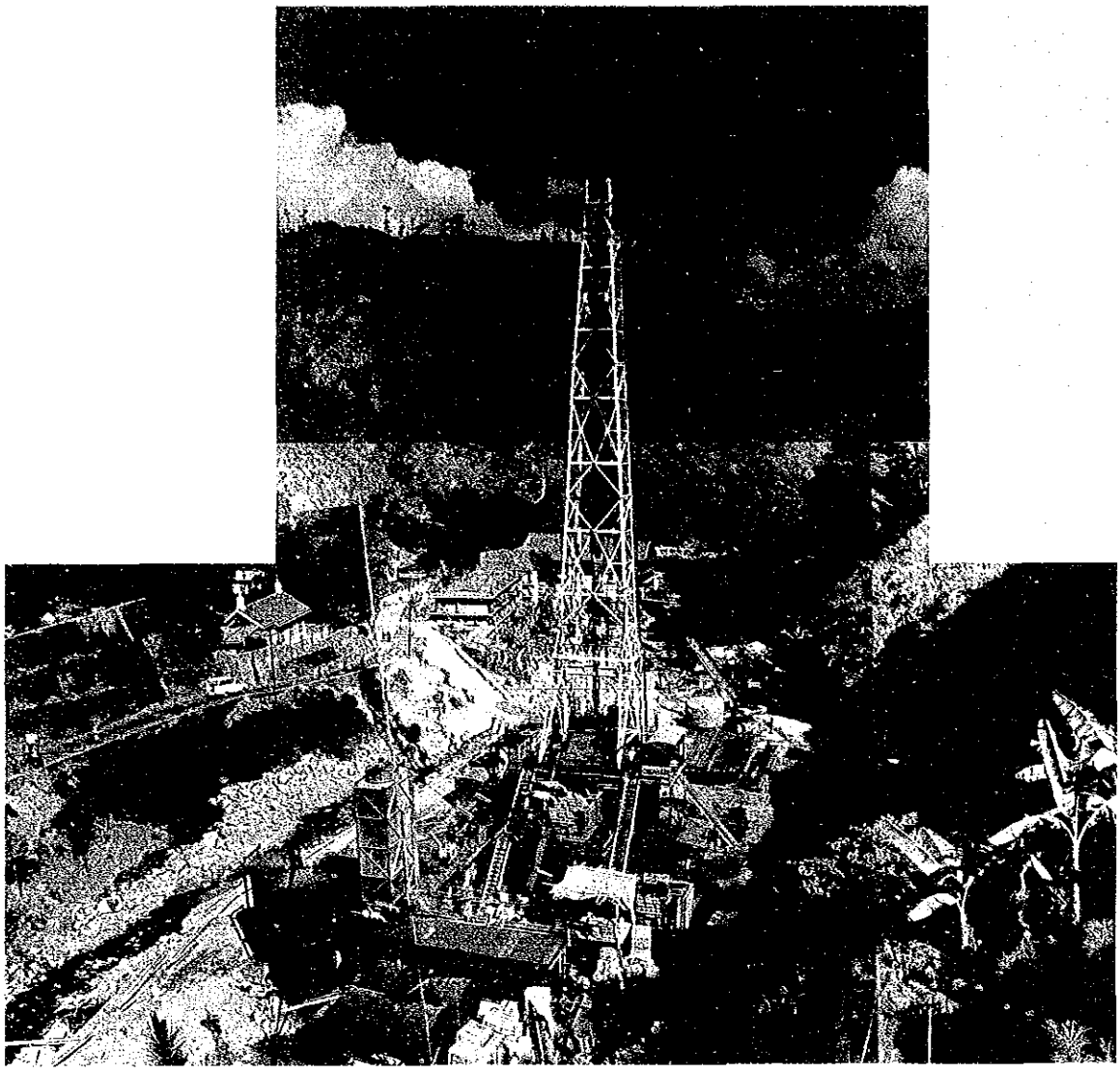


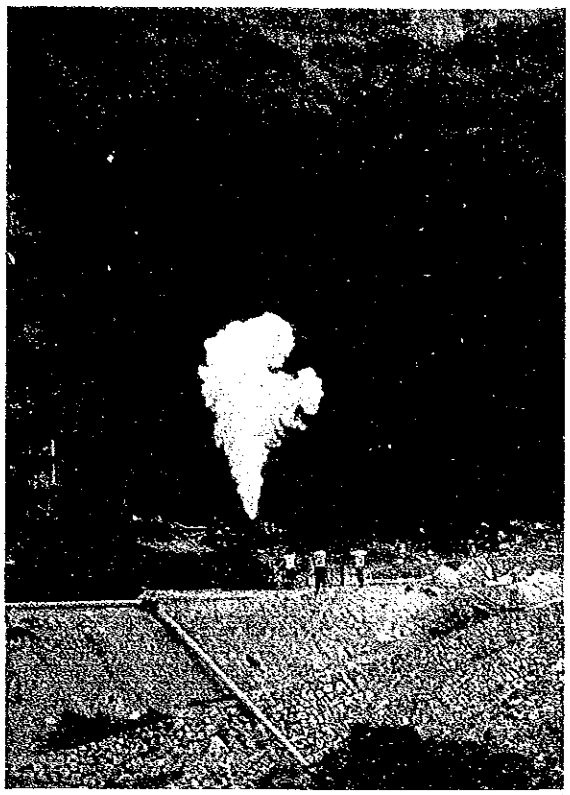
Perspective view of Acupan area

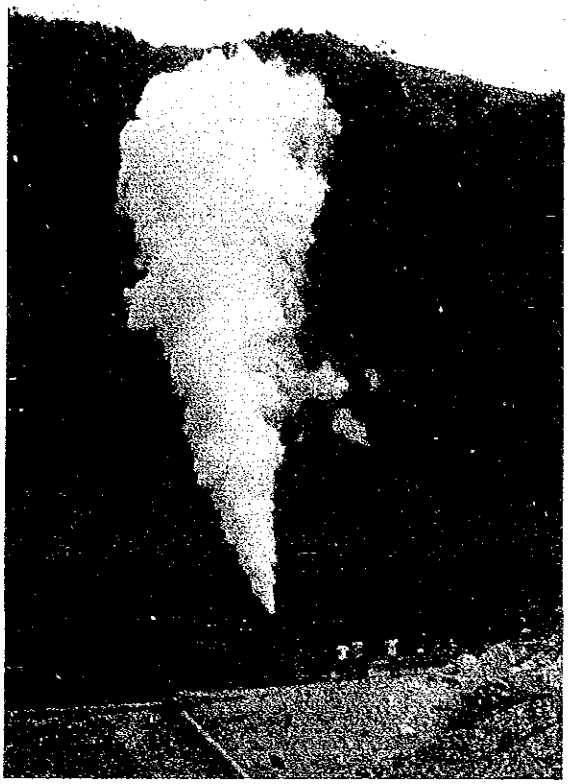


Perspective view of Itogon area



Drilling of the test well (AC – ID) (1)
Jan. / 1985





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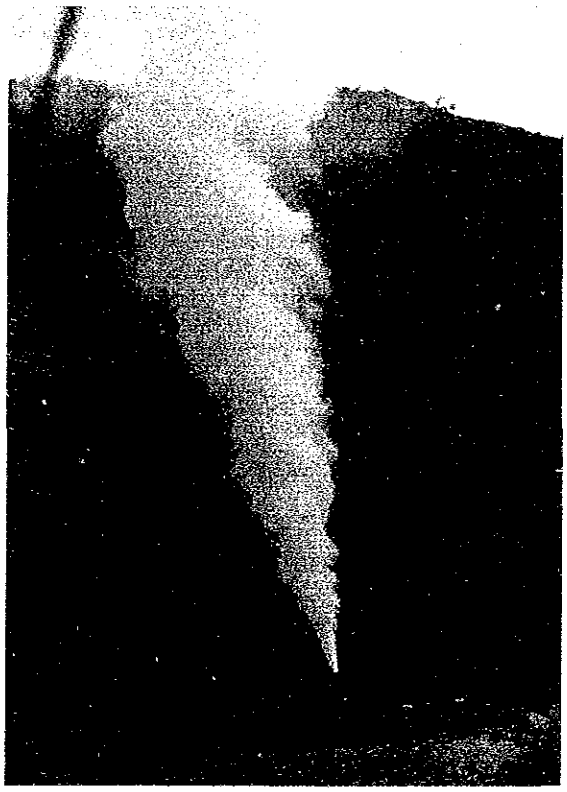
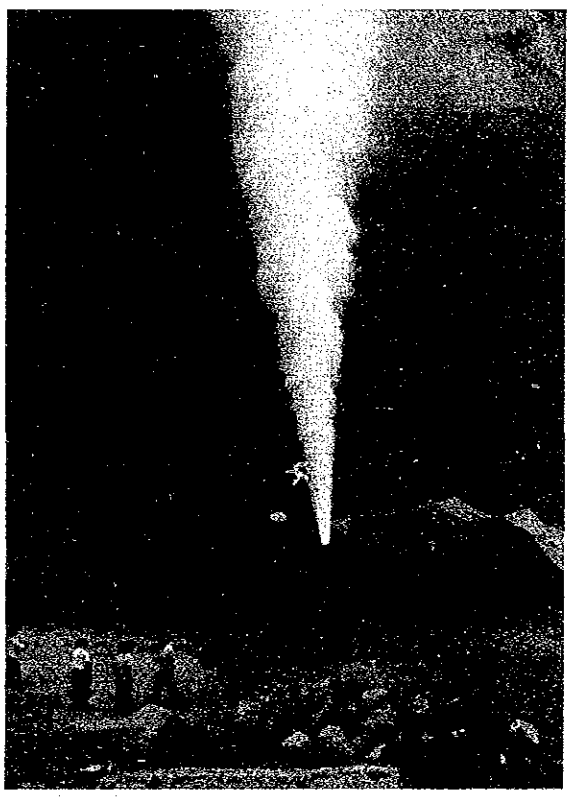
Start of opening of wellhead valve.





Intensity of steam discharge lasted
for about 45 minutes.

Discharging of the test well (AC – ID)
May 14 / 1985

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CHAPTER I INTRODUCTION

1-1 Outline of Surveys

1-1-1 Back ground of the project

In the northern part of Luzon Island, highly prospective geothermal zones exist such as Batong-Buhey, Buguias, Daklan, and Acupan-Itogon, but none of these areas is yet developed for geothermal power generation. On the other hand, the capacity of hydraulic power generating dams near Baguio City, named Ambuklao and Binga, is rather decreasing while demand for power in that area continues to expand year after year. In other words, the power supply situation in the northern part of Luzon Island is being aggravated at a high pace. The two geothermal power generating stations Tiwi (330 MW) and Mak-Ban (220 MW), are presently supplying power that covers approximately 24% of the power demand on Luzon Island. Therefore, the Philippine Government wishes to proceed as soon as possible with geothermal power development, particularly in the northern part of Luzon Island, to improve the existing power supply situation.

Under such background circumstances, the BED (Bureau of Energy Development) of the Philippines requested JICA to conduct surveys by selecting the above-mentioned areas, which are located close to power consumption sites such as Baguio City or the district where mining companies are situated. In response to this request, JICA dispatched a preliminary survey team in March 1982. Upon confirmation achieved by this team on potentialities of geothermal power development in the subject area, an S/W was prepared regarding final surveys, which then was followed by official mutual signing of the relevant Implementing Arrangement Agreement.

1-1-2 Objective of surveys

The prime objective of surveys lied in achieving evaluation

of geothermal potentialities in the Acupan-Itogon areas located in the southeast of Baguio City, Benguet Province. The surveys were composed of three stages. In the initial-year survey, geological, geochemical, and physical investigations were conducted in an area approximately 300 km^2, resulting in selecting areas of 40 km^2 that offer high potentialities for geothermal power development. As to the second-year survey, various actual in-the-field investigations were conducted, including drilling of temperature-measuring holes on the targeted survey areas. Also included in this phase of work were the preparation of conceptual geothermal structure models of the survey areas as well as preliminary studies on spots for drilling survey wells for the purpose of directly confirming the existence of geothermal fluid.

In the third-year survey, drilling of 1,500 m-deep survey wells was initially planned. However, the temperature rise was revealed to be slightly lower than originally estimated, probably on account of drop of underground water levels caused by mining excavation in the neighborhood. Consequently, the drilling depth was extended to 2,000 m. While details of the findings obtained by this actual drilling of survey wells are included in this paper, this report outlines the summary results of our analyses on geothermal potentialities in the target areas on the basis of the said details of survey findings.

1-1-3 Structure of survey team

Membership structure of the survey team is as follows.

JICA team:

Manager : Yasunori Sakai, followed by 16 persons (Bishimetal Exploration Co., Ltd.)

Organizer: Kuniaki Nagata, Katsuhiko Ozawa (Mining & Industrial Planning & Survey Dept., JICA)

BED team:

Manager : Alfredo C. Troncales, followed by 22 persons (Bureau of Energy Development, Ministry of Energy)

1-1-4 Survey schedules

The survey schedules are as follows.

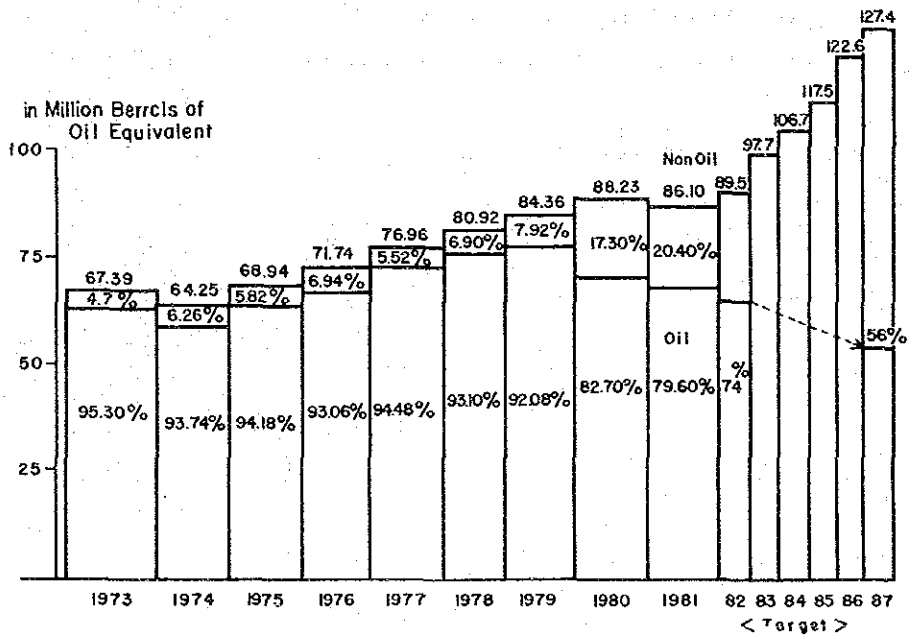
	Date	1982	1983	1984	1985
	Contents of Survey	A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S O N D	J F M A M J J A S
Phase I	Geological Survey	8 — 6			
	Geochemical Survey	6 — 6			
	Gravity Survey	27 — 5			
	Electric Survey	27 — 5			
	Report		*		
Phase II	Geological Survey		28 — 6		
	Geochemical Survey		28 — 11		
	Microearthquake Survey		28 — 21		
	Temperature Gradient hole Survey		18 —	— 27	
	Report			*	
Phase III	Drilling of Test well			22 —	— 16
	Logging and Completion Test				23 — 14
	Flaching Test				15
	Report				*

1-2 General Conditions in the Republic of Philippines

1-2-1 Energy supply and demand

While oil consumption by the Philippines is increasing year after year, the degree of dependency on oil is drastically decreasing, having been triggered by the so-called "oil shock" experienced by the nation in October 1973.

During the decade of the 1960's, 1.05 barrels of oil were consumed per capita by the population of 36 million in the Philippines. In the early part of the 1980's, this figure increased to 1.75 barrels per capita by the population of 49.5 millions. The statistics indicate that by 1987, oil is predicted to mark the consumption of 127.38 million barrels in total, or a per capita consumption of 2.24 barrels by the population of 57 million.



On the other hand, the rate occupied by oil in the total energy consumption, which registered a high level of 92% during 1973-1979 period, dropped to 82.7% in 1980 as a result of an increase of non-oil energy supplies such as coal and geothermal or

hydraulic power generation. In 1981, this rate was further reduced to 79.6%. Plans by the nation are targeted to lower the oil dependency rate to 44% by 1987, supported by an increased supply of energy of 13.97% by geothermal power generation.

According to future programs, among non-oil energy, coal is being planned to further increase supplies to boost its dependency rate. When an oil equivalent conversion is made, coal is expected to exceed 18% in terms of the energy dependency rate, with hydraulic power generation reaching 12% and geothermal power generation sharing 14%. Particularly, geothermal power generation is planned to supply 1,554 MW by 1987, a level of 19% of all power supplies in the Philippines.

1-2-2 Trend of geothermal power development

Geothermal power development in the Philippines displayed a remarkable growth during 1970's. In 1983, operation was commenced in the plants at Palimpinon and Tongonan, having caused a hike in the nations's geothermal power generation capacity to 781 MW. This high level has firmly established the Philippines as the second largest country of geothermal power generation, next only to the U.S.A.

