ARGENTINE REPUBLIC
FINAL REPORT ON THE NORTHERN NEUQUEN GEOTHERMAL DEVELOPMENT PROJECT

THIRD PHASE SURVEY

NOVEMBER 1984

JAPAN INTERNATIONAL COOPERATION AGENCY

PREFACE

It is great pleasure that I present this report entitled the "Pre-Feasibility Study for the Northern Neuquén Geothermal Development Project" to the Government of the Argentine Republic.

This report embodies the result of field surveys which were carried out in the Northern Neuquén Province, in three stages during February 1982 to March 1984, by the Japanese survey team commissioned by the Japan International Cooperation Agency following the request of the Government of the Argentine Republic.

The survey team, headed by Mr. Kaneo Kakegawa, had a series of close discussions with the officials concerned of the Government of the Argentine Republic and the staffs of organizations, and conducted a wide scope of field surveys and data analyses.

I sincerely hope that this report will be usefull as a basic reference for development of geothermal resources in the country.

I am particularly pleased to express my appreciation to the officials concerned of the Government of the Argentine Republic and the staffs of organizations for their close cooperation extended to the Japanese team.

November, 1984

Keisuke Arita

Keisuke Arita
President
Japan International Cooperation Agency

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Conclusions

The stepwise investigations have been carried out on this survey, from the regional investigation to the detailed investigation, in order to determine and select the most promising area for the future geothermal development and surveys. All possible areas in the northern region (of the Province of Neuquén, the Argentine Republic) were investigated for which the possibility in existence of geothermal resources had been anticipated. Various methods were used throughout the first phase to the third phase of surveys.

As a result, the geological structure, fracture systems, the distribution and the nature of geothermal manifestations, the quality and a temperature of expected geothermal fluid, the structure of geothermal reservoir, etc. in the region were clarified, and the most promising areas were selected.

In a broader sense of a geographical area, the region is located at the external edge of the east side of the Andes, in which an active diastrophism and valcanic activities from the time of the creation of the Andes to the Pleistocene in the Quaternary period were recognized.

Following the first and the second phases of the survey, selected is the most promising area in the vicinity of a triangle zone (temporarily named as the Domuyo Triangle Zone) between the A° Manchana Covunco and the A° Covunco at the west of Co. Domo in the Domuyo district.

Fumaroles of particularly hot and intensively hot springs are distributed in this area with the highest concentration within the region concerned. Abnormalities in ground temperature and in geochemistry were clearly recognized, and the structure of the basements, the structure of fractures, etc. were clearly determined according to analytical results of gravimetric prospecting. It was also found that the distribution of the dominant geothermal manifestations was restricted by those structures.

The geothermal fluid expected to exist is either of a water-vapor-mixed type or of a vapor-dominated type in common saline springs of 200°C or higher, according to the geochemical thermometers.

On the other hand, the hydrological study indicates that this region is located within the river systems of A° Manchana Covunco and A° Covunco, originated from cryocrowns and glaciers in the Vn. Domuyo mountains rising high behind the eastern region. A stable water supply is, therefore, maintained throughout a year, blessed with excellent water balance as a geothermal fluid source.

As the results of the third phase survey, more details and interesting results were found on the geology and the structure of reservoir, etc. within the Domuyo Triangle Zone, and the 2 areas of Ⓐ and Ⓑ were selected as the most promising areas to be investigated in a coming development survey.

The depths of the geothermal structural basements exceed 800 m in both the areas, and a crushed or collapsed structure is assumed to exist within these areas. The development of the structure to the depths as the reservoir or the passage of geothermal fluid, can be expected in these areas. The areas are adjacent to the geothermal manifestations which accompany a dominant blowout of water·vapor-mixed type. The similarity and relation to the manifestations in the structure can be assumed in the areas.

Area Ⓐ

The Area Ⓐ is situated at the north of Los Tachos geothermal manifestation and has dimensions of 2.5 Km north-south in length and 1.0 Km in the east-west direction, covering a space of 2.5 Km^2. Andesitic to dacitic tuffs of the upper Mesozoic to the Tertiary are expected to be a reservoir, being low to medium in density and moderate to high in porosity.

The geophysical prospectings have indicated a structure in which a large collapse of the basements and an overlying succession of beds is supposed. The concentration and development of faults and crushed zones are expected and these phenomena will provide a potential for a reservoir structure which may extend not only in lateral directions but also to the depth.

Area Ⓑ

The Area Ⓑ is located at the south of El Humazo geothermal manifestation, being 1.2 Km in north-south and 0.5 Km from east to west, covering an area of 0.6 Km^2. Expected is an existence of rocks which are high in density and low in effective porosity. The geothermal manifestation at El Humazo and the analytical results of various geophysical prospectings indicate that a reservoir structure in the Area is formed of an intensive collapse in local, faults and crushed zones in the basements or overlying formations of the lower Mesozoic. The structure is expected to extend to the depths.

As a target of the next stage of geothermal exploration to be carried out in the future, the best priority is given to the Area Ⓐ from view point of physical properties in rocks, tectonic characteristics in the structure and a scale of the target.

Recommendations

The surveys, stipulated in and agreed upon the S/W signed between the Government of Japan and the Government of Argentine will be completed by the submission of this report.

Extremely interesting findings were obtained on the existence of geothermal resources, and the promising potentials are pointed out from the results of investigations and analyses which were carried out during a period from the first to the third phases. The Area Ⓐ in the Domuyo Triangle Zone is selected as the target of the top priority for development surveys to be done in the future.

Generally speaking, an exploration and exploitation of geothermal resources are accompanied by high risks in technology and economy, and it is preferable to proceed as stepwise as possible for the development of geothermal resources, considering technical environments and experiences in Argentine.

From this point of view, the completion of the present surveys means a progress in the first half of basic study -- i.e., a step of surface investigation of so-called potential evaluation, has been completed. Steps that should be taken in future will be as follows. With emphasis placed on the excavation of investigation wells, in order to verify findings obtained by the surface investigations, various related surveys should be done to delineate the structure, the scale and the production capacity of the reservoir to evaluate regional potentials. At the same time, socioeconomical effectiveness and influences on the development of the geothermal resources in adjacent areas should also be investigated, so that conclusions on the potential evaluation may be drawn through the overall analysis. A decision for and against the next step and a selection of measures to be taken will be based on these valuations.

Recommendations are made in regard to surveys and investigations required in future, based on conditions mentioned so far.

1. Drilling of an investigation hole of a 400 m for measurements of temperature and heat flow

The hole was scheduled to be drilled in the third phase surveys, but the drilling operation was interrupted due to seasonal and weather conditions. The drilled of a 400 m class investigation hole in the Area Ⓐ should be resumed, and planned temperature measurements should be carried out. More detailed data with the geothermal gradient should be obtained, in order to predict the depth of the reservoir with a higher accuracy.

2. Drilling of an investigation well of a 1,500 m-class

A well of a 1,500 m-class should be sunk in the Area Ⓐ in order to delineate a geothermal reservoir. Since the depth to the layers of a high temperature or to the reservoir has been assumed to be relatively shallow, it will be necessary to take sufficient preventive measures, depending on the results obtainable in the hole of a 400 m-class, such as the installation of a prevender, etc. against potential hazards upon drilling.

Planned contents of the investigation well are as follows:

Number of well: 1
Inclination: vertical
Well diameter at the bottom: HQ (97.5 m/m)
Core: all cores should be, as a rule, recovered
Completing the well: the well should be completed by means of casing and cementation, including the installation of strainers at necessary positions.

3. Research of rock properties

Cores obtained by drilling of the investigation wells should be subject to measurements of the density, effective porosity, magnetic susceptibility, resistivity, thermal conductivity, elastic wave velocity, etc. The X-ray analyses and microscopic observations should be done of altered minerals, in order to obtain basic data for various loggings of investigation wells, and for the evaluation of the reservoir.

4. Temperature and electric loggings of an investigation well

Temperature and electric loggings should be done in the investigation well, in order to estimate the vertical dimension and physical conditions of the reservoir, and to provide data for re-analysis, together with findings already obtained.

5. Geothermal fluid blowout test

Static and dynamic tests should be carried out of the blowout of the geothermal fluid, in order to determine and analyze blowout characteristic of the investigation well, and to verify the production capacity of the geothermal reservoir.

6. Overall re-analysis

Findings of the foregoing and data already obtained through previous surveys should be re-analyzed comprehensively, not only for the verification and evaluation of the target concerned, but also to increase the accuracy on the estimation of the structure of the geothermal reservoir of the entire region.

7. Economic and social feasibility study (Pre-feasibility study)

Stepwise surveys described in 1 through 6 above should be implemented, in order to verify the structure and the production capacity of the geothermal reservoir in the area. After the delineation of the overall and general geothermal potentials, pre-feasibility study should be made on socioeconomic effectiveness and influences of the development of expected geothermal resources on the northern region of Neuquén, which is one of the least developed and depopulated areas in Argentine. Overall evaluations should be done by putting all data together, and the course of direction and the steps to be taken at the next phase of development should be studied.

1. General Remarks

1. General Remarks

1.1 Purposes and Methods of the Survey

This survey was started in accordance with the S/W (Scope of Work) signed on the day of February 25th, 1982, based on the agreement between the Japanese Government and the Government of the Argentine Republic. The aforementioned S/W was signed by the duly authorized persons of the following organizations related to the matter.

From the Japanese side:

- Japan International Cooperation Agency (JICA)

From the Argentine side:

- Planning Coordination Undersecretariat, Planning Secretariat of the President of the Nation'
- Subsecretariat of Fuels Resources of the State Energy Secretariat
- Secretariat del COPADE, the Government of the Neuquén's Province

The survey in question, concerned with geothermal energy resources and covering an area of 15,000 Km^2 in the northern part of the Province of Neuquén, Argentine, was carried out in three distinct phases ranging from the regional survey to the detailed survey by using various methods of investigation, has two principal purposes, i.e., to make the final selection of the most promising area containing a geothermal reservoir structure, with elucidation, comprehension and evaluation of the structure of the said layer, and to propose an appropriate course and a plan about the investigations to be carried out in the future, including considerations on drilling of investigation wells and other details regarded to be necessary.

The surveyed areas, the flow chart of the three-phase survey and the stages of execution of work are shown in the Fig. 1-1, Table 1-1 and Table 1-2.

1.2 Outline of the First Phase Survey (First Year)

The first phase survey (first year) was carried out in February and March of 1982. The target of the promising area for geothermal development was narrowed down to 200 Km^2, as a result of the interpretations of satellite (LANDSAT) images covering 15,000 Km^2 and aerial photographs covering 5,000 Km^2, being in the northern part of the Province of Neuquén. That promising area was selected as a target of the second phase survey (second year).

1.3 Outline of the Second Phase Survey (Second Year)

The second phase survey was commenced with the topographical mapping of the survey area (200 Km^2) prior to the execution of the field survey. Later on, the field survey consisting of a geological survey, a petrographical work and a rock sample test, a gravity survey, an alteration zone survey, an 1 m depth ground temperature survey, a geochemical survey, a hydrological survey, a survey of hot springs and fumarolic gas and vapour was carried out from November 1982 to March 1983. The geology, the geological structure, the heat flow structure, the geothermal fluid circulation mechanism and the geothermal reservoir structure are elucidated by making a comprehensive analysis of the aforementioned surveys. Extremely promising and interesting information was obtained as a result of the studies. Such being the case, the best priority was given to a promising area of 40 Km^2 to be investigaed in the third phase survey (third year) and the concrete measures for implementation of the survey are planned.

1.4 Outline of the Third Phase Survey (Third Year)

The field survey in the third phase was carried out from November 1983 to March 1984. The third phase survey consists of electrical prospecting, seismic prospecting, a heat flow survey utilizing 100 m-deep holes, an isotopic analysis of hot-spring waters, laboratory measurement of physical properties of rocks and an overall analysis which covers the results obtained through the first phase to the third phase surveys.

As the results of the studies, the geothermal system in the area was clarified, and the most promising areas were extracted. Recommendation was made in regard to surveys and investigations which might be required in the future.

1.5 Members and Progress of the Survey Team

The members of the Japanese survey team and Argentine counterparts and the survey progress are as follows.

(1) Survey team of the first phase

Japanese team			Argentine team		
Post	Name	Belong to	Post	Name	Belong to
Leader	Mr. Kaneo KAKEGAWA	JICA	Leader	Mr. Alfredo ESTEVES	Gov. of Neuquén Prov.
Geology	Mr. Fukio KAYUKAWA	"			
Remote sensing	Mr. Tokihiro TANI	"	Geochemistry	Mr. Jose L. SIERRA	"

Survey period (Period of stay in Argentine)

February 25th 1982 to March 31st 1982

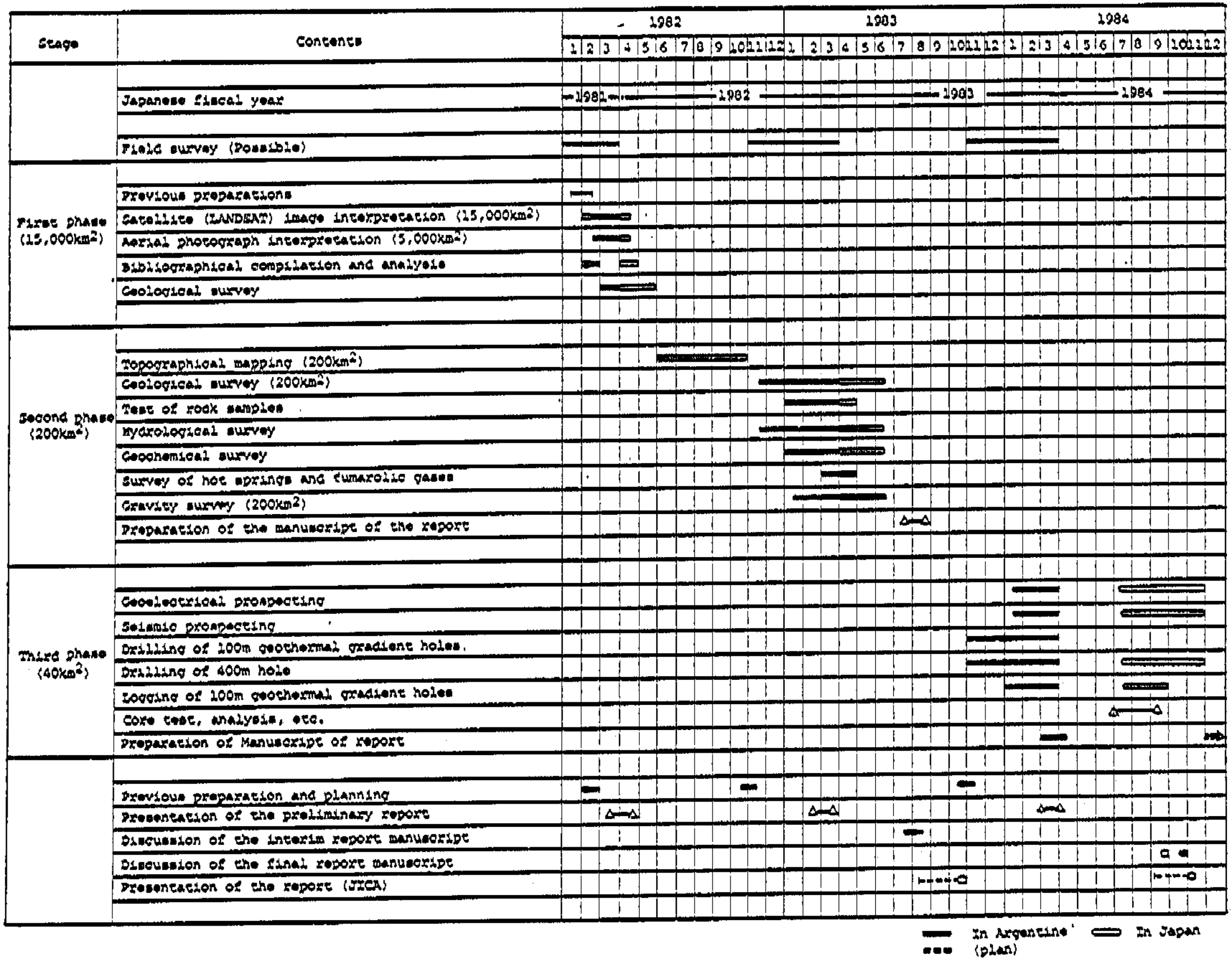
Field survey period

March 8th 1982 to March 20 1982

Table 1-1 Flow chart of the survey in three phases

Stage	Survey area	Methodology	Contents of survey	Expected data
First phase (First year)	(First part) 15,000 km^2	. Bibliographic compilation and analysis . Interpretation of satellite (LANDSAT) images	. Identifications of geology, structure, volcanoes, distribution of geothermal manifestations, fracture system, fault zones, drainage textures, grade of relative porosity, use of the land, characteristics of the geothermal manifestations, accessibility and topography.	. Background of the magmatic and geothermal activity. . Water balance, hot water storage structure, geothermal manifestations and volcanoes. . Determination of the most promising and adequate area for geothermal development. . Estimation of the geothermal system.
		⇓ Selection of 5,000 km^2		
	(Second part) 5,000 km^2	. Photogeological interpretation quick looking of 5,000 km^2 mapping of 1,200 km^2 . Reconnaissance geological survey (ground survey and investigation of geothermal manifestations)		
		⇓ Selection of 200 km^2		
Second phase (Second year)	200 km^2	. Topographical mapping . Geological survey . Petrographical work . Hydrological survey . Survey of alteration zones . Test of rock samples (density, porosity, magnetic susceptibility, Xray analysis, microscopic analysis, age dating) . Geochemical survey (temperature at 1 m depth, Hg in soil, CO_2 in soil air, hot spring, fumarolic gas) . Gravity survey	. Geological constitution, stratigraphy, geologic structure, fracture systems, surface discharges, runoff, estimation of the infiltration and its scheme, distribution, types and extension of the alteration zones. . Texture, composition, density, porosity, alteration, age, relation with temperature, Hg and CO_2. . Distribution of hot springs and fumaroles, tendency of distribution. . Flow, composition, temperature, pH and electrical conductivity of spring water. . Gravity, underground structure.	. Extension of the layers, stratigraphic relation, thickness, microscopic structures of the rocks. . Water balance, scheme of supply of water as geothermal conductor. . Geothermal and magmatic activity (heat source) in terms of absolute age, thermal history, geothermal system, magnitude and temperature of the reservoir, scheme of ascent of the hydrothermal fluids. . Structure of the deep underground. . Model of geothermal reservoir.
		⇓ Selection of 40 km^2		
Third stage (Third year)	40 km^2	. Geoelectrical prospecting (Schlumberger method) . Seismic prospecting (reflection method) . Geothermal gradient holes (100 m) . Geothermal gradient holes (400 m) . Core & cuttings survey . Isotopic investigation . Core test (density, porosity, magnetic susceptibility, electric resistivity, microscopy, thermal conductivity, elastic wave velocity)	. Electric resistivity, deep structure . Elastic wave velocity (P waves) . Geothermal gradient, temperature distribution, electrical resistivity. . Distribution and spacial variation of the rock density, porosity, resistivity, magnetic susceptibility, alteration, thermal conductivity and elastic wave velocity.	. Extension, depth and form of low electric resistivity zones, geothermal structure. . Underground structure, extension, depth and form of low-velocity layers, temperature of heat sources, estimation of heat dispersion, underground temperature distribution and gradient, geothermal system, variation of the rock texture. . Model of geothermal reservoir (from the geothermal reservoir engineering standpoint). . Estimation of origin of hot water. Evaluation of geothermal potential Proposition of the exploration well drilling program

Table 1-2 Progress of the survey in 3 phases



(2) Survey team of the second phase

Japanese team			Argentine team		
Post	Name	Belong to	Post	Name	Belong to
Leader	Mr. Kaneo KAKEGAWA	JICA	Leader	Mr. Alfredo ESTEVES	Gov. of Neuquén Prov.
Geology	Mr. Fukio KAYUKAWA	"	Geochemistry	Mr. Jose L. SIERRA	"
Geology	Mr. Osamu MIYAISHI	"	Geology	Mr. Mario O. GINGINS	"
Geochemistry	Mr. Hisanao KOIZUMI	"	Geology	Mr. Luis C. MAS	"
Geochemistry	Mr. Kazuyasu SUGAWARA	"	Geochemistry	Miss Miriam LOEWY	"
Geophysics	Mr. Kenichi NOMURA	"	Topography	Mr. Juan de D. ALBORNOZ	"
Geophysics	Mr. Shigeo MORIBAYASHI	"	Topography	Mr. Carlos R. FERNANDEZ	"
Geophysics	Mr. Ikuo TAKAHASHI	"			