Further, based on the 6-year Energy Development Plan up to 1987, geothermal power generation is to be developed in eight more areas by the end of 1987. With this addition, the number of geothermal power generating fields in the Philippines will increase to 14.

The six geothermal power generating fields presently under operation are as follows.

Tiwi	Albay	330 MW
Makiling-Banahaw	Laguna	220 MW
Tongonan	Legte	115.5 MW
Palimpinon	Southern Negros	115.5 MW

Manito	Albay	under exploration
Daklan	Benguet	under exploration

Eight more highly prospective fields are as follows.

Batong-Buhay
Acupan-Itogon
Batangas
Davao
Nothern Negros
Cagayan
Zambales
Cotabato

In these areas, earth surface investigation by drilling is presently under way. By the end of 1987, the cumulative number of test wells drilled for investigation purposes will reach as many as 556. As a result of such extensive survey work, the utilizable vaolume of geothermal steam is predicted to increase sizably, or to as much as 3,076 MW. Since present steam volume is 1,750 MW, this expansion means an increase of 880 MW in four years. As for power generator capacity, it is expected to reach 1,554 MW by the end of 1987.

The volume of geothermal steam already confirmed to exist in the Philippines continued to reveal a level in excess of the power generator capacities developed until now. In other words, the present situation in the country is that a shortage of power generators against steam availability is being covered by the continuous addition of power generators whenever budget allotment is possible.

In 1983, two new geothermal power generating stations were constructed by the Philippine National Oil Company (PNOC), one with a capacity of 115.5 MW at Tongonan and the other with that of 115.5 MW at Southern Negros (Palimpinon). These two plants

increased the nation's total geothermal power generating capacity to 781 MW as per the following breakdown.

Tiwi	55.0 MW x 6 unit = 330
Mak-Ban	55.0 MW x 4 unit = 220
Tongonan	37.5 x 3 + 3.0 x 1 = 115.5
Southern negros	37.5 x 3 + 3.0 x 1 = 115.5

CHAPTER II SUMMARY OF SURVEY

The following represent the summaries of surveys through Phase I to Phase III.

2-1 Surface Mapping

2-1-1 Geological survey

Results from both the regional reconnaisance survey of Phase I and the semidetailed survey of Phase II reveal the following concerning the geology in this area (Fig. 1).

(1) The regional geological structure of northern Luzon is characteriz-ed by a block structure stretching in the N-S direction, which consists of the Central uplifted zone and the Subsidence zones at both sides of the former. The survey area is located at a transitional zone between the uplifted zone and its west side subsidence. The Buguias area, where exploration work was conducted with JICA-BED technical cooperation in 1981, is on the east side opposite the uplifted zone, about 45 km to the north of the Acupan-Itogon area.

(2) The Central uplifted zone consists of Dalupirip metamorphic rocks of late Cretaceous and Aguno batholith of the late Oligocene to Pliocene. On the other hand, both the eastern and Western subsidence zones mainly consist of Miocene sedimentary rocks, for example the Klondyke formation. The youngest volcanisms of andesite complexes and dacitic plugs occurred at the Transitional zone during the late Pliocene to late Pleistocene.

(3) Fractures trending mainly NS, NE-SW and NW-SE in direction are dominant in the transitional zone, while they are not so well developed in both zones of the Central uplifted zone and

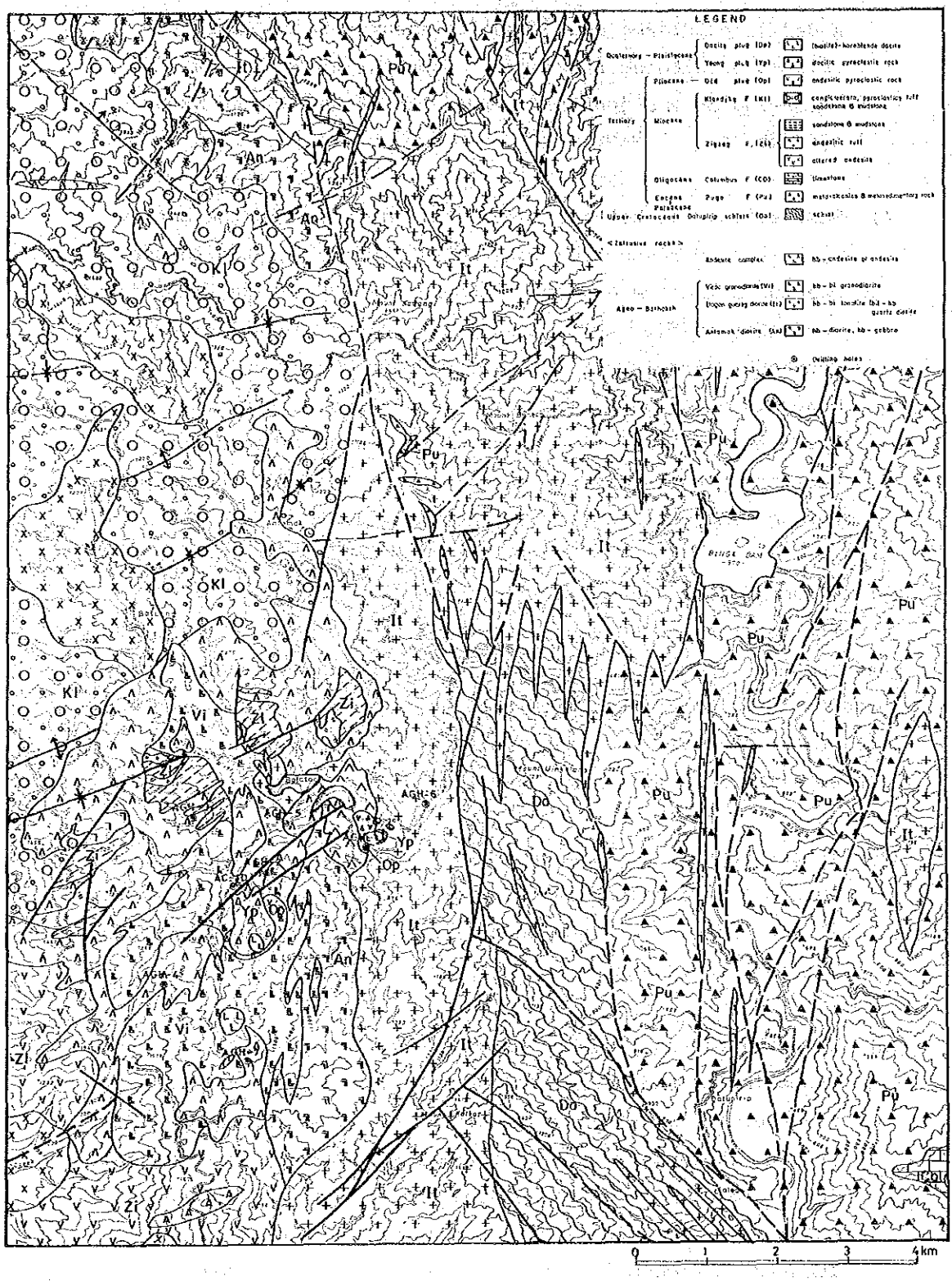


Fig. 1 Geological map

the Western subsidence zone. Moreover, young volcanisms of Andesite complexes and plugs are assumed to be closely related with these fractures. Especially, the plugs occurring on the junctions of faults of the NS and NE-SW systems.

(4) Some seepage of hot spring water is observed in the survey area, all of these locations being closely related to the fractures mentioned above. Furthermore, the high-temperature hot water is flowing at Acupan and Itogon, in which the youngest volcanisms of plugs occurred. But in the Acpan Mine, in which gold mining is now under operation, hot springs are discharging water of very high temperature. Because of such reasons the target location for the deep test well on Phase-III survey was determined.

2-1-2 Geochemical survey

The geochemical survey consists of ground surface temperature measurements, which includes the temperature analyses of mercury contents in soil and the radon gas concentration in soil air, as well as the chemical and isotopic analyses of spring water samples. The following is an abstract of the survey.

(1) Temperature at the 1 m depth reveals certain anomalies above 27.8°C from a standpoint of statistical procedures. However, it does not reflect the thermal structures at further depths, but only representing topographic influences.

(2) When the threshold value is set at 90 T/D statistically, the anomalies of radon gas concentration are observed mainly in the vicinity of the Acupan Gold Mine. However, rather than showing the underground geothermal structures, is shows only the width of open space between the ground surface and the water level, considering that most of the anomalies are located at ridges.

(3) Mercury content in soil is quite characteristic (Fig. 2). That is, anomalies (above 478 ppb) are evident intermittently at the peripheries of the Balatoc plug and the Itogon plug, spreading and stretching in the NE-SW direction. While mercury anomalies seem to relate to gold mineralization of the Acupan Mine, at the same time, they are also assumed to respond to geothermal manifestations.

Table 1 shows representative manifestations observed within and around the survey area. The pH values range between weak acid to weak alkali, and thermal seepage with high temperatures are seen at the tunnel of the Acupan Mine and Itogon. The following are revealed.

Table 1 List of spring water samples

Sample Code	Hot Spring Location	Elevation H.a.s.l.	Temperature (°C)	pH	Discharge Vol. (ℓ/min)	Acid gas V%		Deposit	Country Rock/Geology
						CO_2	H_2S		
DA	Dalupirip	420	42.5	5.5	>50	–	–	calcite & quartz vein $CaSO_4$ & $FeSO_4$ films	gravels on Pugo formation
IT-1	Itogon	680	89.5	7.5	5	99.94	0.66	calcite veinlet calcite sinter, gypsum-like	Balatoc Plug
IT-2			62.2	7.5	5	–	–	crystals, $FeSO_4$	along the contact between lower Balatoc plug and overlying detritus
KL	Klondyke	240	49.5	7.5	10	<0.05	<0.005	calcite veinlet	andesitic tuffaceous sandstone (Rosario Formation)
AS	Asin	260	73.8	8.0	not sure	<0.05	<0.005	none	gravels
PU	Pugo	80	36.3	7.0	5–6	<0.05	<0.005	none	gravels on tuffaceous sandstone (Rosario Formation)
LA-1	Laboy	660	47.5	7.0	10	–	–	calcite thin veinlet along jointing	hb. qtz diolite
LA-2		700	47.5	7.0	15	–	–	calcite epidote veinlet	granite
BA-1	Balatoc (Acupan Mine)	Acupan min 3300 level (519 m)	81.0	7.5	25	–	–	gypsum and calcite vein	diorite
BA-2		3150 level (565 m)	62.1	8.0	60–80	?	?		andesite
103C	Liang	530	66.0	8.3	4	–	–		diorite
76-B-12	Antamok	Antamok 1850 level	51.7	?	?	?	?	?	?

(4) The geochemical temperature estimated from T_{SiO_2} and $T_{Na-K-Ca}$ shows 147-229°C and 193-236°C respectively at Acupan and Itogon. This temperature is high enough to expect a geothermal reservoir at depth.

(5) The thermal fluid is assumed to have originated in meteoric water recharged from precipitation.

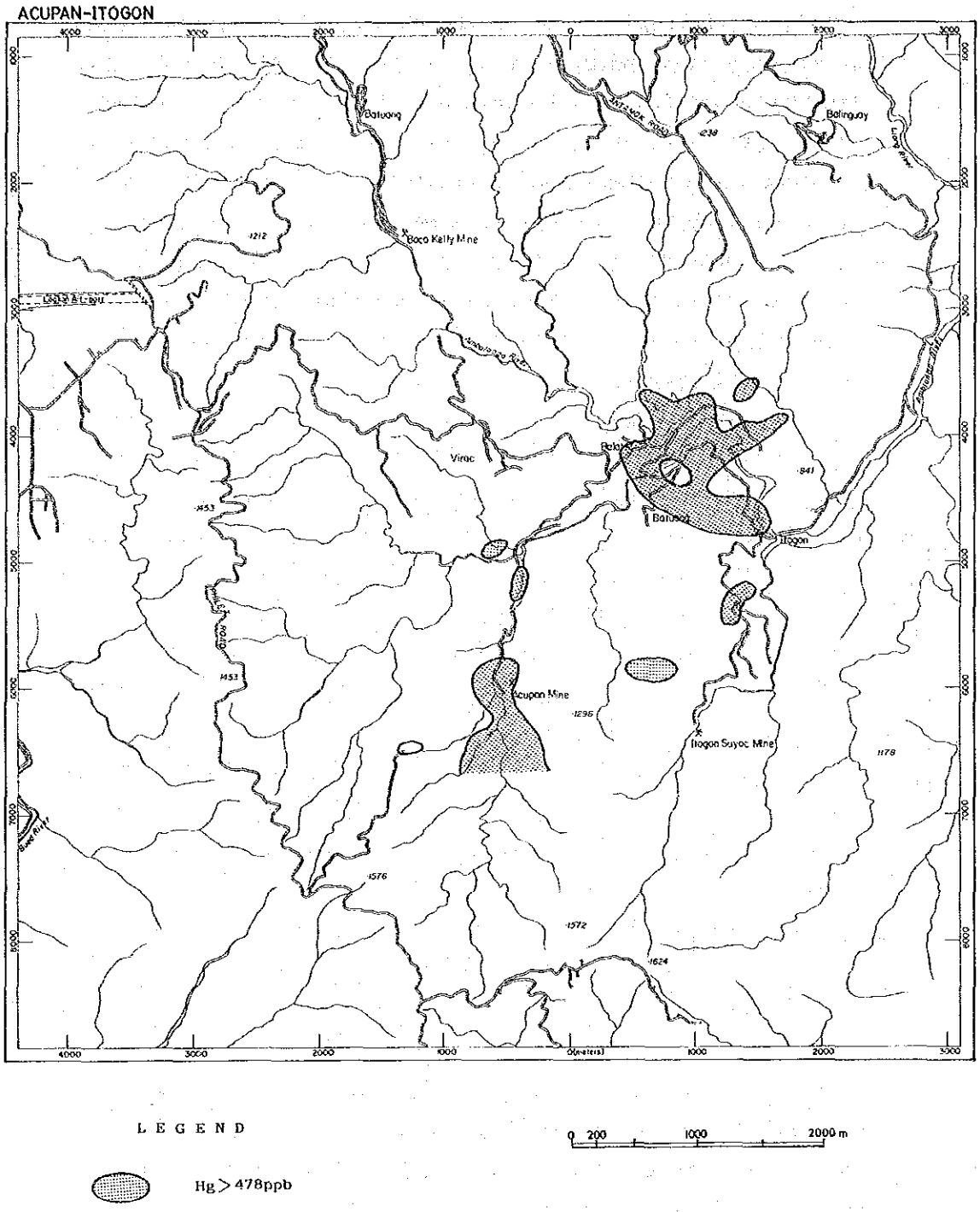


Fig. 2 Hg anomaly map

(6) The thermal fluid is classified in three types from the viewpoint of chemical composition--namely, Na/Cl type, Ca/SO_4 type, and Na/SO_4 -HCO_3 type.

(7) In the Acupan Mine, seepage of Na/Cl type fluid are closely related in and at the periphery of the Balatoc plug, while fluid of the Ca/SO_4 type seeps from the outer zone of the former. An oxygen shift in thermal water is evident only in the Na/Cl type.

(8) Thermal fluid at Itogon belongs to the Na/SO_4-HCO_3 type, with Cl content ranging from 5 to 45 percent in total equivalents of anions.

2-1-3 Grvity survey

Stations are set at 500 - 700-meter intervals along roads and ridges, and the average station density is 1.7 points/km^2. The second derivative map are shown in and Fig. 3. The following is an abstract of interpretations on these results.

(1) The average density of rock samples collected from the surface is comparatively as high as approximately 2.7, showing only a little difference in each rock type. Accordingly, as for the Bouger anomaly, the difference is comparatively small, ranging from 49 mgal minimum to 77 mgal maximum.

(2) The Bouger anomaly map, corrected by using a density of 2.6, is assumed to be the best to reveal underground geology.

(3) The low Bouger anomaly running at the east side of the Itogon Bridge in the N-S direction seems to respond to occurences of acidic rocks of Itogon quartz-diorite and tonalite, whose silica contents are high. On the other hand, high anomaly at the western part of the survey area well reflects the distribution of basic rocks such as andesite lava.