Survey period (Period of stay in Argentine)
November 15th 1982 to March 31st 1983
Field survey period
December 9th 1982 to February 28th 1983
Period of analysis and interpretation
April 1st 1983 to August 10th 1983

(3) Survey team of the third phase

Japanese Team			Argentine team		
Post	Name	Belong to	Post	Name	Belong to
Leader	Mr. Kaneo KAKEGAWA	JICA	Leader	Mr. Alfredo H. ESTEVES	Gov. of Neuquén Prov.
Geophysics	Mr. Harunobu SUMIDA	"	Geochemistry	Mr. Jose L. SIERRA	"
Drilling	Mr. Yutaka SHIRAISHI	"	Geology	Mr. Mario O. GINGINS	"
Geology	Mr. Susumu HIDAKA	"	Geology	Mr. Luis C. MAS	"
Geophysics	Mr. Tomoyoshi TANAKA	"	Geochemistry	Mr. R. Miriam LOEWY	"
Geophysics	Mr. Masasamu OYANAGI	"	Geophysics	Mr. Delio G. LANCHAS	"
Geophysics	Mr. Toshiaki FUJIMOTO	"	Geochemistry	Mr. Jose A. DATES	"
Geophysics	Mr. Shinichi SUGIYAMA	"	Drilling	Mr. Antonio SANCHES	"
			Topography	Mr. Carlos R.FERNANDEZ	"
			Topography	Mr. Juan de D. ALBORNOZ	"

Survey period (Period of stay in Argentine)

November 8th 1983 to March 27th 1984

Field survey period

November 20th 1983 to March 15th 1984

Period of analysis and interpretation

July 9th 1984 to November 30th 1984

1.6 Implementation of the Survey

The survey work carried out so far in the first phase, in the second phase and in the third phase are summarized in the Table 1-3.

Table 1-3 Specific survey work carried out by the survey team

Phase	Contents			Volume of work
First Phase	Interpretation of LANDSAT images (1:250,000 scale)			15,000 Km^2 (3 images)
	Interpretation of aerial photographs (1:50,000 scale)			1,200 Km^2 (150 sheets)
	Reconnaissance geological survey	Explored distance of regional survey		500 Km
		Explored distance in Domuyo area		150 Km
Second Phase	Preparation of topographic map (1:25,000 scale)			200 Km^2
	Geological survey	Surveyed area		200 Km^2
		Explored distance		315 Km
		Quantity of specimens	Thin section	110
			X-ray analysis	130
			Age dating	8
			Physical properties	60
		Measurement of discharges		28 points
	Geochemical prospecting	Temperature at 1 m depth, Hg concentration in soil, CO_2 concentration in Soil-air	Regional survey	460
			Detailed survey	57
			Total	517
		Hot spring samples		18
		Gas samples		9
		Condensed water sample		9
	Gravity prospecting	Leveling	By autolevel	85 points
			By theodolite	137 points
			By altimeter	94 points
			Total	316 points
		Gravity measurement		316 points
		Regional survey	Measuring points	31 points
			Surveyed distance	1,050 Km
Third Phase	Construction of road		Length	32.5 Km
			Drilling platform	14 sites
	Point setting		By theodolite	23 points
	Leveling		Surveyed distance	28.3 km
			Measured points	2,830 points
	Drilling of a 100 m hole		Number of holes	12 holes
			Total drilled length	1,162.5 m
	Drilling of a 400 m hole		Number of hole	1 hole
			Drilled depth	*80.0 m
	Temperature logging			12 holes
	Electrical prospecting		Measuring points	50 points (5 lines)
			Total length surveyed	26.5 Km
	Seismic prospecting		Measuring points	1,000 points (5 lines)
			Total length surveyed	22.0 Km
	Isotopic investigation			8 samples

* Planning to start re-opening at December, 1984

2. Outline of the Fifst Phase Survey

2. Outline of the First Phase Survey

2.1 Contents of the First Phase Regional Survey

The first phase regional survey corresponds to the first step of the three-year program for geothermal energy development surveys in the Province of Neuquén, Argentine Republic.

Aiming to extract and select a promising area of about 200 Km^2 for the second phase survey, the following surveys were done in a preliminary investigation area covering approximately 15,000 Km^2 in the northern part of the Province.

(1) Analysis of Landsat image

Analyses of three scenes of Landsat image (Path 248 · Row 86, Path 249 · Row 86 and Path 249 · Row 85), covering the whole area of about 15,000 Km^2, were conducted in Japan before field surveys.

The analytical method for three scenes of false color composite image in a scale of 1:250,000 is photogeologically to make out distributions and relations of geological units, such as basement rocks of Paleozoic and Mesozoic formations, Tertiary formation and younger volcanic rocks of Quaternary age. Keeping place with these analyses, principal tectonic lines were studied geologically.

By collation these results with available geological data, outlines of regional geology and geologic structure were compiled (Fig. 2-1).

(2) Photo-geological interpretation

Photo-geological interpretations for the area of 5,000 Km^2, which had been selected by studies of the analysis of Landsat image as well as regional geological map (Fig. 2-2), were done through the period of field surveys. The aerial photographs in a scale of 1:50,000 were available in Argentine, and their composite photographs were used for this study.

Because the subject area of photogeological interpretation covers a wide area, a method of "Quick looking" by observations of composite and/or unit aerial photographs were employed for the greater part of the whole area except areas considered to be promising. These studies resulted in the assistance of analyses of Landsat image.

For the promising areas, drawings of detailed drainage map and detailed geological interpretations were conducted by a three-dimentional observation of aerial photographs.

As a result of these studies combined with results of a reconnaissance geological survey, geology and the geologic structure as well as geothermal manifestations in the area for the second phase survey were clarified. The area includes western parts of the Domuyo Volcano and those surrounding areas (Fig. 2-3).

(3) Reconnaissance geological survey

Based on analyses of Landsat image and photogeological interpretations combined with studies of available geological data, following three routes of reconnaissance geological survey were selected, where younger volcanos such as Domuyo Volcano, Mt. Cruzada, Tromen Valcano and Mt. Carrere are located in the Cordillera del Vient, and geothermal manifestations related to younger volcanos are known. (Fig. 2-4).

1) Route along the Neuquén and Varvarco Rivers from Chos Malal through Andacallo, Las Ovejas and Varvarco to geothermal manifestation areas located at western parts of Domuyo Volcano.

2) Route from Chos Malal through Chapua to Tromen Volcano.

3) Route from Chos Malal through Chacayco and Auquinco to El Tril located north of Mt. Carreere.

2.2 Regional Geology and Geologic Structure

2.2.1 Outline of Geology

(1) Stratigraphic sequence

Basement rocks in the region consist of sedimentary rocks and volcanic – pyroclastic rocks, which have been placed in the Permian and/or Triassic Time, and of plutonic rocks intruded into older formations.

Mesozoic formations, mainly consisting of sedimentary and pyroclastic rocks unconformably overlie the basement rocks.

Andestic volcanic activity occurred in the Tertiary age, and followed by related plutonic activity. At the end of the Tertiary age, acidic volcanic activity consisting of lava flows and pyroclastic rocks took place covering the basement rocks of Paleozoic and/or Mesozoic formations, and large-scale intrusive bodies of quartz porphyry and others were formed in the area centering around Domuyo Volcano. These rocks of acidic activity, in the lump, are called the Domuyo Volcano Complex.

At Quaternary time, younger volcanism of intermediate to acidic took place in this region and yielded lava flows of basaltic andesite, andesite, dacite and rhyolite.

(2) Basement rocks and Mesozoic formation

Choiyoi Group of the basement, considering to be Permo-Triassic System, is represented by well stratified mudstone interbedded with sandstone and limestone occasionally with intercolations of basalt or propylite lavas, along areas of the routes from Chos Malal, to Varvarco, Tromen Volcano and El Tril.

Along the route from Varvarco to Domuyo, rhyolitic lava flows and their pyroclastic rocks dominate the Group and are intruded by diorite, granodiorite and fine-grained granite.

Mesozoic formations are divided into Chacay Melehue Formation, Auquilco Formation, Tordillo Formation and Mendoza Group in ascending order. Chacay Melehue Formation unconformably covers Choiyoi Group. It is composed of breccias constituting by dominant rhyolitic fragments and sandy or tuffaceous matrix in the lower part, and of white-grey sandstone, black mudstone and dark colored marl in the upper part. Auquilco Formation conformably overlies Chacay Melehue Formation, and consists of beds of limestone, sandstone and evaporite gypsum from lower to upper parts. Tordillo Formation succeeds Auquilco Formation and mainly consists of sandstone, which increases limonite in proportion to the upper part. Mudstone is predominant in the Mendoza Group.

(3) Tertiary formations and Domuyo Volcano Complex

Tertiary formations are divided into following three units. Namely, Pelan Formation is composed of andesite, andesite-porphyry, diorite-porphyry and fine-grained quartz diorite. Charilehue Formation consists of lava flows of andesite or basaltic andesite together with their pyroclastic rocks. Palao Granite is a stock-type intrusive body into Mendoza Group and forms Mt. Palao. Each Tertiary formations are believed to be Miocene in age.

Domuyo Valcano Complex can be divided into effusive facies and intrusive facies. The former consists of alternating beds of rhyolitic tuff, lapilli tuff and tuff breccia, and of lave flows of rhyolite and dacite. It distributes at the western slope of Domuyo Volcano. The later forms stocks-shaped intrusive bodies centering around Domuyo Volcano and crops out in an area of approximately 24 Km^2. The lithology of the intrusive facies ranges from rhyolite-porphyry to granodiorite-porphyry, and shows felsitic lithology in case of dikes.

The activity of Domuyo Volcano Complex is considered to range from middle Miocene to early Pliocene in age.

(4) Volcanic rocks of late Tertiary to Quaternary

A sequence of volcanism took place in the region, and forms formations of lava flow and pyroclastic rock of basaltic andesite, andesite and decite. They are divided into Sierra de Flores Formation, Atreuco Formation, Ponchehue Formation and Celletas Formation. The latest volcanism in the region is Domo Volcanic Rocks distributed at the southwestern slope of Mt. Domuyo. They are composed of rhyolitic lava flows and pyroclastic rocks, and an absolute age of 0.72 ± 0.10 Ma is obtained from one of lava flows at the rather early stage which form Mt. Domo.

2.2.2 Outline of Geologic Structure

Regional geologic structure, as shown in Fig. 2-2, is characterized by the fold structure trending in approximately N-S direction and plunging toward the north. As is mentioned in the later chapter, the areas of high gravity anomaly are entirely identical with those of anticlinal structure where basement rocks and Mesozoic formation are distributed. On the other hand, the areas of low gravity anomaly completely correspond to those of synclinal structure where cenozoic volcanic rocks are dominant. In addition, values of Bouguer anomaly have a tendency to decrease toward the north. This proves fold axes plunging toward north, structurely.

In the area of Domuyo Volcano, box-shaped dome structure has been formed centering around Domuyo anticlinal axis of N-S direction. This dome-shaped upheaval block is composed of Choiyoi Group of basement, Chacay Melehue Formation, Auquilco Formation, Tordillo Formation and Mendoza Group of Mesozoic succeeding from center to outside. At the core of dome structure, intrusive rocks of Domuyo Volcano Complex are widely distributed.

Fault systems of N-S direction parallel to above-mentioned fold axes and of E-W direction are predominant in the region, accompanying with fault systems of NW-SE or WNW-ESE direction and of NE-SW or ENE-WSW direction.

As shown in Fig. 2-3, they can be made out as lineaments having various characteristics of strength and length by photogeological interpretations.

2.3 Regional Geothermal System

2.3.1 Outlines of Younger Volcano and Geothermal Manifestation

(1) Distributions of younger volcanos.

Younger volcanos such as Domuyo Volcano, Mt. La Cruzada, Tromen Volcano and Mt. Carrere are arranged in NW-SE direction in the mountain system of Cordillera del Viento. This volcanic activity was vigorous from latest Tertiary time through Quaternary in age, and erupted on the basement rocks of Paleozoic or Mesozoic formation. It is assumed that the volcanism was large-scale near areas of Domuyo Volcano in the northwestern part and it decreased near areas of Mt. Carrere in proportion to the southeastern part.

Outlines of volcanic activity of Domuyo Volcano were described before in connection with regional geology and geologic structure. In the area of Tromen Volcano, there are old and new volcanos. They hold their original shapes of volcano, and there is a dammed lake between two volcanos which was formed by basaltic lava flows. Volcanism of Tromen Volcano is supposed to be active up-to recent, however, volcano located at north of Tromen Volcano seems to be a little old.

Because volcanism formed Mt. Carrere is not to be large-scale, distributions of younger volcanic rock are limited.

(2) Distributions of geothermal manifestation

1) Domuyo Volcano and environs

Hot springs of El Turleio are 14 Km north of Domuyo Volcano, spring out from four points in flood plain of rivers which are located at western rims of distribution areas of Mendoza Group.

In the western and southwestern areas of Domuyo Volcano, there are the most predominant geothermal manifestations of hot springs and fumarolic gases. Namely, they are Rincon de Las Papas, El Humazo, Las Olletas, La Bramadora, Arroyo Aguas Calientes, Baños del Agua Caliente and Los Tachos. All of them, except La Bramadora, spring out hot water and spout fumarolic gas from the uppermost part of beds of tuff breccia and overlying lava flows covering Mesozoic formations and/or basement rocks. At La Bramadora, fumarolic gas spouts through fissures near boundary between intrusive rocks distributed near Domuyo

Volcano and younger volcanic rocks.

Depositions of travertine and hydrothermal alteration zones can also be observed at areas of these geothermal manifestations.

2) Tromen Volcano and environs

In the areas of Tromen Volcano and another volcano located at north, no geothermal manifestation of hot spring or fumaloic gas is known. Although some underground water spring out, its temperature is as low as 8.5°C. Besides, there are only alteration zones without hot spring or fumaloic gas southwest of Tromen Volcano.

3) Northern area of Mt. Carrere

Agua Termal is known as a geothermal manifestation, where some underground water contained hydrogen sulphide spring out through fissures in mudstone of Paleozoic or Mesozoic formation. However, its temperature is as low as 20°C.

2.3.2 Preliminary Model of Geothermal System

Preliminary model of geothermal system in the western areas of Domuyo Volcano, where the most predominant geothermal manifestations of hot spring and fumaloic gas are distributed, is shown in Fig. 2-5. The model is composed by stratigraphic sequence, geologic structure, heat flow structure and circulation mechanism of goethermal fluid which are based on results of the first phase survey such as those of analyses of Landsat image, photogeological interpretations and reconnaissance geological survey together with studies of available data.

(1) Stratigraphically, the region is occupied by basement rocks of Paleozoic formation and intrusive bodies of granite, unconformably overlying Mesozoic formations, and Tertiary to Quaternary volcanic and pyroclastic rocks of various type. In the vicinity of Domuyo Volcano, younger volcanos of Quaternary age are located.

(2) Strong geothermal manifestation consisting of hot springs, fumaroles, travertines and hydrothermal alteration zones are widely distributed in the place of western part of Domuyo Volcano. It is assumed that a magma reservoir is latent at the depths of the region and is active as a heat source.

(3) Each of the rivers rising from Domuyo Volcano have running water through the whole year which is originated by glacier and eternal snow. There are necessary conditions that surface water permeates into subsurface and forms shallow and deep underground water, and that underground water becomes the source of hot spring water and deep geothermal hot water.

(4) Volcanic and pyroclastic rocks of Neogene Tertiary or Quaternary age range from

compact lava flows to porous rocks like pumice-tuff. The parts of high permeability, caused to well developed fractures and/or porosity-rich beds, present places to form shallow hot water secondarily. However, it is supposed that younger volcanic formations may generally play important cap rocks for deep geothermal fluid reservoir.

(5) Younger volcanic formations have a remarkable unconformable relationship with underlying basement rocks or Mesozoic formations, and the basement is generally situated at the rather shallow depths. Underground water permeated into deep subsurface is heated by heat source and is result becomes deep geothermal hot water having its temperature of 200°C, to 250°C. The deep geothermal hot water forms deep geothermal fluid reservoir along and/or in fracture systems of faults and sheared zone developed in the basement rocks. Geothermal fluid consisting of deep geothermal hot water, steam and gas ascends through fracture systems from deep geothermal fluid reservoir. Then, it mixes with shallow ground water and makes a secondary shallow hot water reservoir having its temperature of 100°C or more along unconformable planes or among permeable strata. Furthermore, hot water, steam and gas ascend and finally reach the surface as geothernal outcrops of hot water and fumaloic gas.

2.4 Extraction of Target Area for the Second Phase Survey Based on the Results of the First Phase Survey

Based on the results of the first phase survey, the most promising area of approximately 200 Km² ranging 20 Km at E-W and 10 Km at N-S was selected among the whole object area for the second phase survey. This area covers drainage systems of Manchana Covunco, Aguas Calientes and Covunco Rivers between western part of Domuyo Volcano and eastern side of Varvarco River,and entierly includes many predominant geothermal manifestations such as Rincon de Las Papas, El Humazo, Las Olletas, La Bramadora, Arroyo Aguas Calientes, Baños del Agua Caliente and Los Tachos.

3. Outline of the Second Phase Survey

3. Outline of the Second Phase Survey

3.1 Preparation of Topographic Map

Topographic maps in scale of 1:100,000 and 1:500,000 of the region including the investigation area are available.

However, more detailed topographic maps which cover the whole object area are necessary, in order to conduct geological survey, geochemical and gravity prospectings and others of the second phase survey. For this purpose, topographic map in a scale of 1:25,000 was prepared by using aerial photographs before field surveys.

The photographs used were offered by the Argentine Republic. They had been taken by Dirección General de Fabricaciones Militales in 1962 and 1963 for the Plan Cordillerano. Conditions of photographing are as follows;

Camera used : WILD RC8 (focal distance 152.4 mm)
Flight hight : 8,534 to 10,668 m
Scale of photographing : approximately 1:50,000
List of aerial photographs : shown in Table 3-1

Table 3-1 List of aerial photographs

Course No.	Photograph Number	No. of sheets
C-6	3,120 ~ 3,124	5
C-7	2,041 ~ 2,048	8
C-8B	3,208 ~ 3,212	5
C-8	2,159 ~ 2,163	5
C-9	2,263 ~ 2,265	3

Fundamental topographic maps prepared are of a scale of 1:25,000, and enlarged maps in a scale of 1:10,000 and reduced maps in a scale of 50,000 are used for field surveys and for attached maps of this report, respectively. Fig. 3-1-1 shows a bird's-eye view map based on the topographic map.

3.2 Geology in the Investigation Area

3.2.1 Geology

Geology of the investigation area is divided into four units. Namely, the basement consists of metamorphic rocks such as crystalline schist and hornfels belonging to Choiyoi Group of Pesmo-Triassic age and of granodiorite of Varvarco Plutonic Rocks. Mesozoic formations of Jurassic age, Chacay Melehue Formation, Auquilco Formation and Tordillo Formation in ascending order, unconformably overlie on the basement. Tertiary formations of Miocene to Pliocene age follows unconformably, and granodiorite-porphyry concidered to be a member of intrusive facies of Domuyo Volcanic Complex is locally distributed at southeastern parts of the area. Younger volcanic rocks, occured during periods from end of Tertiary to Quaternary time, are composed of lava flows of andesite, dacite and rhyolite erupted from earlier to later stage, and are accompanied with their pyroclasitic rocks (Figs. 3-2-1, 3-2-2 and 3-2-3).

3.2.2 Determination of Absolute Age

Absolute ages of younger volcanic rocks determined by fission-track method range from 0.55 ± 0.10 Ma to 0.11 + 0.02 Ma. These ages together with 0.72 ± 0.10 Ma of previous data indicate that Quaternary Volcanism took place during periods from early to late Pleistocene time. Absolute ages of granodiorite of the basement determined by fission-track method are doubtful because of their younger ages than geological age of unconformably overlying Mesozoic formations indicated by ammonite fossils. However, as a result of datings by K-Ar method, absolute ages of granodiorite are determined as 227 ± 16 Ma and 259 ± 13 Ma. These ages are of late Permian and end of middle Triassic time, and support stratigraphic sequences in the investigation area.