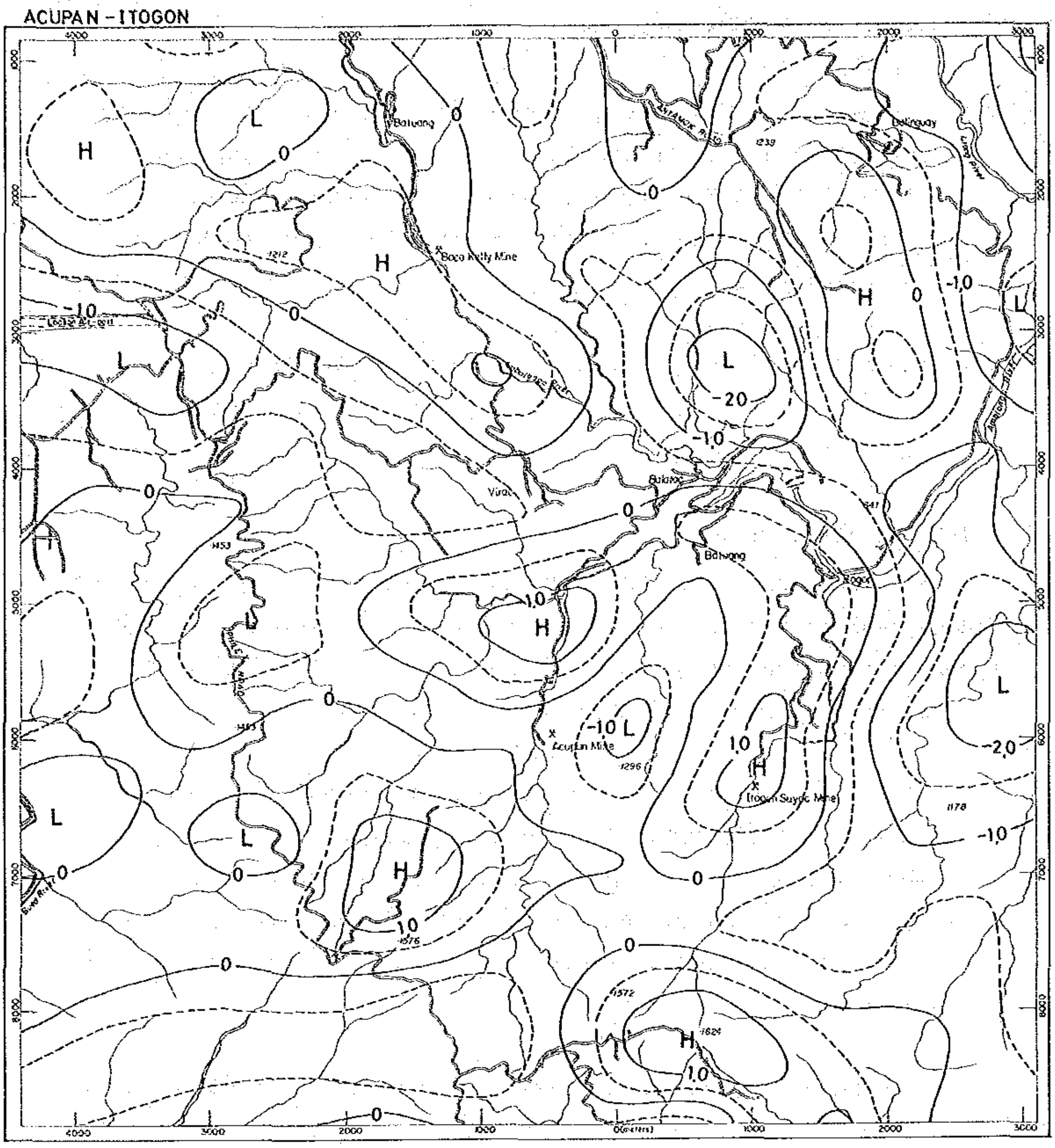


Fig. 3 Second derivative map of gravity

(4) The average density of rock samples collected from the Balatoc plug is as low as 2.46. The minor low anomaly in the vicinity of the Acupan Mine is considered to reveal a plug which is characterized by acidic rocks of high silica content.

(5) Fractures comprising such a depression as basin structure are not evident in the survey area.

(6) The N-S direction low anomaly running at the east of the Itogon Bridge, previously mentioned, could not be fully explained by density differences caused by rock type differences. There might be certain other factors that reduced density, such as fractures and alteration at deep strata.

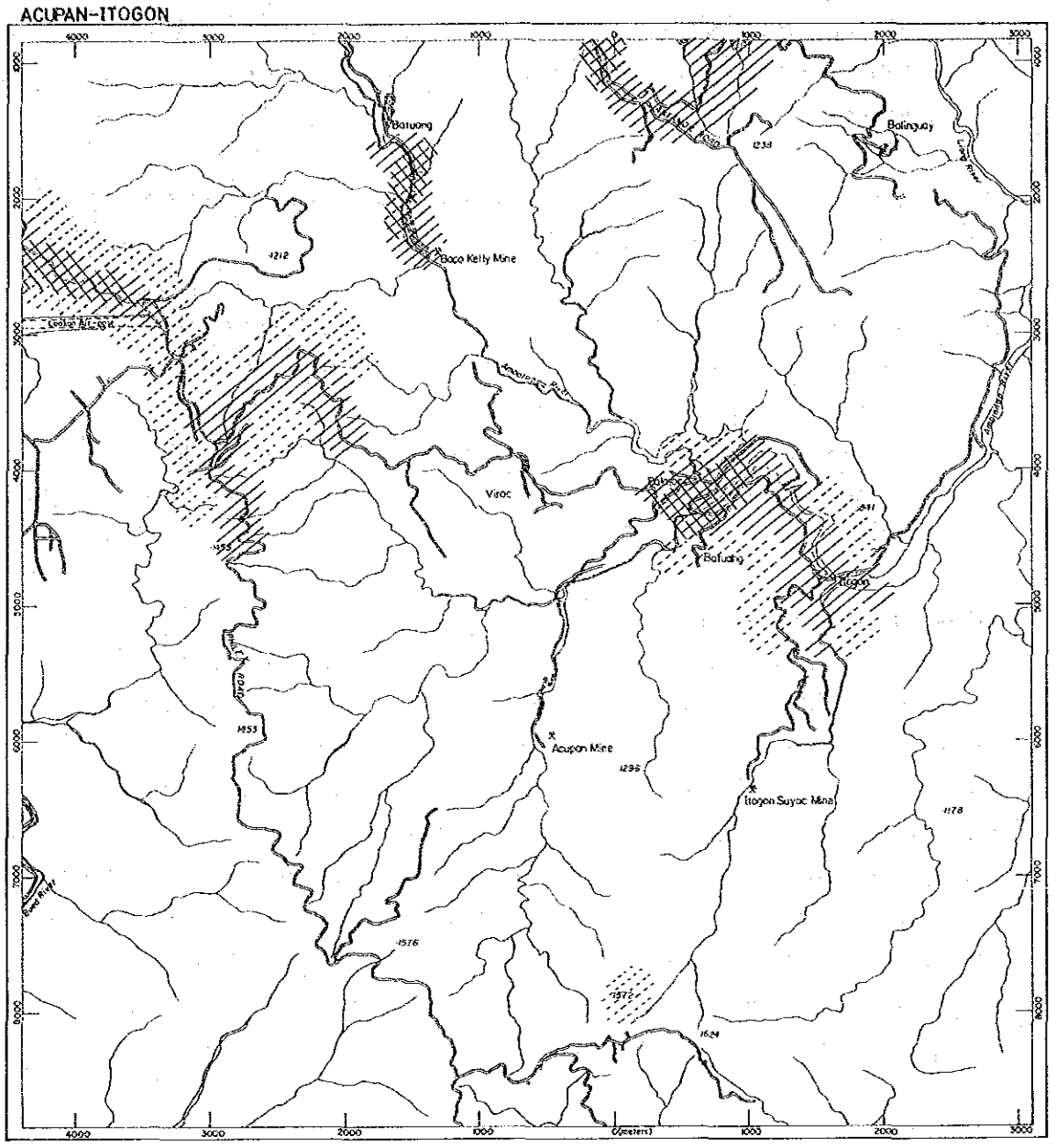
2-1-4 Electrical survey

The electrical noise caused by mine operations are not negligible, making it difficult to use an ordinary resistivity survey such as the Schlumberger method or the magneto telluric method. Accordingly, a specially designed Signal Enhanced DC Resistivity Meter was used, with 3 Hz square wave signals. The survey lines along roads are composed of nine traverses up to 69.6 km total in length. However, as for the Dalupirip area, both the Schlumberger and the Dipole-dipole method were applied because the distance is long enough to avoid noise from the mine. The followings is the abstract (Fig. 4).

(1) Resistivities of the near-surface range is approximately from 50 to 1,000 Ωm.

(2) High resistivities over 500 Ωm prevail at the eastern part of the survey area, where Dalupirip schist and Itogon quartz diorite with no hydrothermal alteration crop out.

(3) In the Dalupirip hot spring area, a low resistivity zone



L E G E N D

low resistivity zone

100m depth (50Ω-m)

200m depth (100Ω-m)

300m depth (100Ω-m)

0 200 1000 2000 m

Fig. 4 Resistivity map

trending N-S to NNW-SSE in direction is observed. It is assumed that geothermal fluids are restricted to near the surface along a fault.

(4) Some other low resistivities are detected in the following areas. Among those, anomalies in Antamok, Baco-Kelly, and the Itogon Bridge could be related to hydrothermal alteration caused by gold mineralization, considering their proximety to the mine. Low resistivities near the air strip and at the northwestern corner of the survey area are also assumed to be related to mineralization.

2-1-5 Microearthquarke survey

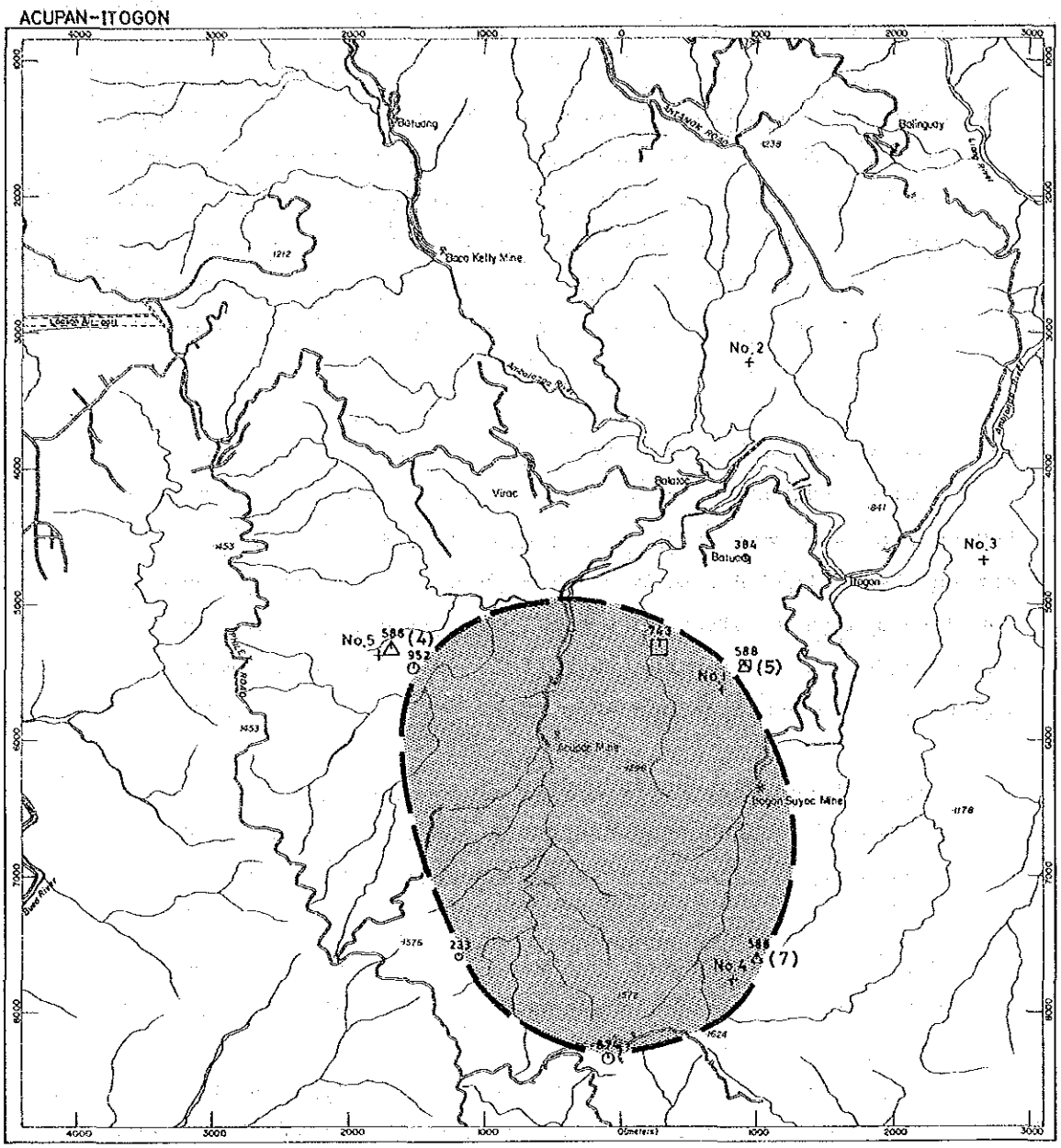
Microearthquake observation was conducted during 55 days of the period from October 14 to December 7, 1983. The 213 earthquakes with S-P time of less than 5 seconds were processed for data analysis, although a total of 973 earthquakes were detected during the monitoring period. The following is an abstract of interpretations (Fig. 5).

(1) Three dimensional distribution of focused earthquakes are confined in the northern part of the survey area, with considerable occurrence in depth towards the west.

(2) The density of focuses of the earthquakes is higher in the northern survey area, while rare in the south.

(3) A pipe-like distribution of earthquake focuses can be observed in a small scale around the Acupan Mine to Itogon.

(4) The distribution patterns of focuses mentioned above correspond well to the geology and geological structures. That is, the plate structure, defined from the distribution of focuses, reveals the tranditional zone between the Central uplifted zone and the Western subsidence zone, while the pipe-like structure would reveal the Balatoc and the Itogon



LEGEND

No 1

+ Seismograph

	Magnitude (M)		
Depth (Z)	0≦M<1	1≦M<2	2≦M<3
0<Z≦10	○	⊙	◯
10<Z≦20	□	⊡	⊡
20<Z	△	△	△

Anomalous microearthquake activity zone

0 200 1000 2000 m

Fig. 5 Epicentral distribution map

plugs, along which thermal fluid is assumed to ascend to the surface.

2-2 Down Hole Survey

2-2-1 Gradient hole survey

Seven holes were drilled. Their locations and details are shown in Fig. 6 and listed in Table 2 respectively. The geological and thermal loggings are also shown in Fig. 7. Fig. 6 shows the isothermal line estimated at the 1,000 (m) b.s.l. The following is an abstract of the survey.

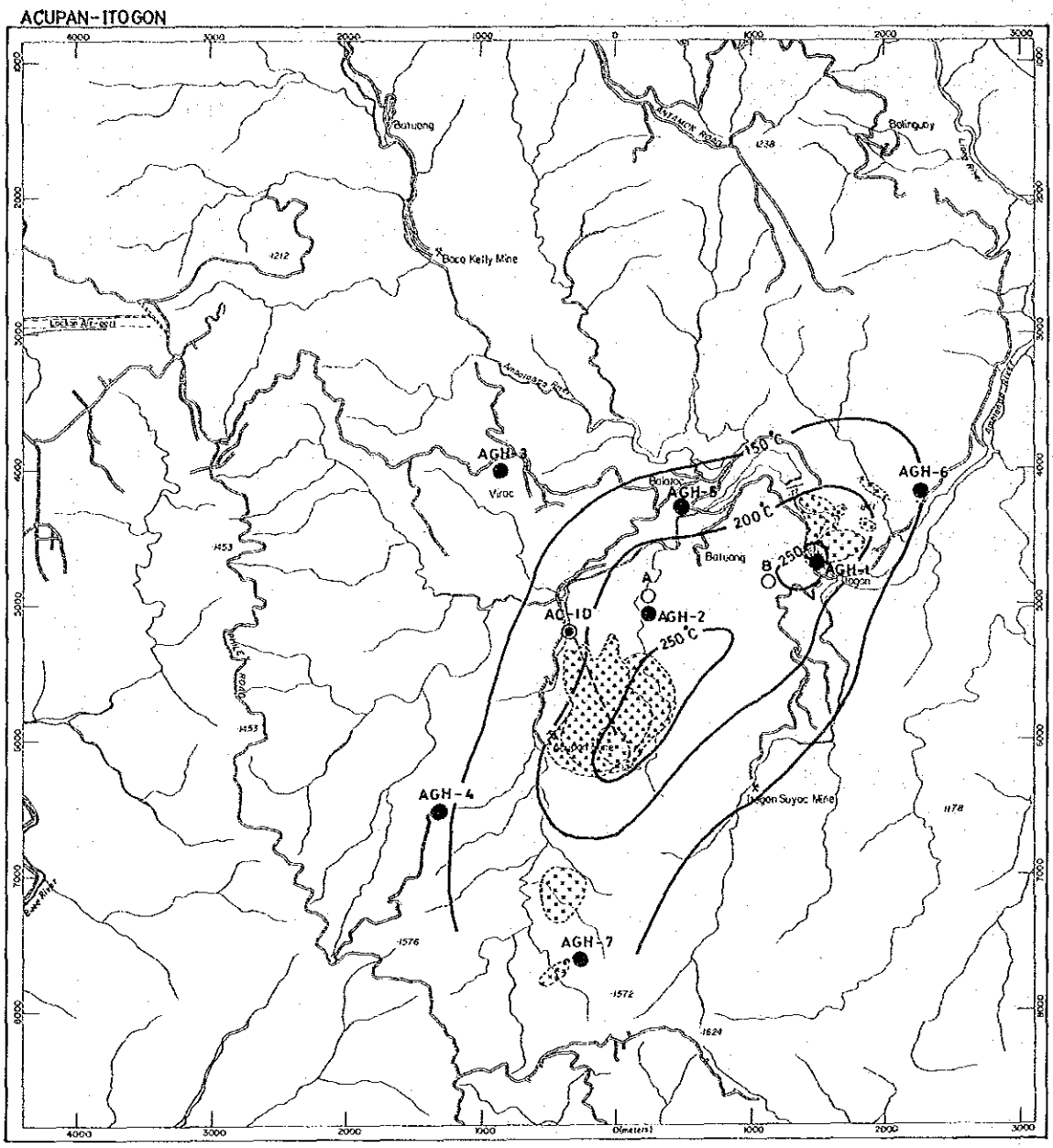
Table 2 Temperature of gradient holes and test well

	Well. No.	Well Head a.s.l. (m)	Depth (m)	Water Level (m)	Bottom Temp. (S.F.T. °C)	Gradient (°C/100m)	(Estimated)-Actual Formation Temperature			
							500 m	1,000 m	1,500 m	2,000 m
Gradient Hole	AGH-1	690	112.85	0	90.7	?				
	AGH-2	905	357.50	190	115.0	28 (14)	(136)	(206)	(276)	
	AGH-3	977	322.50	0	24.0	?				
	AGH-4	1,350	538.0	185	24.0	?				
	AGH-5	755	400.0	30	62.0	8	(70)	(110)	(150)	(190)
	AGH-6	685	207.15		32.0	4	(44)	(64)	(84)	(104)
	AGH-7	1,451	301.5	55	29.4	?				
Test Well	AC-1D Vertical Conversion	821	2,000.0 1,677	230	221	11	55	125	195	

(1) Hydrothermal alteration, seen widely, is characterized mainly by montmorillonite, sericite, chlorite, α-quartz, and calcite. Kaolinite, epidote and anhydrite are also evident intermittently. However, it is difficult to effect zonation because of a lack of differences in the alteration mineral assemblage.