3.2.3 Petrographic Characteristics of Holycrystalline Rocks

Holocrystalline rocks in the area are composed of granodiorite of Varvarco Plutonic Rocks of the basement, and of granodiorite-porphyry to be considered a member of intrusive facies of Domuyo Volcano Complex. As a result of measurements of Q-Kf-Pl mode, as compared with all of the former show rather homogeneous lithofacies of granodiorite, the later has some deversities of their lithofacies ranging from granodiorite to quartz monzosyenite and quartz diorite (Fig. 3-2-4).

3.2.4 Petrographic Characteristics of Younger Volcanic Rocks

Based on a chemical analysis of younger volcanic rocks, it is revealed that Quaternary volcanism taken place during periods from early to late Pleistcene age is characterized by a sequence of magmatism of calc-alkaline series ranging from intermediate to acidic composition.

3.2.5 Physical Properties of Constituent Rocks

Regarding physical properties of constituent rocks in the investigation area, the following results are obtained.

Density changes regularly from high to low in portion of the basement at bottom of sequence to younger volcanic rocks at top of sequence, and the lowest density is of pyroclastic rocks such as scoria tuff and pumice tuff. Effective porosity has good negative correlation with density. And its values show low percentage in basement rocks and Mesozoic formations, and high percentage in Quaternary pyroclastic rocks. Values of susceptibility are high in andesites and their pyroclastic rocks among Tertiary and Quaternary volcanic rocks, and generally correspond to lithofacies. As compared with FE values shown those of usual rocks, values of resistivity are relatively high which the highest value is of basement rocks followed in order of values by volcanic rocks, sedimentary rocks and tuffs. Values of thermal conductivity are higher in rocks of lower sequence and become lower in portion of in rocks of upper sequence, and fairly higher values than common cases are obtained from lower half of Mesozoic formations and basement rocks (Fig. 3-2-5).

3.3 Geologic Structure in the Investigation Area

3.3.1 Geologic Structure Based on Geological Distribution

The investigation area is geotectonically divided into two areas. In western half, basement rocks consisting of metamorphic rocks and granodiorites exist at rather shallow parts from the surface, and younger volcanic rocks widely covers their flat paleotopographic surface. On the contrary, in eastern half, Mesozoic formations overlying on hidden basement rocks at depths are influenced by regional fold structure and local dome structure.

3.3.2 Subsurface Structure Based on Physical Properties of Constituent Rocks

Subsurface structure based on physical properties of constituent rocks forms two-layed structure. Namely, two-layered structure in western parts is composed of upper layer of younger volcanic rocks represented by low density and high effective porosity and of lower layer of basement rocks represented by high density and low effective porosity. On the other hand, two-layered structure in eastern parts is composed of upper layer of younger volcanic rocks and of lower layer of underlying Mesozoic formations represented by medium density and effective porosity, and basement rocks of high density and low effective porosity are latent at depths.

3.3.3 Subsurface Structure Based on Gravity Survey

(1) Regarding regional gravity distributions, high Bouguer anomalous area corresponds to distributions of pre-Tertiary formations and low Bouguer anomalous area corresponds to distributions of Cenozoic volcanic rocks. It is a clear tendency to decrease values of Bouguer anomaly toward north, and the trend shows good correspondence of direction of fold structure and fault system (Fig. 3-3-1).

(2) On the basis of distributions of Bouguer anomaly, the investigation area can be roughly divided into three districts; namely, A-district of high gravity area at west, C-district of low gravity area at east and B-district placed between A and C-district forming long and slender transition belt of N-S direction. Younger volcanic rocks of Quaternary age has no relevancy with general and regional gravity distributions, but only local relevancy is recognized between distribution of tuffs of low density and low gravity anomaly (Fig. 3-3-2, 3-3-3).

(3) A-district of high gravity area harmonizes with underground structure to exist basement rocks of high density at rather shallow subsurface. On the surface, Mesozoic formations

of intermediate gravity are widely distributed in B and C-districts, and no consistence is recognized between intermediate density and Bouguer anomaly in transition zone of B-district. However, in C-district at east which is bordered from B-district by gravimetric lineaments having remarkable gravity gradient and presuming as major fault zone, low gravity area of Bouguer anomaly cannot interpretate its characteristic without presuming considerably extensive rocks and/or strata of low gravity in underground (Fig. 3-3-4).

(4) Structure of gravity basement at west analized by two-dimensional method gives flat paleotopography of the basement and its depth of less than 700 m at the deepest part. On the other hand, depths of gravity basement at east suddenly increase and reach more than 6,000 m deep from the surface in case of calculations by a balance of densities of 0.2 g/cm^3 (Figs. 3-3-5, 3-3-6 and 3-3-7).

(5)- As one of the hypothesis for geological factor to form low gravity area at eastern parts of the investigation area, Mesozoic formations of very low density containing very much water in their fracture. However, no positive evidence is obtained geologically. Although it is proved enough at present, geologic structure at east of the area is presumed that low density bodies of acidic porphyry to be considered a member of intrusive facies of Domuyo Volcano Complex exist beneath Mesozoic formations with considerable scale both horizontally and vertically.

3.3.4 Investigation on Fracture System

Fracture systems in the region and the investigation area are represented by those of N-S and E-W direction. N-S system is large-scale and is recognized universally from older formations to younger volcanic rocks, and E-W system is rather weak and mainly observed in older formations. Fracture systems of NW-SE and NE-SW direction are characteristically recognized by faults, gravimetric lineaments and joints in granodiorite, and conjugate with large-scale fracture system of N-S direction.

3.4 Heat Flow Structure in the Investigation Area

3.4.1 Alteration Zone

Hydrothermal alteration zones and travertines are observed at areas of geothermal manifestation such as hot springs and fumaroles. Alteration zones are divided into 1) crystobalite zone, 2) holloysite zone, 3) kaoline zone and 4) montmorillonite zone. They generally show zoning of alteration having a tendency of kaoline zone in core, montmorillonite zone in middle and crystobalite in shell (Fig. 3-4-1).

3.4.2 Consideration on Hydrothermal and Solfataric Alterations as Geothermal Manifestations

Taking a general view of alteration zoning in the whole area, characteristics of geothermal system is summarized as follows; namely, alteration zones at La Bramadora, El

Humazo and Los Tachos in eastern parts of the area are characterized by kaoline alteration with alunite alteration under acidic condition of low to high temperature, which is originated from vapor dominated system or water•vapor-mixed system. On the contrary, alteration zones in western parts of the area are considered to be gradually changed into montmorillonite zone under intermediate to alkaline condition of low temperature togethor with overlapped crystobalite zone under acidic condition of low temperature, which is caused by water dominated system.

3.4.3 Distribution of Ground Temperature at 1 m Depth and Hg-CO_2 Concentration

As a result of ground temperature survey at 1 m depth, anomalous areas of residual ground temperature calculated by altitude correlation trend on a line of NE-SW direction connected with geothermal manifestation areas in central-western and central-eastern parts. However, no anomalous area is found in northern geothermal manifestation areas.

Anormalous areas of Hg-concentration in central-eastern parts show good correspondence with those of ground temperature trending in NE-SW direction, and only small-scale semi-anomalous areas exist in central-western parts.

Although anomalous areas of CO_2-concentration at El Humazo are identical with those of ground temperature and Hg-concentration trending in NE-SW direction areas. The most characteristical trend of CO_2-concentration anomalies is shown by two parallel arrangements in NW-SE direction elongating from northwest to southeast in the investigation area (Figs. 3-4-2, 3-4-3 and 3-4-4).

3.4.4 Considerations on Anomalous Areas of Ground Temperature and Geochemistry

Fracture systems and grades of geothermal activity in the area, based on anomalous areas of ground temperature and Hg-CO_2 geochemistry, are summarized as follows; namely, central-eastern parts are mainly characterized by anomalous areas of ground temperature and Hg-concentration accompanied with fracture systems in NE-SW direction, and grades of geothermal activity is higher than those in western parts. On the contrary, although anomalous areas of CO_2-concentration in western parts of the area which mainly prove fracture systems in NW-SE direction, grades of geothermal activity is rather low. In addition, there are fracture system of N-S and E-W direction indicated by Hg-CO_2 geochemical anomalies (Fig. 3-4-5).

3.4.5 Magma Reservoir as Heat Source

Heat source bringing present geothermal phenomena in the area is considered to be magma reservoir which is related to younger volcanism of Quaternary age including Domo Volcano taken place during periods from 700 to 100 thousands years ago. One of the centers of volcanism is inferred to exist at depths of La Bramadora area, and heat source expands widely in subsurface of the area.

3.5 Circulation Mechanism of Geothermal Fluid in the Investigation Area

3.5.1 Hydrological Survey

In the investigation area forming western slopes of Domuyo Volcano, there is running water in the rivers through the whole year which is supplied by melting snow. This river water penetrates into underground, and forms aquifers in strata or rocks having high effective porosity and/or high permeability. Although most of shallow underground water circulates in aquifers and flows out the surface, some of water reaches to more depths through fracture systems. Thus, shallow and deep underground water is very important to form hot water and deep geothermal hot water, and there is enough supplies in the area (Fig. 3-5-1).

3.5.2 Hot Water and Fumarolic Gas

Hot springs in the investigation area can be classified and divided into zonal distributions on the basis of chemical compositions of each hot water and relations with fumarolic gas as well as their geothermo-temperatures. They are summarized as follows;

i) Sulphate hot spirngs of La Bramadora located at central-eastern area are rich in Ca^{++} and SO_4^{--}, and are characterized by vapor-dominated type consisting mainly of volcanic hot springs having ratio of $SO_4^{--}/Cl^- > 1$ of fumarolic gas. And, they are considered to be high temperature qualitatively based on compositions of fumarolic gas.

ii) Common salt hot springs (a) of El Humazo and most of Los Tachos located at central area are rich in Na^+ and Cl^- with relatively rich in K^+ and poor in Ca^{++}, and are characterized by vapor·water-mixed type consisting mainly of hot springs and a large amount of fumarolic gas. And, they form a group of hot springs having the highest geothermo-temperatures ranging from 214° to 223°C.

iii) Common salt hot springs (b) of western most of Los Tachos, Las Olletas, Arroyo Aguas Calientes excluding AC-2 and Baños del Agua Caliente located at central-western area are also rich in Na^+ and Cl^- with relatively poor in K^+ and rich in Ca^{++}, and are characterized by water-dominated type consisting mainly of a large amount of hot springs without or with a very little fumarolic gas. And, their geothermo temperatures range from 160° to 188°C.

iv) Hot spring of AC-2 at Arroyo Aguas Calientes is so-called simple hot spring containing less soluble ions in it, and its geothermo-temperature shows 183°C. This has no different origin from its surrounding hot springs, but it is formed by mixture of a large amount of underground water.

v) Ca-Mg bicarbonate hot springs of Rincon de Las Papas and Arroyo Ailinco are rich in Ca^{++} and HCO_3^-, and poor in SO_4^{--}. And, their geothermo-temperatures are low as 135° to 174°C.