(2) The contents of Si, K, As, and Rb in country rocks are enriched at the paths of geothermal fluid, while the contents of Ca, Na and Sr are depleted. Well observed in the hole of AGH-2, this is assumed to be caused by the desolution of rock forming minerals such as plagioclasse, and also to be caused by the deposition of secondary minerals such as sericite.

(3) Physical properties of core samples are as listed in the Table 3.



LEGEND

- gradient hole
- test well
- proposed drilling site for test well
- isothermal line (-1000m a.s.l.)
- dacite plug
- young plug
- old plug
- isothermal line at -1000m a.s.l.

0 200 1000 2000 m

Fig. 6 Disposition map of gradient holes and test well

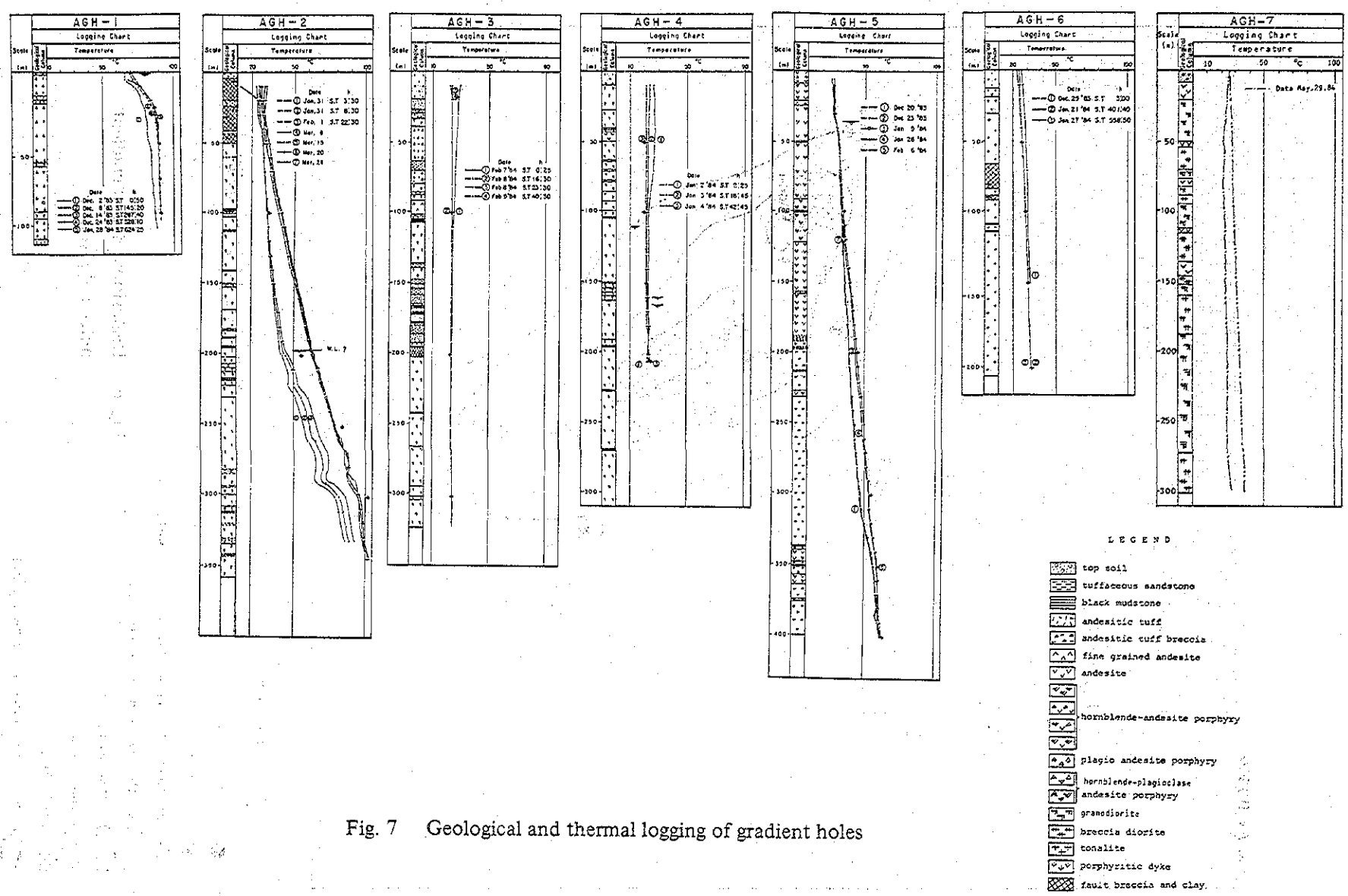


Fig. 7 Geological and thermal logging of gradient holes

2-2-2 Completion of test well

Location of the test well is shown in Fig. 6 together with gradient holes. The summaries of drilling record is as shown in Table 4. The trajectory of the directional drilling and the casing program are shown in Figs. 8 and 9 respectively.

2-2-3 Loggings of the test well (AC-1D)

The followings represents summaries covering results of the geological, geochemical, and geophysical studies of the test well (Fig. 10).

(1) Balatoc plug, the target point of survey, was encountered by the well.

(2) The bottom temperature expected is 221°C, which satisfies the necessary condition for a geothermal reservoir.

(3) Judging from the alteration mineral assemblages and the chemical properties in and of the cuttings, infiltration paths for the hydrothermal fluid are estimated at about 660 m, 1,040 m, and 1,550 - 1,620 m depths, although it is not certain as to whether or not they are active at present. Among those paths, one at depthd of 1,550 - 1,620 m was verified by thermal logging after water injection.

(4) Judging from the thermal logging, the infiltration path is also at depths of 1,850 - 1995 m, made after the injection test. However, it was not detected as to alteration minerals and chemical properties.

(5) Infiltration paths at depths of 1,550 m and 1,850 - 1,995 m were made by a water injection test, whose hydrogical conditions are as follows:

Flow rate: 1.0 t/min. $\pm$

Pressure : 100 kg/cm^2 $\pm$

(6) The permeability is as follows.

Table 3 List of rock mechanical properties

Formation or Body	Sonic velocity (km/sec)	Thermal conductivity ($\times 10^{3}$ cal/cm·sec·°C)	Density (g/cm^3)			Porosity (%)	Permeability (darcy)	Specific electric resistance (Ω·cm)	Specific heat (g/cal)
			natural condition	wet	dry				
Old plug	3.63	6.245	2.66	2.68	2.63	4.96		9.25×10^{5}	0.230
Andesite porphyry dyke	5.07	6.828	2.77	2.77	2.76	0.83		4.06×10^{6}	0.219
Andesite complex	5.29	6.103	2.79	2.79	2.79	0.18		2.68×10^{6}	0.208
Virac granodiorite body	5.42	5.880	2.78	2.78	2.78	0.40		1.59×10^{6}	0.214
Itogon quartz diorite body	5.45	6.663	2.71	2.72	2.71	1.41		8.98×10^{5}	0.212
Miocene sedimentary rocks	4.34	6.623	2.67	2.71	2.66	4.71		1.98×10^{5}	0.222

Table 4 Summaries of the test well

Location	:	Acupan, Benquet Province
Date spuded	:	December 22, 1984
Date completed	:	February 17, 1985
Total depth drilled	:	2000.0 mMD/1,677.1 mVD
CHF elevation	:	821 AMSL
CHF coordinates	:	5,180 S ; 345 W
Bearings	:	155.7°
Bottomhole coordinates	:	6,055 S ; 35 E
Bottomhole throw	;	942.5 m
Kick-off point	;	296.2 m
Rate of inclination	;	2.5° / 30 m
Programs of drilling / casing		
26" / 20"	;	61.48 m / 59.04 m
17 1/2" / 13 3/8"	;	282.10 m / 278.35 m
12 1/4" / 9 5/8"	;	1,392.60 m / 1,387.69 m
8 1/2" / 7 5/8" (slotted)	;	2,000.00 m / 2,000.00 m
top of slotted liner	;	1,382.1 m

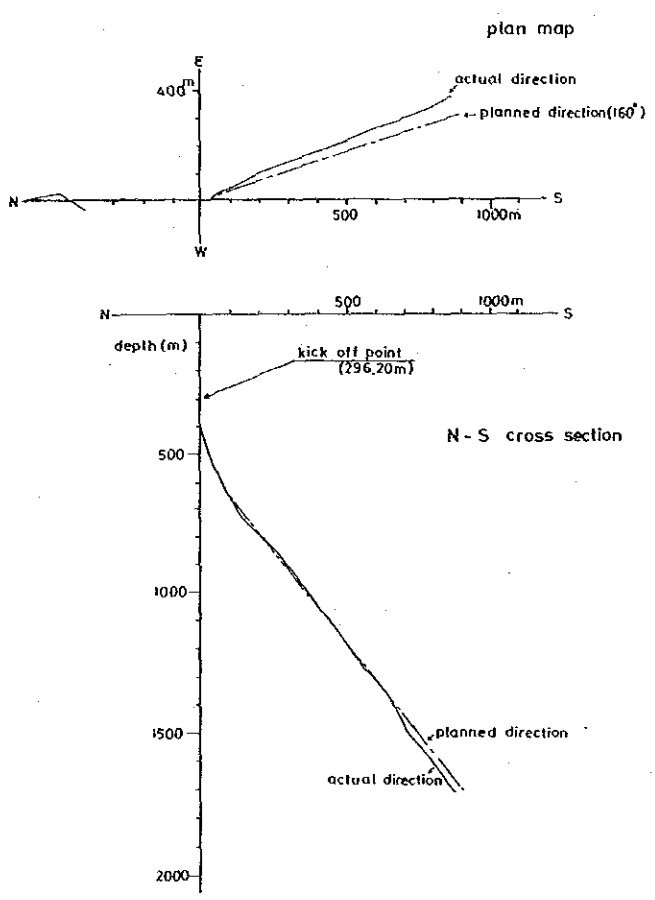


Fig. 8 Trajectory of the test well

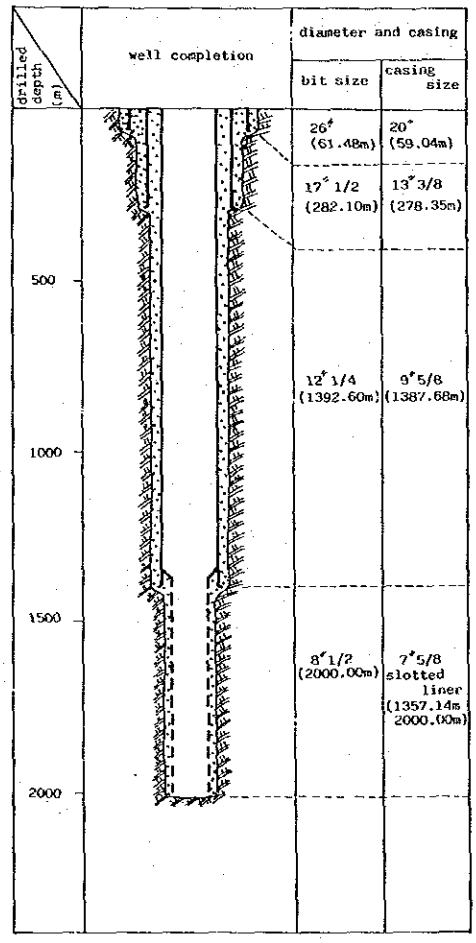


Fig. 9 Completion of the test well

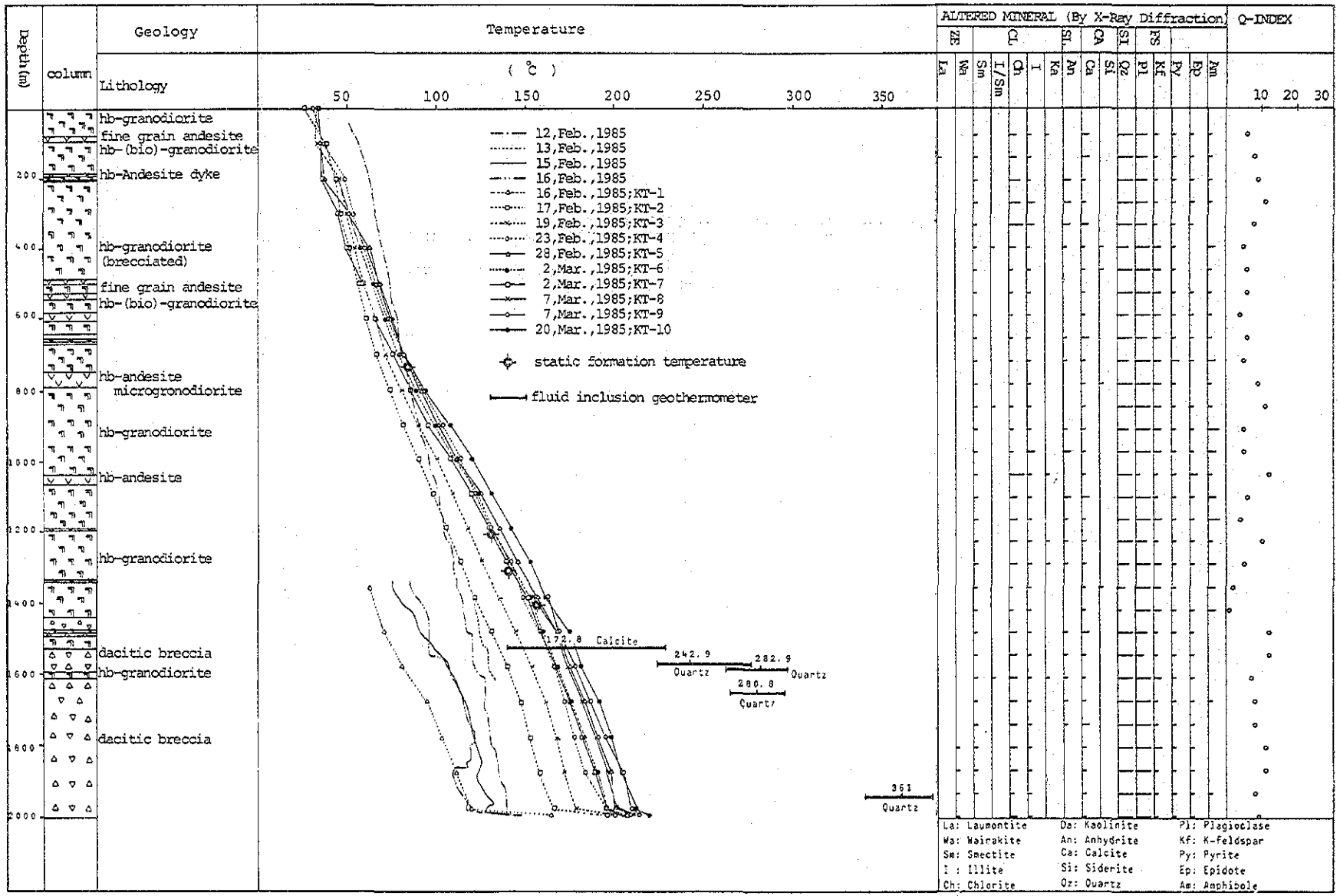


Fig. 10 Geological and thermal logging of the test well

Permeability: 11 l/min.kg/cm^2 +

Permeability · formation thickness

: 0.2 darcy·m

This figure is not large enough to warrant constructing a production well.