Fumarolic gas are observed in hot springs of vapor-dominated type at central-eastern area and of vapor·water-mixed type at central area. More than 99% of fumarolic gas is steam, and most of remainder is uncondensed CO_2 gas. Although it is impossible to search quantitative geothermo-temperatures of fumarolic gas based on its concentration and ratio of constituent gas, qualitatively they are not inconsistent with classification and zoning of hot springs.

3.5.3 Relation between Circulation Mechanism of Hot Water-Fumarolic Gas and Heat Flow Structure

(1) Mutual relations between geothermal manifestation and hydrothermal alteration zones are summarized as follows; Namely, alteration zones indicating acidic condition of intermediate to high temperature well correspond to hot springs and fumaroles of vapor-dominated type at La Bramadora area, those indicating acidic condition of low to intermediate temperature well correspond to hot springs and fumaroles of vapor·water-dominated type at El Humazo and Los Tachos area, and those indicating intermediate to alkaline condition of low temperature overlapped by alterations under acidic condition of low temperature well correspond to hot springs of water-dominated type at Las Olletas, Arroyo Aguas Calientes and Baños del Aguas Calientes at central-western area. In addition, alteration zones including opal indicating very low temperature are recognized at western most area of Arroyo Ailinco, and low geothermo-temperatures well correspond to temperatures of hot springs in this area.

(2) It is clear that there are three-dimensionally inseparable relations each other between magma reservoir as heat source at depth and anomalous areas of ground temperature and of Hg-CO_2 geochemistry, and geothermal manifestations of hot spring and fumarole (Fig. 3-5-2).

3.6 Model of Geothermal System

3.6.1 Model of Geologic Structure

Synthetic interpretation map of geologic structure shown in Fig. 3-6-1 is composite map made summarizing by the following geological and structural factors. Namely, they are 1) distributions of older formations such as basement rocks and Mesozoic formations together with faults which are confirmed by geological survey, 2) high and low gravimetric anomalous areas and gravimetric transition zone together with gravimetric lineaments and gravimetric anticlinal and synclinal structures which are searched by gravity prospecting, 3) fracture systems assumed by trends of anomalous areas of ground temperature at 1 m depth and Hg-CO_2 geochemistry, and 4) distributions of geothermal manifestations of hot spring and fumarole (Fig. 3-6-1).

(1) Model of geologic structure based on stratigraphic sequence and gravity anomaly

a) Characteristics of geologic structure based on geological distributions and physical properties of constituent rocks.

Geologic structure in the investigation area is divided into eastern and western halves based on geological distributions and physical properties of constituent rocks.

In the western half, basement rocks exist in relative shallow portions and younger volcanic rocks widely overlie on them, which form two-layer structure consisting of lower layer represented by high density and low effective porosity and of upper layer represented by low density and high effective porosity.

On the other hand, in the eastern half, the area is occupied by Mesozoic formations of intermediate density and effective porosity as lower layer and by younger volcanic rocks of low density and high effective porosity as upper layer, and basement rocks is assumed to be latent at great depths.

b) Characteristics of geologic structure based on Bouguer anomalies of gravity

Geologic structure in the investigation area based on distributions of Bouguer anomaly is divided into three areas, namely, high gravity anomalous area at west, low gravity anomalous area at east and gravity transition zone between two anomalous areas.

There is a good harmony in the western area tectonically between distribution of high gravity anomalous area and geologic structure where basement rocks exist in shallow depths, and also there is no big inconsistency between volues of Bouguer anomaly at transition zone and distributions of Mesozoic formations. Low gravity anomalous area at east, which is bordered on the west by large fault zone inferred through gravimetric lineaments of great gradients, is not agreed with geological distributions on and near the surface. Therefore, it cannot be interpreted structurely, if an existence of rocks or strata of low gravity expanding widely and deeply at depths.

As tectonical factors to form low gravity anomalous area at east, it may be possible to consider structurely that acidic porphyrys of relatively low gravity which correspond to intrusive facies of Domuyo Volcanic Complex underlie Mesozoic formation and expand widely at depths.

(2) Model of geologic structure based on fault and fracture systems

a) Characteristics of fault systems by geology and fracture system by gravity

Fault systems of N-S direction are of large scale regionally, and are common to be developed through whole formations of the oldest to the yougest in geological age, and those of E-W direction mainly develope in older rocks. Besides, fault systems of NW-SE and NE-SW trend are also recognized forming conjugating systems with those of N-S direction.

Although fault systems of N-S and E-W directions are observed in the investigation area as shown in Fig. 3-6-1, fault systems of NW-SE direction and of NE-SW direction including NNE-SSW, NE-SW and ENE-WSW directions are dominant in the area.

Geologic structure based on gravimetric lineaments is tectonically characterized by fracture systems of N-S direction which are bordering on the both sides of gravity transformable zone. They are formed by combinations of N-S fault with NW-SE and NE-SW faults. Gravimetric lineaments corresponding to faults are also recognized in other areas, and gravimetric anticlinal and synclinal structures of NW-SE and NE-SW directions characterize geologic structure in the investigation area.

b) Characteristics of fracture systems based on anomalous areas of ground temperature and geochemistry as well as geothermal manifestations.

On the basis of anomalous areas of ground temperature at 1 m depth and those of Hg and CO_2-concentrations, fracture systems of NE-SW direction are dominant together with accessary systems of NW-SE, N-S and E-W directions in central and eastern portions of the area, and those of NW-SE direction with accessory NE-SW direction are common in western portions.

Next, fracture systems based on distributions of geothermal manifestation such as hot springs and fumaroles are generally characterized by these trends of E-W direction from Rincon de Las Papas to Arroyo Ailinco, the same direction from La Bramadora through El Humazo to Las Olletas, ENE-WSW dirction from Las Olletas through Arroyo Aguas Calientes to Baños del Agua Caliente, and E-W direction at Los Tachos.

If trends of each geothermal manifestations are studied individually, it is made clear that they are structurely controlled by fracture systems confirmed through interpretations on faults, gravimetric lineaments, gravimetric anticlinal and synclinal structures, and/or by those assumed by trends of anomalous areas of ground temperature and geochemistry. Especially, intersections of fracture systems of two or more and their surrounding areas are considered to be most favorable for geothermal manifestations.

3.6.2 Model of Heat Flow Structure

Synthetic interpretation map of heat flow structure shown in Fig. 3-6-2 is composite may made summarizing by the following geothermal structural factors. Namely, they are 1) classifications and zonings of geothermal manifestations such as hot springs and fumaroles based on their chemical compositions and geothermo-temperatures, together with boundaries of fumaroles and non-fumaroles, 2) trends of anomalous areas of ground temperature at 1 m depth and of Hg and CO_2 concentrations, and 3) zonings of hydrothermal alteration zone (Fig. 3-6-2).

(1) Plane model of heat flow structure

a) Characteristics of heat flow structure based on volcanism

As heat source bringing present geothermal phenomena in the investigation area, magma reservoirs related to younger volcanism of Quaternary age can be assumed in connection with activity of Domo Volcano taken place during periods of 700 to 100 thousand years ago. These activities have occurred centering around plural places in southeast areas of the investigation area. And, one of them is considered to exist at depths near La Bramadora and its vicinity, and its heat supplies from east to west and upward. Accordingly, the model of heat flow structure in the area which heat supply is most active at central-eastern parts and becomes to decrease toward western parts.

b) Characteristics of heat flow structure based on hot water and fumarolic gas

Hot water from each springs can be classified by their chemical compositions and relations with or without fumarolic gas, and their areal zonings are possible. They are summarized by their classification and zoning together with their geothermometric temperatures by alkaline ratio geothermometer.

i) Sulphate hot springs at La Bramadora of central-east parts being rich in Ca^{++} and SO_4^{--} and showing volcanic hot spring of $SO_4^{--}/Ce^{-} > 1$ are characterized by vapor-dominated type, and their temperatures are considered to be high qualitatively by compositions of fumarolic gas.

ii) Common salt hot spring (a) at El Humazo and most of Los Tachos of central parts being rich in Na^{+} and Cl^{-} with relatively rich in K^{+} and poor in Ca^{++} are characterized by vapor·water-dominated type hot springs accompanying with large amounts of fumarolic gas, and their geothermo-temperatures are high as more than 200°C.

iii) Common salt hot spring (b) at western margin of Los Tachos, Las Olletas, Arroyo Aguas Calientes and Baños del Agua Caliente of central-western parts being rich in Na^{+} and Cl^{-} with relatively poor in K^{+} and rich in Ca^{++} are characterized by water-dominated type hot springs with very little amounts of fumarolic gas, and their geothermo-temperatures are less than 200°C. Hot spring AC-2 of Arroyo Aguas Calientes is simple hot spring which has no different origin from its surounding hot springs, but it is formed by mixture of a large amount of underground water.

iv) Ca-Mg bicarbonate hot springs at Rincon de La Papas and Arroyo Ailinco of northern parts being rich in Ca^{++} and HCO_3^{-} are characterized by water-dominated type hot spring without fumarolic gas, and their geothermo-temperatures are about 170°C or less than that.

Plane model of heat flow structure based on grades of goethermal activity, which are studied by classification and zoning of hot springs, their geothermo-temperature and compositions of fumarolic gas, shows semi-dome structure having an axis of E-W direction and inclining toward west. At northern wing of semi-dome structure, grades of geothermal activity tends to decrease rapidly.

c) Characteristics of heat flow structure based on hydrothermal alteration zones, and anomalous areas of ground temperature at 1 m depth and geochemistry

As zonings of hydrothermal alteration in the investigation area, kaoline-alunite zone indicating acidic condition of intermediate to high temperature occupies areas centering around La Bramadora, and kaoline zone indicating acidic condition of low to intermediate temperature surrounds it. And, alteration zones of montmorillonite indicating intermediate to alkaline condition of low temperature, overlapped by crystobalite zone indicating acidic condition of low temperature, distribute further outside of them. This boundary between kaoline zone and monmorillonite-crystobalite zone is very close to boundary between vapor-water-mixed type common salt hot springs (a) and water-dominated type common hot springs (b), which shows semi-dome structure inclining toward west.

Alteration zones of very low temperature accompanying with opal distribute at west of hot spring RC-3 of Arroyo Ailinco which is of the lowest temperature.

Thus, zonal distributions of hydrothermal alteration is quite in agreement with tendencies of grade of geothermal activity indicated by characteristics of hot water and fumarolic gas. Namely, both of them form model of heat flow structure in the investigation area having semi-dome structure inclined toward west radically.

In addition, characteristics of heat flow structure based on anomalous areas of ground temperature and geochemistry are summarized as follows; Namely, three anomalous areas of ground temperature at 1 m depth and Hg-CO_2 concentrations are almost identical with each other, in eastern parts of the area, and they prove their high intensities and high grades of geothermal activity. On the other hand, in westen parts of the area, three anomalous areas distribute separately decreasing their intensities, and they indicate lower grades of geothermal activity. Furthermore, no anomalous area of ground temperature and geochemistry is recognized at Rincon de Las Papas and Arroyo Ailinco.

As is described above, there are relations of the trinity between heat flow structures based on anomalous areas of ground temperature and geochemistry, classifications and zonings of hot water and fumarolic gas, and hydrothermal alteration zones.

(2) Sectional model of heat flow structure

Fig. 3-6-3 and Fig. 3-6-4 show model of circulation mechanism of geothermal fluid and geothermal reservoir structure at E-W and NW-SE sections. In these figures, boundaries of classification of hot springs and existences of fumarolic gas are shown modifying vertically.

As shown in Fig. 3-6-3, heat supplies from magma reservoir which is inferred to exist at depths near La Bramadora. Because its supply decrease in propotion to westward and upward, heat flow structure having semi-dome structure inclined toward west horizontally is assumed vertically to be sectional model of heat flow structure having arc-shaped zonings centering arround magma reservoir.

On the other hand, as shown in Fig. 3-6-4, sectional model of heat flow structure presents modified variations from vapor·water-dominated type common hot springs (a) of high temperature at Los Tachos, through water-dominated type common hot springs (b) of relatively low temperature at Las Olletas, to water-dominated type Ca-Mg biocarbonate hot springs of rather low temperature at Arroyo Ailinco.

3.6.3 Model of Circulation Mechanism of Geothermal Fluid and Geothermal Reservoir Structure

(1) Model of formation of deep geothermal hot water

As genesis of hot water in the geothermal field, various theories have been presented. Namely, 1) meteoric water origin presents that hot water has been formed from underground water originated from rain water and surface water and heated by heat source at depths, 2) magmatic water origin, and 3) mixed origin of 1) and 2). Recently, trials to research on genesis of hot water are carried out by studies on ion-concentrations and isotopes of $\delta^{18}O$ and δD in hot water.

As a results of these studies, very low ratio of magmatic water in the whole hot water is made clear. And, the following interpretation regarding genesis of hot water is accepted. Namely, deep underground water which penetrated into depths spending long time has been heated by heat of thermal conductivity of rocks and heat of thermal transfer medium such as gas, steam and a little amount of magmatic water. Then, heated deep underground water has reacted chemically with its surrounding rocks, and converted into deep geothermal hot water. This deep geothermal hot water accompanying with gas and steam ascends from its geothermal fluid reservoir through fracture system, and hot water has been formed from relatively a little amount of deep geothermal hot water mixed with a large amount of shallow underground water.

Main ion-concentrations in river water is known as 5 ~ 10 mg/l in Na^{+}, Ca^{++} and Cl^{-}, 1 mg/l in K^{+}, and 15 ~ 20 mg/l in SO_4^{--} and HCO_3^{-}. In case this river water penetrates into subsurface and converts to shallow underground water, general tendencies of changes of ion-concentrations in it is also know as increasing in Na^{+} and HCO_3^{-}, decreasing in Ca^{++} and SO_4^{--}, and almost no change in K^{+} and Cl^{-}.

Accordingly, ion-concentrations in deep geothermal hot water, which shallow underground water converts into deep underground water penetrating more deeply and is heated, are results of chemical reactions with surrounding rocks at depths under balance conditions of temperature, pressure and solubility of minerals. Generally, deep geothermal hot water is characterized by high salinity of rich in Na^{+} and Cl^{-}, and contains Li^{+}, K^{+}, Ca^{++}, Mg^{++}, SO_4^{--}, B^{-}, HBO_3^{-}, Fe, SiO_2 and Hg. And, it is called "chloride water".

Deep geothermal hot water, having these chemical compositions and accompanying with SO_2 and CO_2 of volcanic gas and steam, is considered to form geothermal fluid reservoir at two to three kilometers deep having its temperatures of 200° to 300°C. Fig. 3-6-3 shows models of heat supplies from magma reservoir, flows of shallow and deep underground water, and geothermal fluid reservoirs of deep geothermal hot water together with gas and steam.

(2) Model of circulation mechanism of geothermal fluid

Geothermal fluid consisting of deep geothermal hot water, gas and steam ascends from geothermal fluid reservoir through fracture systems reached to depths. In proportion to shallow subsurface, it mixed with shallow underground water in various ratios and forms shallow geothermal fluid reservoirs in aquifers of high porosity strata or of permeable strata and rocks. Temperatures in shallow geothermal fluid reservoir are assumed to be 100° to 200°C.

In case amounts of geothermal hot water of high temperature are relatively abundant with low mixture of shallow underground water, vapor-dominated system is formed consisting mainly of steam accompanying with fumarolic gas. In proportion to decrease amounts of shallow underground water, it converts into vapor · water-mixed system and finally into water-dominated system without steam and fumarolic gas.

Furthermore, shallow geothermal fluid ascends from its reservoirs, and mixes with unconfined underground water originated from meteoric water and/or river water. As a result of this mixture, temperatures decrease and ion-concentrate of HCO_3^- increase. Finally, hot water and fumarolic gas reaches to the surface and forms geothermal outcrops of hot spring and fumarole. Fig. 3-6-3 and Fig. 3-6-4 also show models of ascents of deep geothermal hot water, formations of shallow geothermal fluid by mixture with shallow underground water, conditions of shallow geothermal fluid reservoir, and classifications of hot water and its spring out.

(3) Model of geothermal fluid reservoir structure

a) Characteristics of structure of deep geothermal fluid reservoir

Deep geothermal fluid reservoirs considered to be formed at two to three kilometers deep from the surface are existing in basement rocks and/or near bottoms of intrusive rocks. In these rocks, it is very difficult to consider that these reservoirs have large expansions horizontally because rocks are of very low effective porosity and of usually massive body.

Accordingly, shapes of deep geothermal fluid reservoir are interpreted to have shapes of plate or pipe elongating vertically.

b) Characteristics of shallow geothermal fluid reservoir based on stratigraphic sequence

As shallow geothermal fluid reservoirs in the investigation area based on stratigraphic sequence are considered as follows; Namely, they are 1) pyroclastic rocks in younger volcanic formation of Quaternary age, and 2) pyroclastic rocks in Tertiary and upper Mesozoic formations.

As shown in schematic columnar section of effective porosity of Fig. 4-3-1, pumice tuff, scoria tuff and some of andesite lava among younger volcanic formations have high porosity as maximum of more than 30%, and the former two show high values as average of 20 to 30%. On the other hand, andesitic tuff breccia of Tertiary formations and dacitic tuff of upper Tordillo Formation of Mesozoic have porosities of maximum 30% and averages of 15 to 25%. Because unpermeable strata such as lava flows and beds of welded tuff overlie on each permeable strata, it is considered to be favorable strata to form aquifers having cap rocks.

If unconformable planes accompany with conglomerate or coarse sandstone, it is reported that these planes form strata-bound aquifers in some of geothermal fields. However, in the investigation area, Mesozoic formations unconformably overlie on the basement without conglomerate or coarse sandstone, but lava flows of basalt and andesite with their pyroclastic rocks directly cover it. Beside beds of limestone in Mesozoic formations are lithologically compact and of rather thin. Thus, these planes and beds are considered unfavorable for aquifers.

c) Characteristics of geothermal fluid reservoir formed in and along fracture system

Distributions of present geothermal manifestation in the area generally trend in E-W direction. However, in case of search them individually, they are structurally controled by faults, gravimetric lineaments, gravimetric anticlinal and synclinal structures, and fracture systems assumed by anomalous areas of ground temperature and geochemistry. And, superior hot springs and fumaroles are distributed at intersections of two or three fracture systems or their vicinities.

This fact indicates that structures of shallow geothermal fluid reservoir present shapes of plate, pipe and pocket. In case these vertically elongated reservoirs having some widths interesect with above-mentioned strata having possibility to form strata-bound aquifers stratigraphically, these places are of the most favorable to form geothermal fluid reservoirs.

3.7 Summary of the Second Phase Survey

The results of the second phase survey are summarized as follows.

3.7.1 Geological Structure

(1) Geological stratigraphy of the survey area

The survey area consists of superposed formations of Mesozoic formations and Tertiary systems on a basement of metamorphic rocks of the Permian and Triassic systems and Varvarco granodiorites. Furthermore, there are distributions of younger volcanic rocks, whose activity took place from the late Pliocene to the Pleistocene, that cover the above-mentioned layers.

(2) Geologic structure based on geological distribution and petrological properties

The west half of the survey area forms a two-layered structure where basement rocks with physical property of high density and low porosity are located shallow beneath younger volcanic rocks with physical property of low density and high effective porosity. On the other hand, the east half has a two-layered structure consisting of a Mesozoic formations and Tertiary system with medium density and medium effective porosity properties located beneath younger volcanic rocks, while basement rocks are presumed to be latent at great depth.

(3) Geologic structure based on the distribution of Bouguer anomalies

The survey area is divided in three distinct parts, i.e., the high gravity anomaly area located in the western part, the low gravity anomaly area located in the eastern part and the gravity transition zone extending in the N-S direction in the form of stripe. There is concordance between the Bouguer anomaly distribution of the high gravity anomaly area and the gravity transition zone and the underground structure seen from the standpoint of geological distribution and physical properties of the rocks. In the low gravity anomaly area however, it is necessary to suppose a geological structure as consists of intrusive facies of acidic porphyries of the Domuyo Volcano Complex expanding widely and deeply at depth.