(7) Considering the high content of S, $-H_2O$, Ign.Loss and high silica content, infiltration paths for thermal fluid are assumed to be sealed by secondary minerals such as quartz and clay minerals.

2-2-4 Steam discharge testing

After conducting a injection test on February 13, 1985, a waiting time was provided to cause the temperature in the survey wells to recover. At 14:30 on May 14, 1985, a boiler was used to continue injecting heated steam into the wells for 27 hours, followed the next day of May 15, at 17:40, by opening of valves to start the steam discharge test. Before and after this steam discharge test was conducted, fluid samples were collected from the survey wells and electrical logging were conducted. The results of these sample analyses and inspections are summarized as follows.

(1) Well inlet pressure immediately prior to steam discharge test was 720 psi.

(2) Temperature of the injected steam was 245.6^{o}C and injection was continued for 27 hours.

(3) Pressurized injection of heated steam caused the waterfront surface, that existed at the depth of about 200 m from the well inlet, to be lowered to the depth of 600 m.

(4) After opening of the valves, steam continuously spouted for approximately 40 minutes, followed by a shift to intermittent discharge. After a lapse of about 24 hours, steam ejection

completely stopped.

(5) The observed steam discharging implies that the majority of hot water that existed in the wells before discharging remained within the wells even after completion of steam discharging. This assumption was confirmed by conducting a chemical analysis of hot water in the wells.

(6) The fact that completely continuous steam discharging was not observed is believed to have been caused by extremely low permeability that existed in the survey wells.

2-3 Simulation of the Geothermal System

2-3-1 Lumped parameter model

Figs. 11 gives the lumped parameter approach used for geothermal reservoir simulation of the Acupan geothermal field.

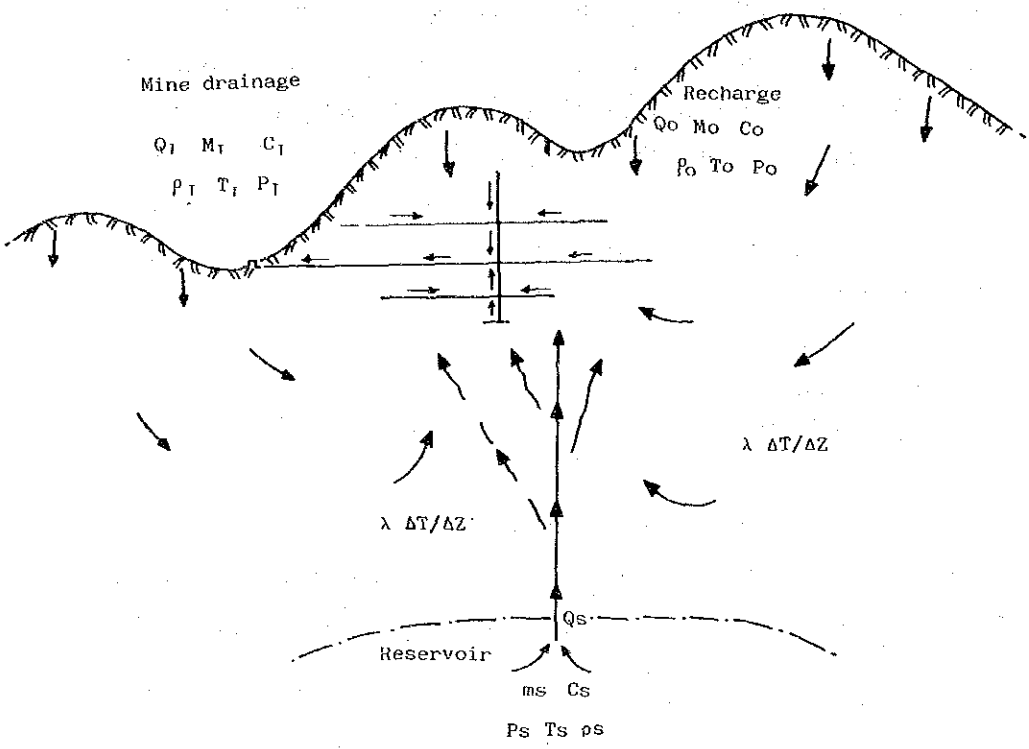


Fig. 11 Lamped parameter model of the Acupan geothermal field

Heat flow in the area is mainly represented by heat flow of the drainage water in the Acupan Mine. This heat flow is discharged from the mine after mixing of underground geothermal fluid coming up through the cracks with recharge water heated by terrestrial heat flow.

In consideration of the equation for the ground water and geothermal fluid flow, three kinds of balance equations can be formulated: mass, energy and solution balance equations. They can be written as:

$$\rho tQt = \rho oQo + \rho sQs \quad (1)$$

$$\rho tQt \cdot TtCt = \rho oQoToCo + \rho sQs \cdot Ts \cdot Cs + \lambda A \Delta T/\Delta Z \quad (2)$$

$$\rho tQt \cdot Mt = \rho sQs \cdot Ms \quad (3)$$

where the symbols are defined by

Q = fluid flow,	m^3/min
ρ = density of water,	ton/m^3 or g/cm^3
T = temperature,	^oC
C = specific heat of water,	Mcal/ton^oC or cal/g^oC
M = chloride ion concentration,	mg/kg or ppm
λ = thermal conductivity of rock,	W/m^oC
A = area,	m^2
$\Delta T/\Delta Z$ = thermal gradient,	^oC/m

and the subscripts mean

t = mine drainage

s = reservoir

o = recharge

By substituting the mass flow ρsQs of eq. (3) into eq. (1) obtained can be the mass flow ρoQo of the recharge. $TsCs$ of the reservoir is calculated by substituting the conductive heat flow into eq. (2).

And following parameters were discussed to solve the above three equations.

(1) Average water temperature and chloride content in cold spring

(2) Temperature and chloride in the stream

(3) Heat flow of the hot springs

(4) Specific flow

(5) Area affected by mining operation

(6) Heat conductivity

(7) Chloride ion concentration in the reservoir

(8) Status of the aquifer

2-3-2 Two-dimensional simulation

The numerical simulator SHAFTK considered in this study, a revised version of the two- phase simulator SHAFT79, using an

integrated finite difference method, solves the mass and energy conservation equations for two-phase flow phenomena in geothermal reservoirs.

The ground is considered to be formed of many polyhedral elements, in whose center of gravity are given average values of pressure, temperature, and other geothermal fluid properties.

Coupled mass and energy conservation equations for the moving fluid within the element, are as follows:

$$\frac{\partial}{\partial s}(\psi\rho) = -\mathrm{div}F + q \qquad (1)$$

$$\frac{\partial}{\partial t}U = -\mathrm{div}G + Q \qquad (2)$$

where ψ = effective porosity

ρ = density of the fluid

q = mass source

F = mass flux

U = volumetric internal energy

G = energy flux

Q = energy source

and t = time

The mass flux is given by Darcy's law at a two-phase condition. The energy flux contains conductive and convective terms. The volumetric internal energy is given by :

$$U = \psi \cdot \mu \cdot \rho + (1-\psi)\rho_n C_n T \qquad (3)$$

where U = internal energy of fluid

ρ_n = density of rock

C_n = specific heat of rock

and T = temperature

To solve the first two equations, it is necessary to relate their unknown variables of temperature T, pressure P, and saturation factor S to parameters of nonlinear terms. It makes the computation of the two-phase geothermal flow more difficult; however in SHAFT79, the two unknown dependent variables are the specific internal energy and the density. This simulator uses an

effective solver through combination of the Newton-Raphson method and the direct solution method.

Even now, the center of geothermal activity under the deposit is assumed to have at least a total heat flow of 50 MW, most of which is due to hot water flowing up through the cracks. This heat flow occurs within a radius of 3 Kms., with a mountain top of the Balatoc plug as its center. According to the geothermal structure, the model can be approximated as a vertical, cylindrical model or as a rectangular, parallelepiped in the NE direction. A block diagram used in simulation is shown in the geological section crossing the Acupan AC-1D and ACH-3 wellbores, representing a symmetrical cylinder with the Acupan shaft as its center (Fig. 12).

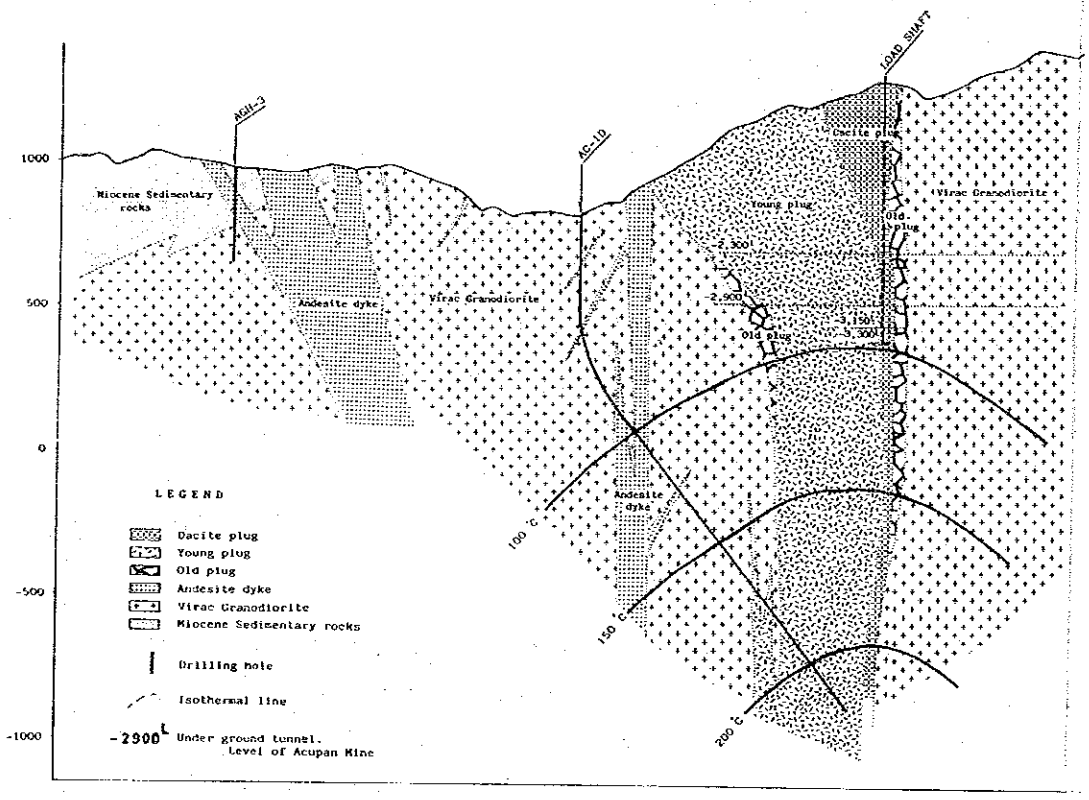


Fig. 12 Geological profile of the test well

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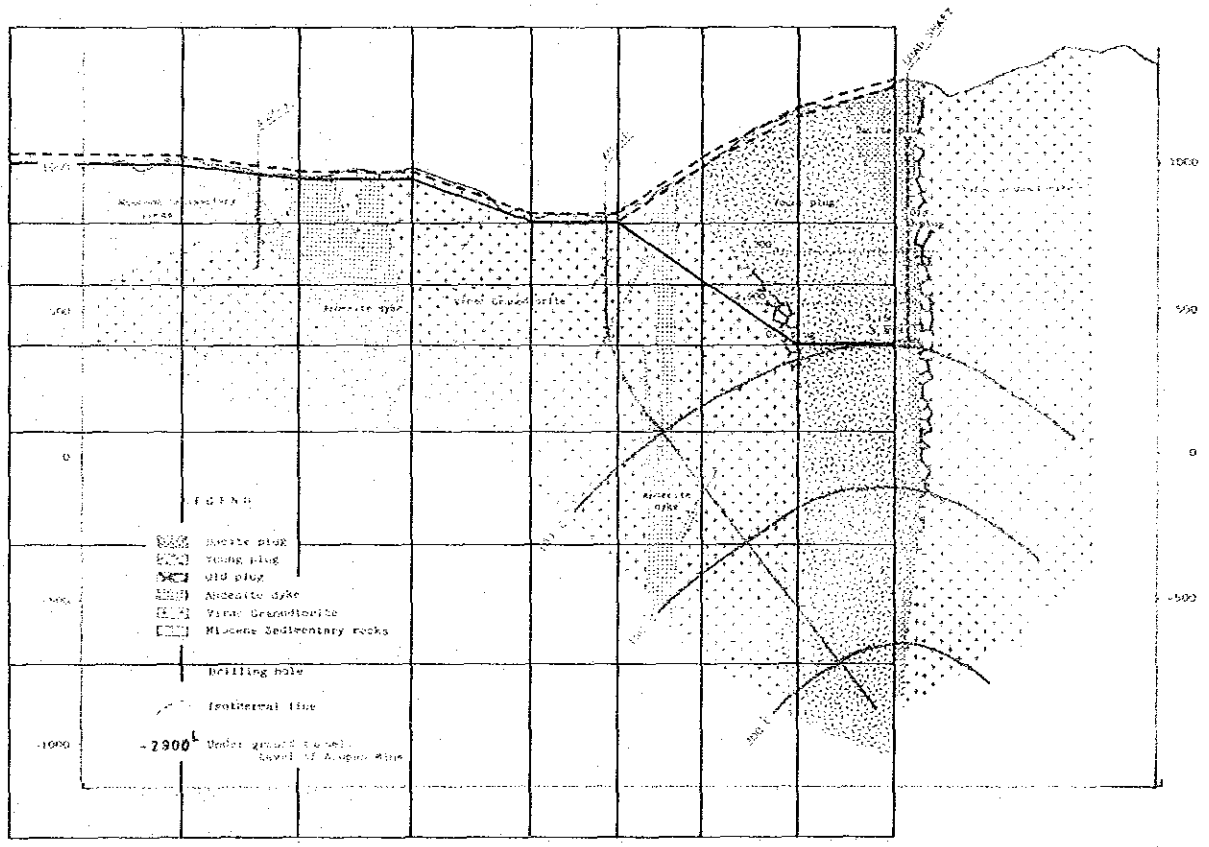

Fig. 12 Geological profile of the test well

Because there were relatively few heat flow and hydrological data available, simulation to be conducted had to be based on certain assumed values. The reduction effected in the number of blocks allowed us to execute faster simulations.

As is evident in the 2-dimensional section of the model in the last Figure, an overburden parallel to topography was given to the surface. This assumption had the intention do simulating recharge caused by rainfall and effectively realizing Newtonian cooling between the surface and the atmosphere. All blocks of lowest levels are receiving 2 HFU of heat flow of the earth's crust, and in addition, a heat flow caused by volcanic activity is being received by the block closer to the heat source. Underground caves resulting from gold mining are related to drop of the water level and to heat loss so that, in this simulation, these two aspects from underground cavings were important points to consider in the matching-process.

CHAPTER III MODEL OF THE GEOTHERMAL SYSTEM

3-1 Geothermal System Estimated from Surface Mapping

3-1-1 Geology

The geological structure of Northern Luzon is basically made up of the Central uplift zone and Subsidence zones of both its sides formed in the north-to-south direction. The majority of Quaternary volcanic rocks are localized in the Central uplift zone with a north-to-south trend. Geothermal manifestations are frequently found in the vicinity of the Quaternary volcanoes.

The investigated area is geologically situated at the transitional zone between the Central uplift zone and Western subsidence zone.

Quaternary dacite plugs, considered to be genetically related with the present geothermal activity of the area, are studded in the direction of northeast to southwest and north-to-south.

Geology of the Central uplift zone in the area is comprised of metamorphic rocks (Dulupirip schists), meta volcanics (Pugo formation) and quartz-diorite (Agno batholith). Likewise, that of the Western subsidence zone consists of Miocene andesite and pyroclastic sediments (Zigzag formation, Klondyke formation). At the boundary between the Central uplift and the Western subsidence zone are volcanic activities of early Pliocene Virac granodiorite, late pliocene andesite, and late Pleistocene dacitic plugs.

The geological setting in the transitional zone of the area is mainly characterized by north-south, northeast-southwest, and northwest-southeast faults and fold structures with trending north-south and northeast-southwest.

On the basis of strike frequencies of dykes and mineralized

quartz veins prevailing in the area, it may be inferred that north-south, northeast-southwest, and northwest-southeast fracture systems are well developed.

These fracture systems are, however, not common in Antamok diorite and Itogon quartz diorite in the uplift zone.

Based on the analysis of fractures and vein systems in the area, development of a significant structural framework seems to be originally generated within the transitional zone located at the periphery of the uplift zone during the upheaval movement.

The heat source of the geothermal system in the area seems to be closely related to the subvolcanic activity of Pleistocene dacitic plugs which occurred near the Itogon Bridge and Acupan Mine, and the geothermal system is structurally controlled by north-south, northeast-southwest and northwest-southeast trending faults and fractures developed at the periphery of the Central uplift zone.

The Balatoc plug is located at the cross point of north-south and northeast-southwest fractures, while the Itogon plug is also situated at the intersection of northeast-southwest and north-south fractures.

Auriferous quartz veins and fault systems such as the Golden Gate and Star fault are well defined, trending northeast-southwest at the Acupan Mine and between the Balatoc and the Itogon plugs.

It may be said that upheavals of the Central uplift zone as well as associated structures have induced a hypabyssal intrusion of the Pleistocene dacitic plug, considered as the possible heat source of the geothermal system in the Acupan-Itogon prospect area.

3-1-2 Heat source

Auriferous mineralization prevailing in the investigated area is regarded as part of the geothermal indications in a broad sense. In fact, whitish argillized zones derived from mineralization are generally observed at many places, as well as geothermal manifestation. The heat source of the geothermal system in the prospected area seems to be related to subvolcanic activities from late Pliocene andesitic volcanics (Old plug) to late Pleistocene dacitic pyroclastics (Young plug) and its intrusive dacite.

In surrounding plugs, high-temperature hot water is discharging. This hot spring water suggests high subsurface temperature from readings of geothermometers.

Especially, significant geothermal indication are revealed underground at the Acupan Mine, which are related to the Balatoc plug, and hot springs discharging near the Itogon Bridge are related to the Itogon plug.

On the basis of geological and geochemical points of view, the detailed survey area was delineated to be the Acupan-Itogon area, where plugs existed. Distribution of surface soil temperature does not reveal any anomalous values, even though the area is considered to have a high-potential geothermal reservoir existing underneath it. The reason for no anomalous temperatures indication is not clear, but it may be inferred that there are:

- many geological fractures on the volcanic activity causing the heat source of the reservoir.
- self-sealing effect caused by mineral deposition from geothermal fluid.
- depression of the water level due to underground mining at Acupan.

Relations, however, between location of the Balatoc plug and

clear correspondence. In fact, the surrounding rock of the plug was brecciated along the periphery of the plug by its up-and-down piston movement. The brecciated zone played a role as is the passage of geothermal fluid, raising rock temperature along the brecciated zone.

On the other hand, rock temperature of the plug core is not very high due to having less permeability than its peripheral zone.

As shown on the soil temperature map and the Hg concentration map of the surface, their anomalous zones appear at the peripheries of the Balatoc and the Itogon plugs.

This map reveals hot thermal fluid ascending through permeable structures and reaching the surface along the peripheries of the plugs. The upflow of geothermal fluid, therefore, is assumed to be principally controlled by the location of the plugs.

Subsurface temperature contour lines at 1,000 m b.s.l. show the distribution of over 200°C extends in the NE-SW direction with the same arrangement as the Balatoc and the Itogon plugs (Fig. 6). An area of a high potential zone of over 200°C spreads about 3.5 km x 1 km in an oval shape. The increasing rate of temperature by depth shows 10°C/100 m, however the reservoir boundary toward NE-SW is very sharp. The anisotropic characteris-tic of the temperature increase rate between reservoir's NE-SW and NW-SE direction is considered to result from the fact that the ascending fluid is not only controlled by brecciation of the plug movement, but also by the geological structure of NE-SW direction fracture system such as the North and Star faults (Fig. 13).

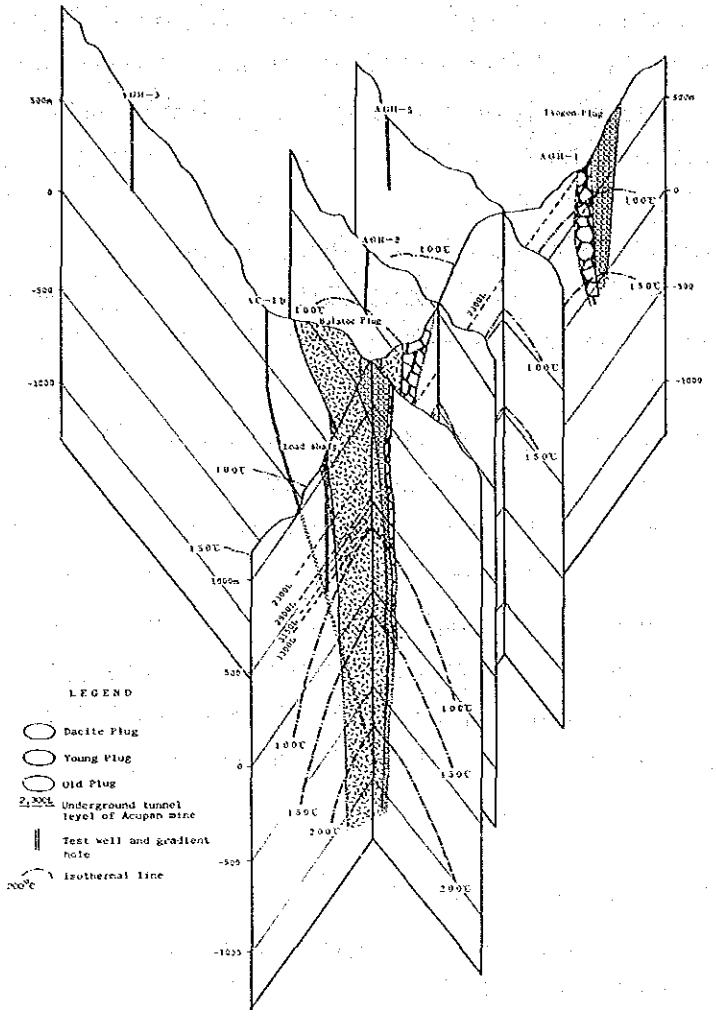

Fig. 13 Block diagram of geology and isothermal profile

3-1-3 Hydrology

There are many discharging hot springs in investigated areas such as Dulupirip, Itogon, Klondyke, Asin, Pugo, Laboy, the Balatoc (underground of the Acupan Mine), Liang and Antamok. Most of these discharging hot springs are geologically controlled by the fracture system of the area, and are localized in the

transitional zone between the Central uplift zone and the Western subsided zone. Especially, the high-temperature hot springs among them are situated near the dacitic plug, whose ages range from late Pleiocene to early Pleistocene.

On the basis of the soluble cation and anion content, the hot spring waters are classified into five types, namely; Na/Cl type (Acupan, Klondyke, Asin, Pugo), Ca/SO4 type (Acupan, Antamok, Laboy), CaSO4/HCO3 type (Antamok), Na/SO4-HCO3 type (Itogon, Antamok), and Na/SO4 type (Dalupilip).

Among them, the Na/Cl type is found localized in and around the peripheral boundary of the Balatoc plug while the Na/SO4-HCO3 type is observed near the Itogon plug, both types equally indicating high temperatures.

The O/H isotopic values of rain, river, and hot spring waters collected in the investigated area fall in a straight line of $\delta D=8\delta^{18}O+15$, which runs parallel to the model line formulated by Craig (1963) though with a slight shift to the left of the model line. On the basis of isotopic values of the samples, the origin of hot spring water could be attributed to meteoric water.

Discharging Na/Cl type, high-temperature water at the underground of the Acupan Mine has indicated some oxygen shift which points to possible chemical interaction between ascending thermal water and the country rock.

Considered from the isotopic point of view of D/H and O^{18}/O^{16}, the origin of the geothermal fluid may have originated from two different areas of meteoric water. That is, Ca/So4-type spring water discharging at the underground of the Acupan Mine, which indicates a 10o/oo lower value of D compared with that of the Na/Cl type. It may be inferred that Ca/SO4 type water originates from a several hundred meters higher altitude than Na/Cl-type spring water. It is also considered that Na/Cl-type spring

water flows from somewhere far away from the site where it was collected.

As stated above, there are two types of discharging hot spring--the Na/Cl and the Ca/SO4 type. Each type of spring water has a different heating mechanism in the subsurface and also a different source of the water.

Another characteristic is that there is no transitional type between the two types, showing no mixing in the subsurface. This inferes that the two types of water are isolated from each other and bounded by an impermeable zone (Fig. 14). From a geological point of view, an impermeable zone such as a shale bed does not exist in that area. The self-sealed zone, therefore, produced chemically by the deposition of soluble materials into the fractures, has occupied a part of the impermeable zone.

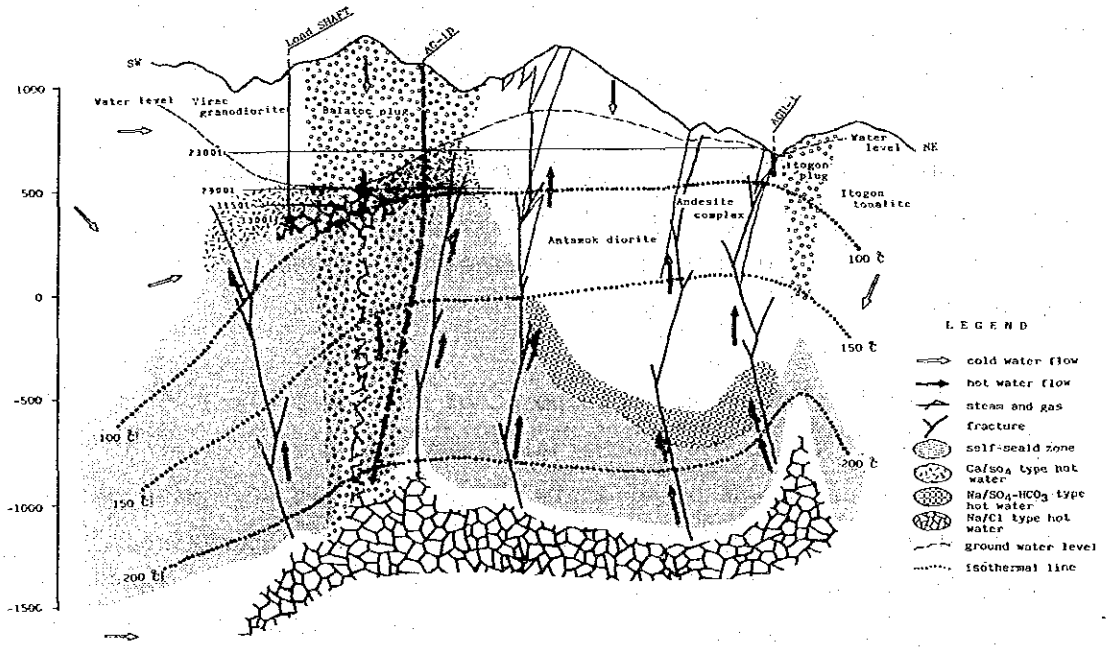

Fig. 14 Conceptual model of geothermal system of the Acupan-Itogon area

Existence of the so-called self-sealed zone is supported by an examination of cuttings and also by an injection test of AC-ID. In summarizing the foregoing statements, the heating mechanism of the hot spring waters prevailing underground at the Acupan and the Itogon areas is considered as follows.

The Na/Cl-type hot water comes from deep-seated water, its origin being underground water recharged from precipitation of low elevation. On the other hand, the Ca/SO4 type is thermal water heated at a shallow depth by H2S and CO2 gases disassociated from the deep-seated hot water. And its origin is underground water derived from the surface around the Acupan-Itogon area.

This is the reason that two types of discharging hot water exist in the underground of the Acupan Mine. The Na/SO4-HCO3-type hot water discharging in the Itogon area is formed in the process of water-rock interaction dissolving Na of the rock during water ascent, which penetrated to the depth and was heated by H2S and CO2 (Fig. 14).

3-2 Results of the First Ezploratory Wall (AC-1D)

3-2-1 Geology, geochemistry and injectivity test

The geology of Well AC-1D comprises granodiorite, andesite dyke and dacite pyroclastics (Young plug). The Young plug in the borehole appears almost at the location estimated from surface geology, decreasing its diameter in the depth. (Fig. 12) The rocks sampled from the borehole generally suffer from hydrothermal alteration, suggesting that the thermal water may be from neutral to weak alkali. Bottomhole temperature in the past seems to have been higher than that of the present, since wairakite is detected near the bottomhole. Spectral analysis of the cuttings reveals that several passageways of thermal water existed in the past. In the course of temperature descending in the aquifer, leaking out of plagioclase and precipitation of quartz, clay, and sulfide minerals caused the cracks to choke. That is, so-called self-sealing.

The static formation temperature of AC-1D (drilled length 2,000 m, vertical depth 1,677 m and bottomhole level 850 m b.s.l.) was estimated to be 220°C. The temperature of the reservoir is high enough to enable discharging geothermal fluid. The rate of temperature increase with depth indicated almost a fixed rate of 11°C/100 m along the inclined borehole, suggesting heat conduction. This infers the existence of an impermeable formation, as stated above, the impermeable zone possibly formed due to the self-sealing effect. As a result of self-sealing, the present formation temperature might be around 60°C-100°C lower at about 1,600 m deep than that in the past, judging from a fluid inclusion temperature test of quartz collected from the borehole.

No circulation loss was observed while drilling of AC-1D, suggesting no permeable zone. On two occasions, hydrofracturing tests created a weak permeable zone, where the passageway of thermal water in the past was reopened. Values of the injectivity index and permeability thickness are 1.79 l/minMPa and 0.257×10^{-12}

m^3 respectively. Those values are not enough high to enable enough discharging steam for power generation, although some flushing of steam is expected.

The permeable zone created by hydrofracturing was observed at two depths of 1,550 m and 1890-1990 m respectively. The upper permeable zone corresponds to the boundary of the Virac granodiorite and the Balatoc plug. On the basis of geochemical data, it is assumed that the boundary zone might have been a high permeable zone in the past. However, at present the zone is filled with quartz and clay minerals.

On the other hand, the permeable zone created near the bottom hole was not prominent in the past, although it indicates better permeability than the upper zone.

As previously stated, the Well AC-1D indicates that reservoir temperature in the area is high enough for geothermal power development, but offers poor permeability due to self sealing. In fact, the bottomhole of Well AC-1D is still located within the self-sealing zone, and has not yet reached the underlaying potential reservoir in the area.

3-2-2 Discharge test

After well completion, the temperature was monitored for 90 days to determine the stabilized reservoir temperature. A discharging test of the well was conducted on May 15, 1985.

Prior to the discharging test, a boiler was used for heating and supplying pressure to water in the well. Steam injection lasted consecutively for 27 hours. The steam temperature injected was 245.6°C, and wellhead pressure during injection was 720 psi. The Wellhead valve was opened at 5 p.m. on May 15.

When the valve opened, steam along with water gushed out for 40 minutes. As shown in the photograph, strong flushing lasted

for the first 10 minutes, with mainly steam and less water. Dry steam flowed out for the last several minutes. After 40 minutes of powerful flushing, intermittent flow continued till the following day and after that.

Fig. 15 is a temperature and pressure log chart before and after the discharging test. The water level of the well before the injection of steam with the boiler was 200 m from the wellhead, as shown at KP-6. By means of steam injection with the boiler, the water level was lowered to 600 m as estimated by temperature log chart (KT-13). This infers that the water level descended about 400 m.

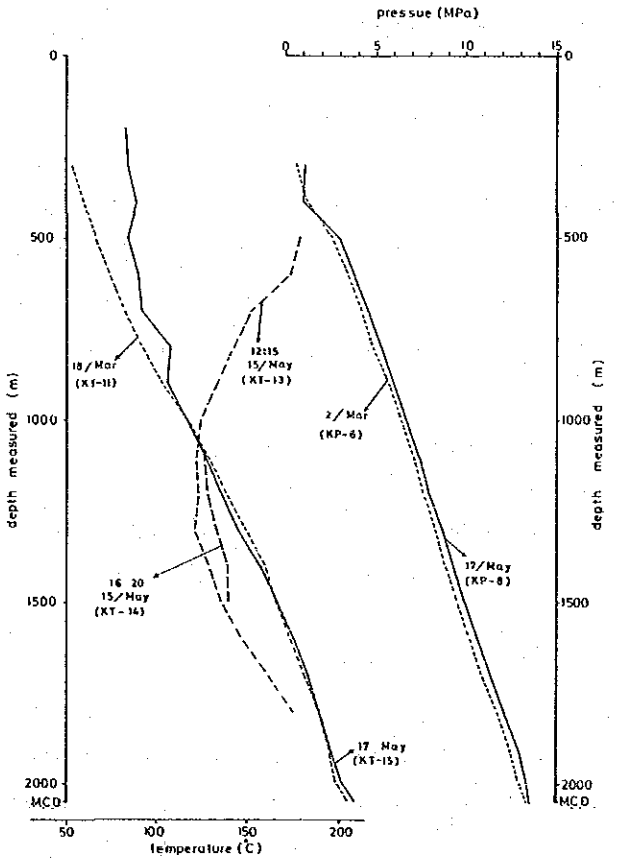

Fig. 15 Thermal and pressure logging after and before the flashing test

After two days of discharge tests, the well temperature and the water level almost recovered to the same level before the test, as seen at KT-15 and KP-8. From these data, it is believed that geothermal fluid was moving in the borehole. After the discharge tests, however, the pH value and chemical components of the water collected from the well revealed contamination by condensed water of the injected heating steam.

The steam and hot water that gushed out from the well, therefore, may have been mainly injected heating steam and a small part of geothermal fluid that existed in the well. This implies that actual values of the injectivity index and permeability thickness were considerablly lower than those values calculated during the well test (1.79 l/m, MPa and 0.257×10^{-12} m^3).

As to permeability, it may be considered that the big difference between the calculated and the actual value could have been caused by a time lag of 90 days. As previously stated, the permeable fracture was artificially made by the hydrofracture, and permeability thickness was calculated to be 0.257×10^{-12} m^3. Considering the discharge test of the well, however, the permeable zone made by hydro fracturing was possibly choked no up again.

3-3 Results of the Simulation

3-3-1 Lumped parameter model

The temperature, pressure in the reservoir, and the fluid flow rate can be estimated from Fig. 16 and 17 which is derived from the balance equations with an assumption that the Ms ranges from 1,600 to 3,200 mg/l. When a chloride concentration Ms is 2,000 mg/l, for example,

$Ts = 273^{o}C$, $Cs = 1.17$ Mcal/ton, $\rho = 0.68$ ton/m^3

$Ps = 198$ bar, $Qs = 2.22$ m^3/min.

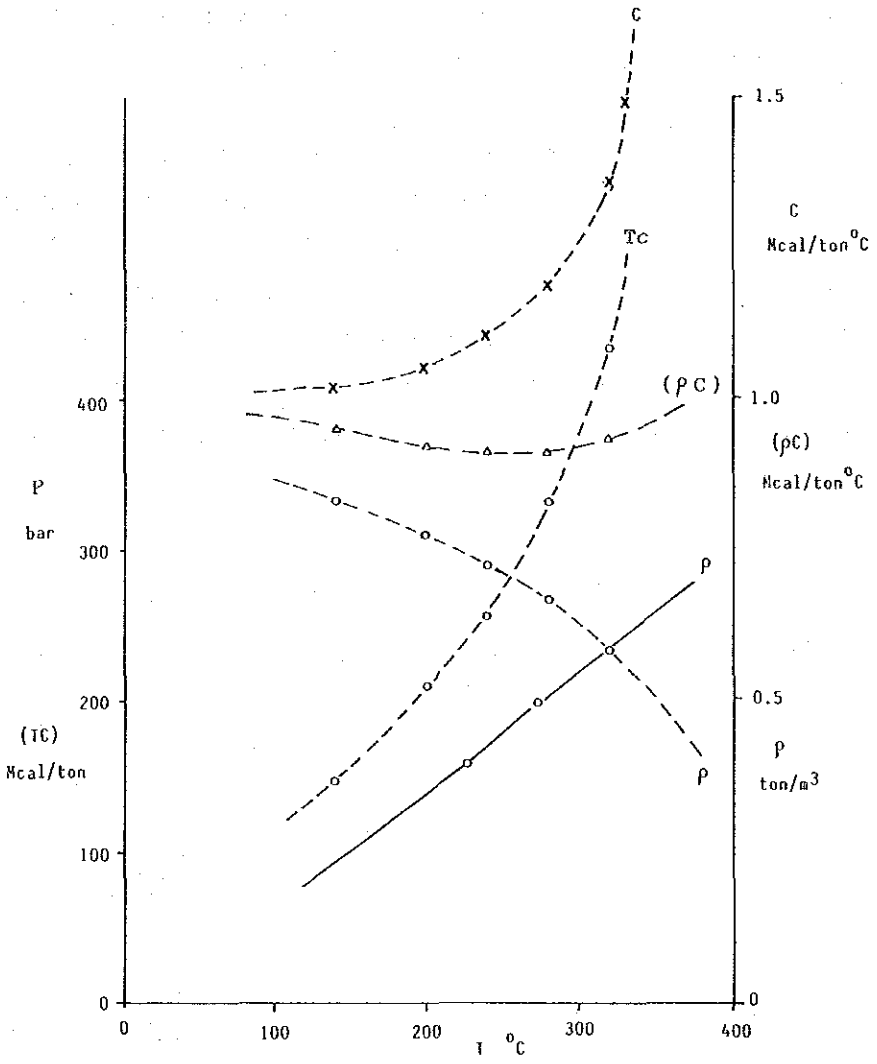

Fig. 16 Estimated properties of the hot water in the reserve

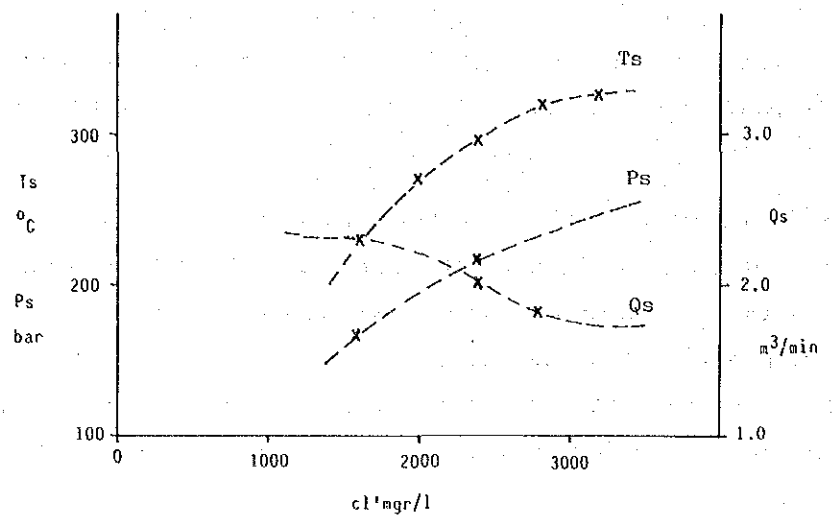

Fig. 17 Relation between the hot water properties in the reserve and the Cl-concentration

The figure indicates that temperature Ts increase with the increase of concentration, however the gradient is smaller, having reached the saturated condition of 320°C when the Ms concentration is 3,200 ppm. In this condition, pressure is estimated in about 250 bars, and judging from AC-1D data, an estimated reservoir exists at 1,700 m b.s.l.

3-3-2 Two-dimensional simulation

All these steps contribute to making easier the lateral flow of the recharge. Based on those concepts, further repetition of the simulations gave the results indicated in Fig. 18.

No significant differences in permeabilities are given between intrusive rocks and basement rocks. Also, the primary geothermal fluid given to the bottom is caused to decrease radially from the center.

Fig. 19 shows the temperature distribution based on initial values adopted by the previous calculation, after nearly 20,000 years. Here the thermal gradient of deep zones is lower than that

of model D, tending to be close to the observed value in AC-1D. On the other hand, the presure distribution given in Fig. 20 does not directly suggest the geothermal structure.

The distribution of geothermal heat and mass flow are indicated in Figs. 21 and 22 respectively, indicating that mass and heat flow in the Acupan Mine are 8.60 Kg/S and 2.30 MW respectively, and thus showing values closer to the observed values than in the case of model D. Should several more runnings of the simulation be conducted, results closer to the observed values could be obtained.

According to the results obtained from several simulations of the underground geothermal structure of the Acupan area, the following can be summarized:

1. Regardless of whether or not the basement rock is an intrusive rock, the permeability was small in the order of 10^{-15} to $10^{-16} m^2$ in spite of of the direction.

2. It is concluded that there is no eminent fracture upstream from the deep geothermal fluid. This is inferred from the fact that a strong sealing effect occurred when gold mineral bed formation was formed and volcanic activity was not so prominent to produce an active fault.

3. Upstream movement of the primary geothermal fluid may not be controlled by the Balatoc plug and the geological structure in the NE-SW direction.
It is considered that the flow rate of upstream movement of the geothermal fluid is nearly the same in this area, and within a radius of at least 3 kms it is assumed to be constant.

4. Most of the geothermal heat flow of 33MW found in the Acupan Mine, caused by the hot spring and by drainage of the underground geothermal fluid, is deeply related to

development of the Acupan Mine. Before development of the mine, manifestations must have been almost the same as hot springs around the Itogon area.

5. This stage, it is somewhat difficult to assure that there could have been developed high permeability fractures outside of the present simulated zone at depths lower than 1,500 m b.s.l.

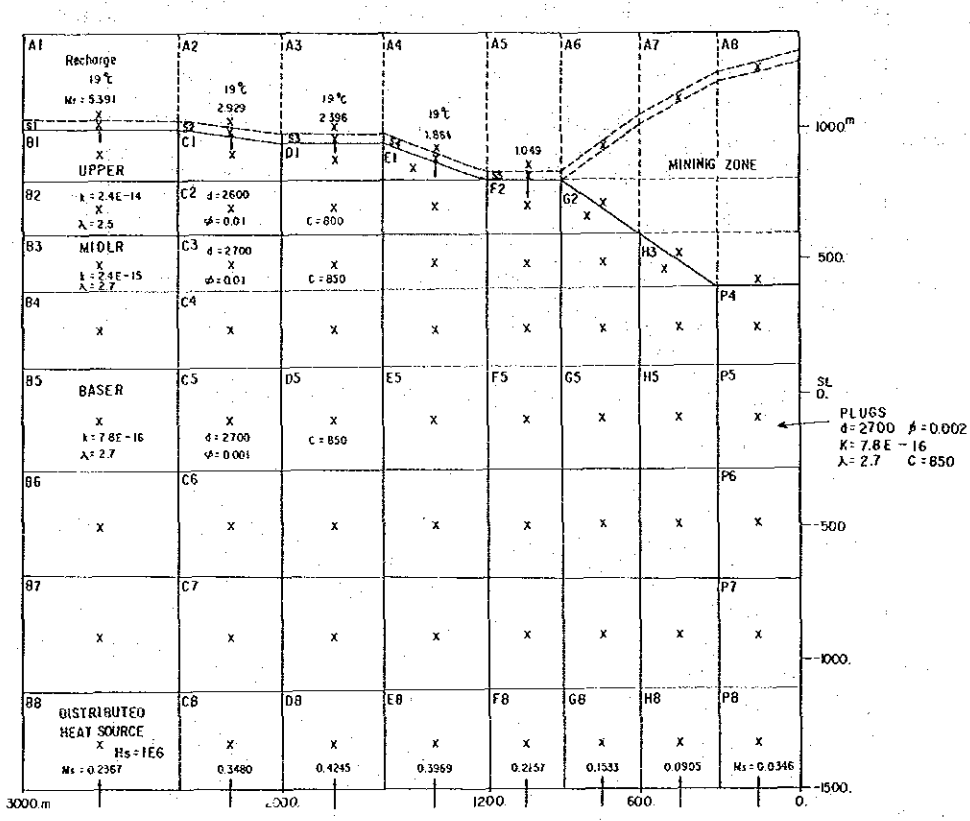

Fig. 18 Simulation model K

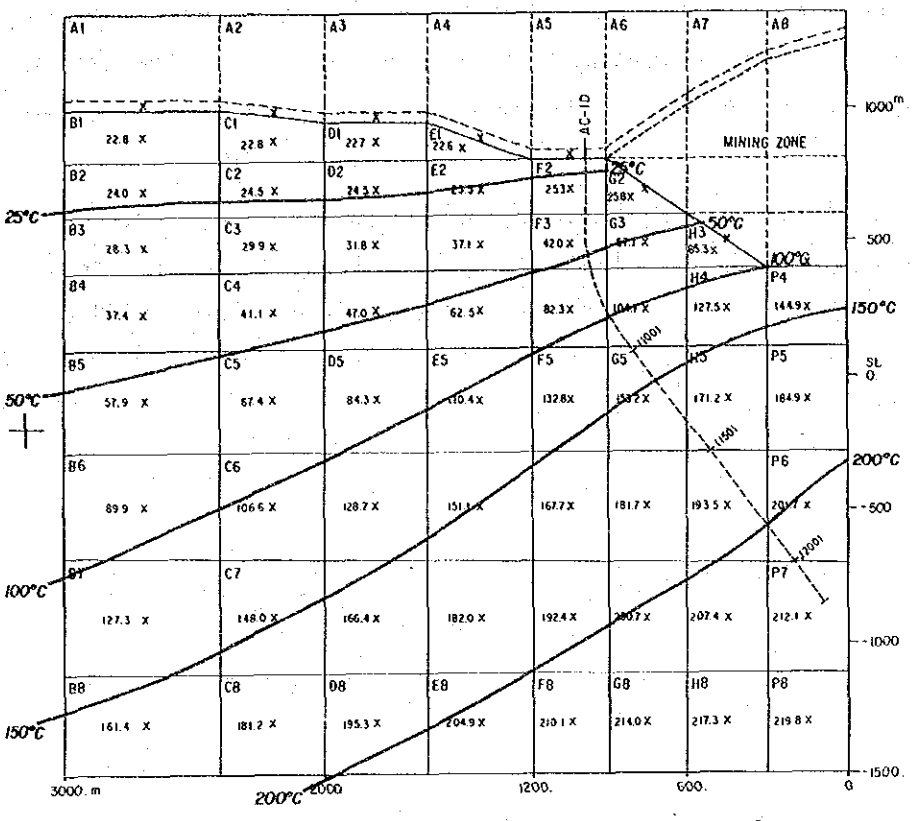

Fig. 19 Temperature distribution (model K) in °C

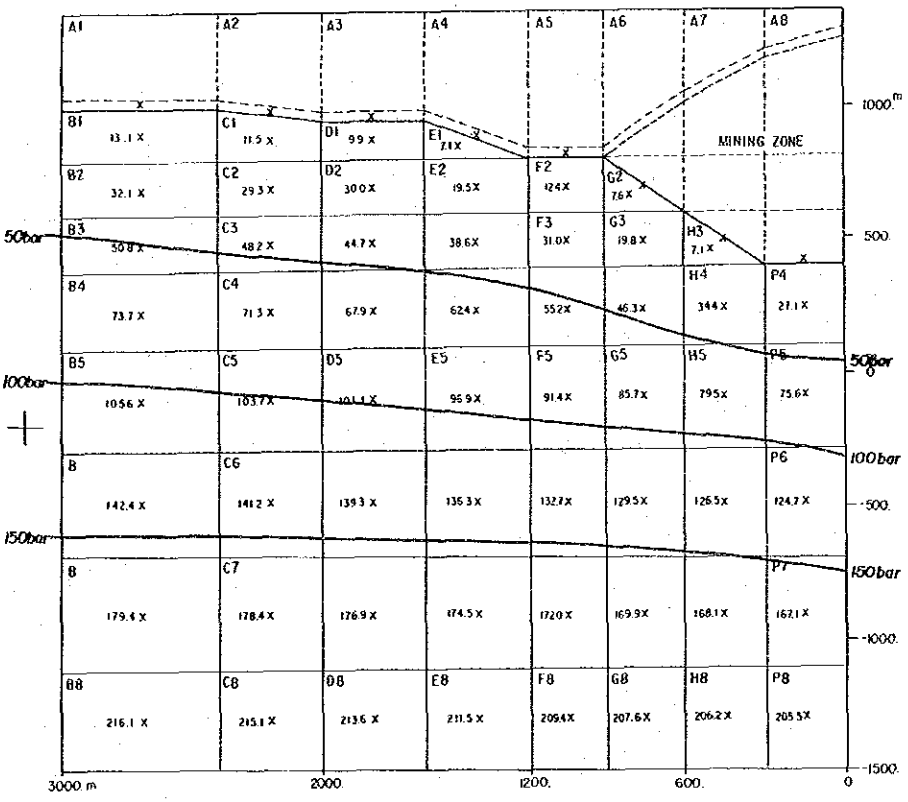

Fig. 20 Pressure distribution (model K) in bar

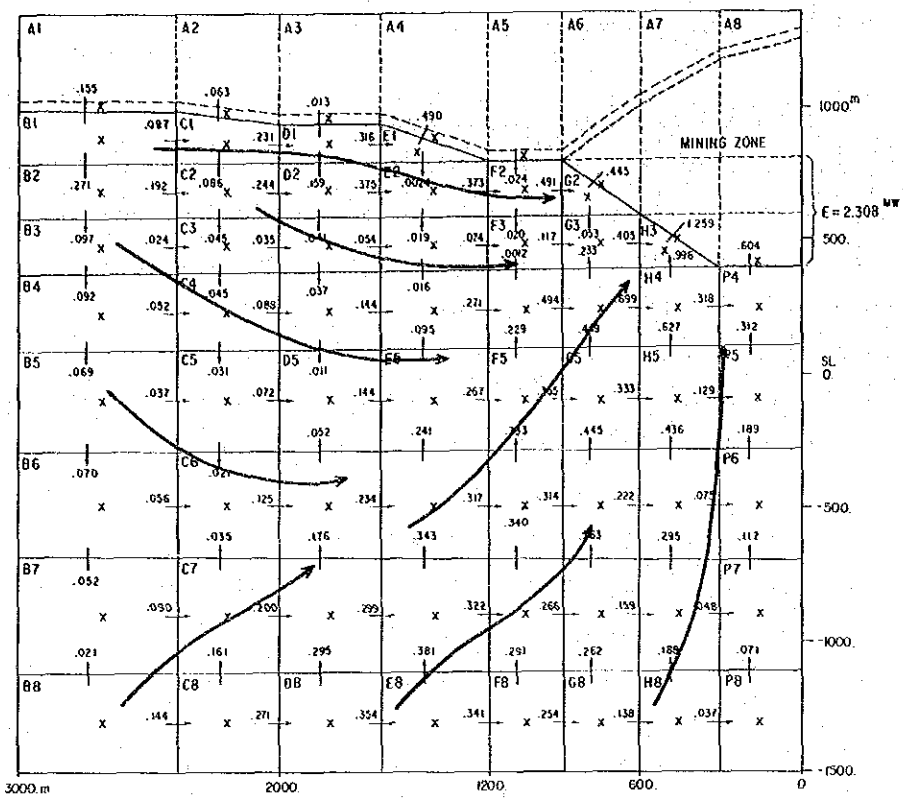

Fig. 21 Heat flow distribution (model K) in MW

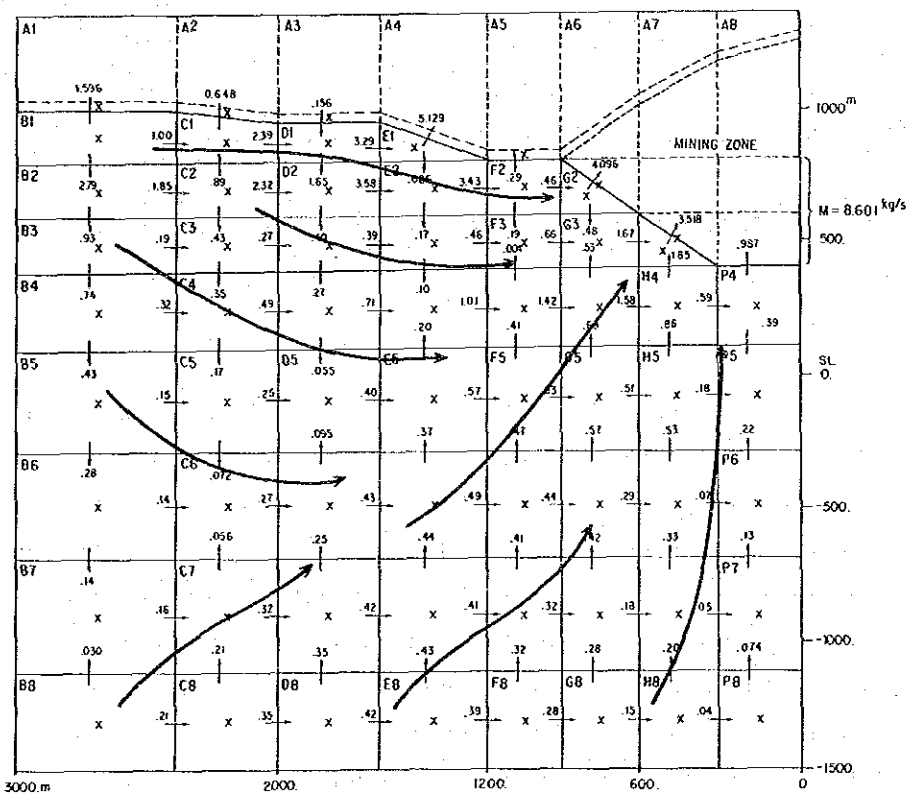

Fig. 22 Mass flow distribution (model K) in kg/s

3-4 Model of Acupan-Itogon Geothermal System

3-4-1 Geological and geochemical model

From the viewpoint of rock mechanics, it must be noted that geology of the the Acupan-Itogon area is composed of volcanic rocks whose porosities are quite low. And the geothermal system can be said to belong to a typical fracture-controlled type, considering that the fractures not only improve the very low porosity, but also allocate the fields for heat-source related recent volcanisms. The isothermal line of the 200°C extends in NE-SW direction, whose dimension is 3.5 kmx1.0 km at 1,000 m b.s.l., is occupied by heat-source related plugs at both ends and by fractures between the two plugs. The thermal fluid was able to flown up along the high-temperature zone, in which the average temperature gradient is about 10°C/100 m. However, to the northwest and southeast of this, the temperature gradients become very low, suggesting that the area is the down-flow zone of thermal fluid. As mentioned above, the model of the geothermal structure can be considered as a plate model when the fractures are viewed as the main point of study, and as the combination of two cylindrical models when the heat-source related plugs at Acupan and Itogon are studied as a key survey point.

The geothermal structure is summarized as follows from the viewpoints of balance of the underground water, energy, and chemical contents in thermal fluid.

Mining operation of the the Acupan Mine should affect the flow of underground water. The underground water level should be depressed broadly at and around the site of mining operation. For example, the actual area estimated for gathering precipitation to recharge water toward the mine site is about 15 km^2, although the topographical apparent recharge area is only about 9 km^2. The ellipsoid, with a long and short radius of 2.6 km and 1.9 km respectively, is equal to the actual area estimated and can cover the Itogon plug when the center is placed at the top of the

Balatoc plug. Ground water recharged at least within this area is believed to flow centripetally toward the Balatoc plug. Among the thermal springs around the the Acupan Mine and Itogon, fluids of the Ca/SO4 and Na/SO4-HCO3 type can be presumed to originate from the groundwater heated up at a depth.

Thermal springs of the Na/Cl type in the Acupan-Itogon area is judged to come from deep-seated thermal fluids. The original ground water assumed to be this type is not from precipitation at the Acupan-Itogon area, but from ground water recharged at an area of lower elevation. The ground water at a depth may solve chemical component of Na and Cl from country rocks while moving in a high-temperature condition. The lower contents of Cl in thermal fluids in the Acupan-Itogon area could mean that the geology is mainly composed of volcanic rocks but lacks marine sediments. The estimated Cl contents in thermal fluids at a reservoir would range from 2,000 to 4,000 mg/l, considering that the maximum Cl contents at the Acupan-Itogon area is about 1,700 mg/l, and also considering both the temperature of spring water samples and the dilution of fluid by surface ground water.

The most prominent seepages of hot springs are at the tunnel of the Acupan Mine. Fluids of the Na/Cl type ascend along the brecciated zone at the periphery of the Balatoc plug, rising through the self-sealed zone and pouring as boiling springs into the tunnel of the mine. Thermal water of the Ca/SO4 type also seeps outward from the Balatoc plug, although the temperatures of those springs are not so high. However, the total heat energy thrown off as drainage water is quite a lot, whose temperature and rate of discharge at the level of 2,900 are 43°C and 20 m^3/min respectively. Further, the estimated total amount of heat energy discharged of at the the Acupan-Itogon area is 33.7 MW, including other minor dischargings. This heat flow is common for geothermal fields.

3-4-2 Numerical model

The geothermal system of the the Acupan-Itogon area can be modeled as a plate joining both the Balatoc plug and the Itogon plug or as two cylinders at each plug. However, the following interpretations shall be based on the cylindrical model because the discharge of heat energy is prominent, and because detail data are located at the Balatoc plug.

Fig. 23 shows a cross section of the cylindrical model joining the Balatoc plug and the test well (AC-1D). The pattern of a self-sealed zone, the ascent of Na/Cl-type thermal fluid along the Balatoc plug, occurences of Ca/SO4-type thermal water genetically correlated with a flow of ground water, and underground isothermal lines are shown in the figure, details of which are as previously mentioned. This model was simulated by using a simulator SHAFT-K; an abstract of the results are as follows. Simulation was effected within the range of a model whose cylinder radius is 3 km and bearings are 15°, and whose bottom is down to 1,500 m b.s.l. A nonstationary flow of the two phases of fluid and steam was assumed in this simulation range.

No geological and geochemical data can be used to derive information about a heat flow at a depth. However, the area of the source for heat supply is estimated to be not only restricted just beneath the Balatoc plug, but also to extend towards the outside of the plug, when the source is estimated at 1,500 m b.s.l. On the contrary, the temperature and the depth should be quite high and deep respectively when the extent of the source is restricted to only beneath the plug. Considering the seepages of hot spring water around the the Itogon plug, it points toward the former sources, although this is uncertain. The high temperature zone expands laterally at 1,500 m b.s.l.

According to simulation of the geothermal system, even the low permeability of a 10^{-15} to 10^{-16} m^2 order is sufficient to feed seepages of thermal fluid seen in the tunnel of the Acupan Mine. This low permeability implies a scarcity of tiny fractures

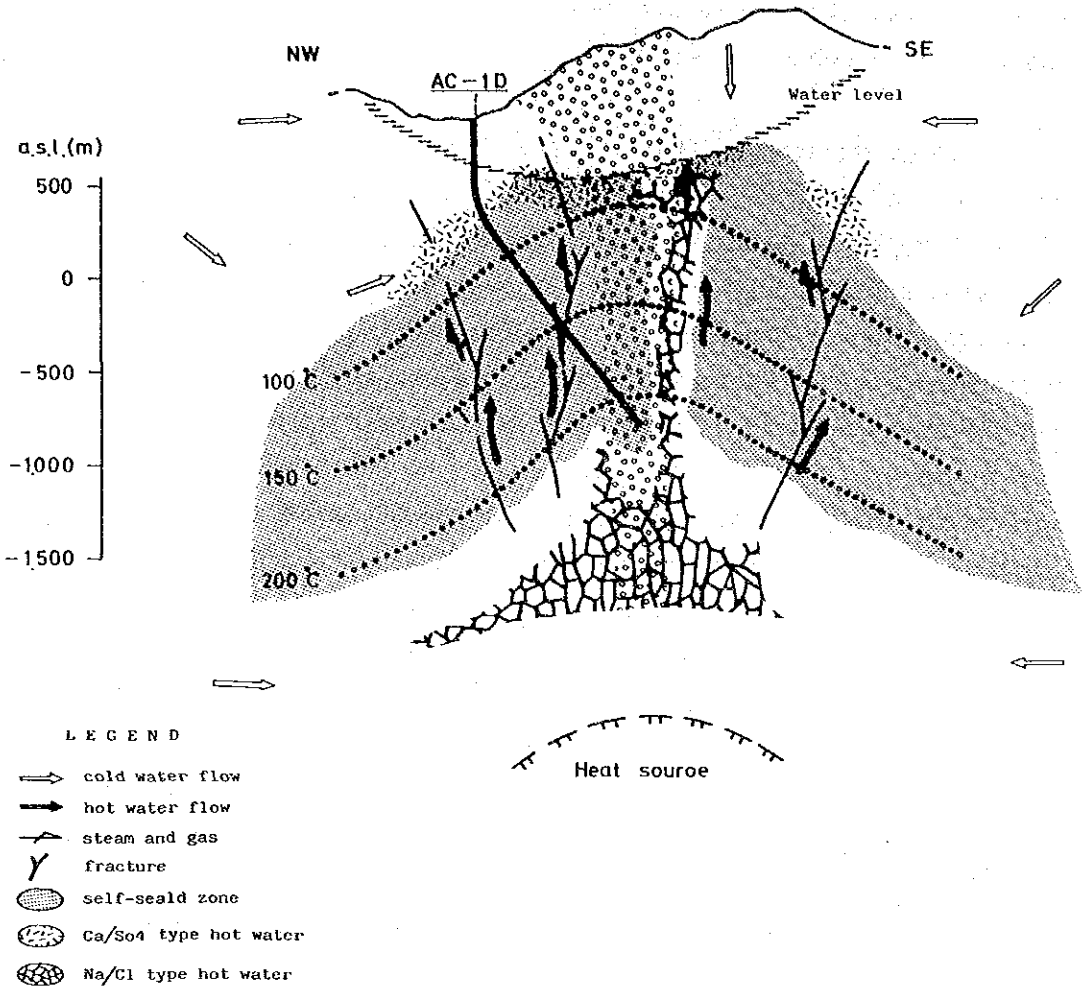

Fig. 23 Conceptual model of geothermal system through the test well

and assures the presence of a self-sealed zone estimated from geological and geochemical data. The permeability of fractures artificially caused by hydro-fracturing of the test well (AC-1D) is also equal to that estimated from the above simulation. As mentioned above, the test well (AC-1D) could not discharge fluid continuously, although it is possible to discharge some amounts of fluid continuously even when permeability is as low as previously stated. This would mean that the test well does not cross the paths which feed thermal fluid from a depth into the tunnel, and

that the fractures caused by hydrofracturing were already shut at the time of discharge test.

A large quantity of thermal spring water with 33.6 MW equivalent of heat energy pours into the tunnel of the the Acupan Mine. A depression of the ground water level caused by mine operation would induce an upflow of deep seated thermal fluid which contributes genetically to thermal springs. If so, pressure reduction caused by depression of the ground water level and the ascent of deep-seated thermal fluid are assumed to be the cause and the effect. From the viewpoints of the cause and effect just mentioned, the potential of geothermal resources at Itogon is almost equal to that of the the Acupan Mine, although the amounts of energy disposed by thermal springs at Itogon is only equivalent to about 0.2 MW. In fact, the Hg content in soil and the intensity of hydrothermal alteration at the Itogon area are almost the same as those at the Acupan Mine.

CHAPTER IV CONCLUSIONS AND RECOMMENDATIONS

4-1 Conclusion

Interpretations of Phase-I to Phase-III surveys lead us to the following conclusions:

1. Geological Structure. The Acupan-Itogon area is located at the transitional zone between the Central Uplift Zone and the Western Subsidence Zone, in which fractures are developed quite well. These fractures not only generate secondary permeability for a geothermal reservoir but also act as loci for Late Pliocene to Pleistocene volcanic activities in the region. This means that the Acupan-Itogon prospect can be classified as a fracture-controlled type geothermal system.

2. Resevoir Temperature. Reservoir temperature estimated from silica contents and the alkali ratio of the thermal fluids are 229°C and 236°C, respectively. These estimates are further substantiated by AC-1D's bottom temperature of 220°C.

3. Shape and Size of Geothermal Reservoir. No information from deep zones could be obtained from geophysical surveys such as resistivity survey due to electrical noise caused by mine operation. However, based on data of the seven gradient holes and the test well, AC-1D, the size and shape of the geothermal reservoir above 220°C are assumed to be 3.5 km x 1.0 km, stretching ellipsoidally NE-SW at 1,000 meters b.s.l., respectively.

4. Origin of Hot Springs. The original water of hot springs could be traced to meteoric water recharged by precipitation. The hot spring waters in Acupan-Itogon area can be divided into three types, namely: Na/Cl, Ca/SO_4, and Na/SO_4-HCO_3 type of waters. The Na/Cl type is assumed to be a deep-seated brine of neutral pH.

On the other hand, both the Ca/SO_4 and Na/CO_4-HCO_3 types could be steam heated ground water.

5. AC-1D:

A. Well Temperature: Formation temperature increase linearly at a rate of 11°C/100 meters showing a conductive heat flow. Bottom hole temperature of AC-1D is 220°C which is lower than that estimated from gradient holes. This temperature, indicates the presence of active heat source in the area which is a necessary condition of a geothermal reservoir.

B. Well Permeability: Two permeable zones were noted around 1,550 meters and 1,850 to 1,995 meters depths during hydrofracturing test. The injectivity index and the permeability thickness of these permeable zones are 1.79 l/min. MP and 0.259 x 10^{-12} m^3, respectively. The observed low permeability is due to the self-sealing effects of alteration minerals in the fractures. This has been indicated by the depletion of Na in the rocks and the abundance of silica, anhydrites, calcite and clay minerals associated with sulfide minerals.

C. Discharge test: Large volumes of steam discharge could not be expected due to the low permeability, but generally speaking, a certain amount of steam should be expected to flow out. However, the well could not discharge geothermal fluid continuously, even though the well was heaated and stimulated by the injection of compressed super heated steam inside the well. It would mean a shutdown of the channels, reopened by hydrofracturing, during the recovering the temperature for about three months.

6. Simulation of the Geothermal System. Based on the total water discharge in the Acupan mine, the estimated heat flow is 33.6 megawatts.

Two dimensional simulation of the geothermal system indicates that: (1) permeability of 10^{-15} -$10^{-6}m^2$ almost equals with the observed permeability of AC-1D. (2) the heat source widens at

depth.

7. Potential of the Geothermal Resources. The Acupan-Itogon geothermal field is covered by a thick self-sealed zone. However, according to the two-dimensional simulation of thermal fluid, the high-temperature zone could spread widely in deep strata, although permeability of the reservoir should be low at its upper part. The reservoir temperature determined by the test well exceeds 200°C, and the thermal fluid of neutral brine is assumed to be appropriate for geothermal power generation. Considering the increase of the bore hole temperature of the test well, the temperature is assumed to become high in the reservoir at deep strata, where the self-sealed zone is no longer expected. The fractures trending N-S and NE-SW in direction would reach down to the deep strata, and would act as space and as channels for the thermal fluid.

Considering the economic viability of Acupan-Itogon prospect to the thriving population of Baguio City and mining industries in the area, the prospect warrants further exploration.

4-2 Recommendations

An additional survey is recommended to test the geothermal model obtained from the survey results of Phase-I to -III and confirm the geothermal resource potential of the area. This will include the following:

1. Fracture Analysis of the Area. This will facilitate interpretation of the distribution of potential fractures.

2. A study of the hydrology and heat flow.

3. To drill an additional test well under the following conditions:

a. The drilling site and depth of the test well shall be determined by: environmental effect of the area; acceptance of the local residents for the continuous well test; and, application of the previously obtained survey results and geothermal model.

b. The maintenance and examination of well logging equipment and so forth shall be satisfactorily performed upon execution of each logging job on the test well.

c. Stimulation method most appropriate to the well shall be applied, e.g., in the case of a well with low permeability, enhancement of permeability shall be made by swabbing or air lift.

4. Judging from the high geothermal potential and stringent conditions of the area from an energy view-point, the establishment of a development organization, including mining companies, are required to implement an effective additonal survey.

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