(4) Faults and fracture systems

There are faults of the N-S system accompanied with wide area folding structures, faults of the E-W system perpendicular to the former ones and also faults of the NW-SE system and NE-SW system conjugating with the former ones. The gravimetric lineament and gravimetric anticlinal and synclinal structures caused by the undulations of the basement coincide with the above-mentioned fault systems and fracture systems. Furthermore, the fracture systems estimated from ground temperature, geochemical anomalies or distribution and arrangement of geothermal manifestations tend to coincide with faults and fracture systems as well.

3.7.2 Heat Flow Structure

(1) Heat flow structure based on the volcanic activities

It is presumed that the magma reservoir related to the younger volcanic activities including the Domo Volcano that was in activity approximately 700,000 to 100,000 years ago is the heat source that brings about the geothermal phenomena of the survey area. In this connection, it is presumed that the heat source spreads out at depths near La Bramadora, in the eastern part of the survey area.

(2) Heat flow structure based on the distributions of hot springs and fumaroles

The survey area is divided in four distinct parts, i.e., eastern part with sulfate hot springs of the vapor-dominated type, central parts with vapor-water-mixed type salt hot springs (a), western part with hot water-dominated type salt hot springs (b) and northern part with water-dominated type Ca-Mg bicarbonate hot springs. These areas have a three-dimensional semi-dome structure inclined to the west and axis in the E-W direction. The intensity of the geothermal activity decreases in the west and north directions.

(3) Heat flow structure based on the distribution of ground temperature and geochemical anomalies

The zoning from the standpoint of mineral combination of the hydrothermal alteration zones and the zoning from the standpoint of the 1-meter depth ground temperature anomalies and geochemical anomalies of Hg concentration and CO_2 concentration and the respective properties coincide with the zoning from the standpoint of hot springs and fumaroles and its property, forming therefore a trinity relationship.

3.7.3 Circulation Mechanism of Geothermal Fluid

(1) Circulation of geothermal fluid

Deep hot water, gas and steam goes up passing through fracture systems reaching deep underground geothermal reservoirs, and when they reach the shallow underground aquifiers they form shallow geothermal reservoirs by mixing with shallow ground water with various proportions. Distinct kinds of systems, such as vapour-dominated system, water-dominated system, etc., and distinct temperatures come about depending with the mixing proportion with shallow ground water.

(2) Geothermal outcrop of hot springs and fumaroles

Geothermal fluids going up further from shallow geothermal reservoirs get mixed with non-pressure ground water originated by rain water and river water. The temperature falls and it reaches the ground surface in the form of hot spring rich in HCO_3^- and accompanied with fumarole.

3.7.4 Structure of Geothermal Reservoirs

(1) Structure of geothermal fluid reservoirs

Geothermal fluid reservoirs presumed to be located 2 to 3 Km deep from the surface are estimated to spread vertically in the form of plates or pipes, along fracture systems developed in the interior of basement rocks or along the crossings of the fracture systems, rather than spreading out in the form of plane surfaces.

(2) Structure of shallow geothermal reservoirs seem from the stratigraphical standpoint

From the stratigraphical and petrographical standpoints the shallow geothermal reservoir of the survey area consists of clastics of younger volcanic rocks of the Quaternary and pyroclastic rocks of the Tertiary system and upper Mesozoic sandwiched by impermeable lava and other kinds of rock from the upper and lower sides. Such being the case, it is presumably suited for formation of a shallow geothermal reservoir with plane spreading.

(3) Structure of the shallow geothermal reservoir formed in the fracture system

The pronounced geothermal manifestations observed at the present time suffer the structural restriction of fracture systems estimated from faults, gravimetric lineaments and ground temperature and geochemical anomalies. Furthermore they are distributed in the crossings of fracture systems developing in 2 or 3 directions and in the environs of the said crossings.

Places where the occurrence of geothermal reservoirs formed in fracture systems developed in vertical direction (plate shape, pipe shape or pocket shape) coincide with the occurrence of geothermal reservoirs with plane spreading seen from the stratigraphical standpoint are best suited for formation of shallow geothermal reservoirs.

3.8 Extraction of Target Area for the Third Phase Survey Based on the Results of the Second Phase Survey

After making a comprehensive judgement taking into consideration the aspects of geology, geological structure, heat flow structure, geothermal fluid structure and geothermal reservoir structure, we come to the conclusion that the geothermal resources of the survey area have high potential, with extremely promising possibility of development, and as a consequence we consider it indispensable to carry out the third phase survey. The following extent is mentioned in the first place as the most promising area for geothermal development which should be investigated in further details in the next phase survey.

The area in question has an extension over 40 Km^2, with 9 Km in the E-W direction from La Bramadora in the eastern part to Las Olletas in the western part passing through El Humazo and approximately 5 Km in the N-S direction, including El Humazo and Los Tachos. This area comprises the district with distribution of vapour-dominated type sulfate hot springs located in La Bramadora, the district with distribution of water•vapour-mixed type salt hot springs (a) comprising most of El Humazo and Los Tachos, and the district with distribution of hot springs accompanied with fumaroles like those ones of the western extremity of Los Tachos and Las Olletas, among the water-dominated type salt hot springs (b).

This area composes the core the heat flow structure and geothermal fluid structure which has its axis in the E-W direction and semi-dome structure inclined to the west. Particularly the area located east of the line drawn between the centers of El Humazo and Los Tachos has high temperature hot springs accompanied with strong fumaroles and is presumed to have the most intense geothermal activities. Therefore, it is the most promising area in terms of possibility of occurrence of high temperature geothermal fluid indispensable for geothermal development.

The runner-up is the area comprising Las Olletas and Aguas Calientes, which corresponds to the outside of the heat flow structure and geothermal fluid structure with semi-dome configuration. This area loses in terms of order of priority because its hot springs are not accompanied with fumaroles in most of the case, but it should be studied with sufficient care because it is located in the western extension of the geothermal structure that crosses the survey area in the E-W direction.

4. The Third Phase Survey

4. The Third Phase Survey

4.1 Physical Properties of Rocks

Four pieces of cores from the drilled hole No. 8 were provided for laboratory measurements of physical properties (Table 4-1-1).

Table 4-1-1 Numbers of rock specimens

Density	Porosity	Magnetic susceptibility	Resistivity	Thermal conductivity	Sonic velocity (P-wave)
4	4	4	4	4	64

The results of measurements are given in Table 4-1-2.

Table 4-1-2 Results of measurement of physical properties

Core No.	Sampling depth (m)	Rock name	Density (g/cm^3)			Porosity (%)	Susceptibility ($\times10^{-6}$ emu/cc)	Resistivity		Thermal conductivity ($\times10^{-3}$ cal/cm-sec-°C)	Sonic velocity (m/sec)
			natural condition	water saturated	oven dry			F.E. (%)	ρ(Ω-m)		
1	20.24 -20.39	Rhyolite	1.79	1.83	1.73	10.11	150	3.1	1,027	3.497	2,372
2	41.05 -41.20	Dacite	2.21	2.26	2.14	10.69	85	4.2	357	3.792	3,450
3	60.82 -61.00	Dacite	2.28	2.32	2.22	9.69	229	3.8	607	4.217	2,301
4	77.50 -79.64	Dacite	2.23	2.26	2.17	9.07	269	2.8	317	3.839	2,169

Sonic velocity

Measured were the sonic velocities of these cores and sixty samples obtained in the course of the second phase survey. The results are shown in Table A-1-1 and compiled in Table A-1-2 with respect to lithological units of Appendix A-1. A diagrammatic columnar section of sonic velocities is illustrated in Fig. 4-1-1.

In general,

a) the velocity in volcanic rocks of Quaternary in age is relatively small ranging from 2,000 to 4,000 m/sec.

b) the velocity in rocks of upper Mesozoic, Tertiary and Tertiary to Quaternary in age ranges from 2,000 to 6,000 m/sec, depending on lithology.

c) in lower Mesozoic sediments and the basement rocks, velocity averages in the order of 4,500 to 6,000 m/sec , and

d) tuffs give a small velocity of sonic waves.

4.2 Heat Flow Survey

4.2.1 Purpose of Heat Flow Survey

Heat-flow measurement utilizing drilled holes is a method to seize a heat flow structure most directly. General distribution of surface temperature was clarified by a geothermal survey of 1 meter depth carried out at the second phase of present investigation. At the third phase, twelve holes of 100 m each were to be drilled over an area of 40 Km^2 and one hole of

400 m deep was to be drilled at the most promising site indicated by the end of the second phase. Heat-flow measurement of these holes will delineate an anomalous area and may point out, from a study of activity of a geothermal fluid, the most promising area for geothermal development.

Geophysical properties are measured on the cores collected from the 400 m hole and applied for an overall analysis.

4.2.2 Drilling

(1) Drill holes, 100 m deep

Drilling of holes to a depth of 100 m each was conducted by the Argentine team using two truck-mounted rigs of a rotary type. Bits of a tri-cone type were provided by the Japanese party. Bits of 8-5/8 inches in diameter were applied to a depth of 6 m, and then, 5-5/8 inches bits were used to the bottom. Casing pipes were inserted to holes, in which a collapse of walls is possible.

During the period from 5th December, 1983 to 9th April, 1984, twelve holes totalling 1,162.5 m were drilled against the scheduled ten holes of 100 m each. Location, drilling records are shown in Table 4-2-1 and Figures 4-1, 4-2-1 and 4-2-2. The geological observation of cuttings were carried out by the Argentine experts and the records are shown in Fig. 4-2-3 with the records of ground temperature and geothermal gradients.

(2) Drill hole, 400 m deep

Drilling of a 400 m hole was designed to recover a core every 20 meters using a large truck-mounted rig. Bits, coring instruments and their handling technics were provided by the Japanese party.

Due to a delay of arrivals of a rig, bits and instruments, the commencement of operation was postphoned. Despite every effort along all the days, the drilling operation was forced to be suspended at a depth of 80 m, because of weather conditions such as snowing and decreasing of temperature down to minus 20°C. (The Argentine partners are planning to start re-opening of the hole at December, 1984.)

The cores recovered down to the depth of 80 m were provided for measurements of physical properties.

4.2.3 Temperature Logging

Temperature of the 100 m holes was measured repeatedly by the normal logging and multi-sensor methods under a technical guidance and a supply of instruments from the Japanese party. The details of measurements and their results are attached to Appendix A.2.2 and A.2.3.

An equilibrium temperature which denotes a temperature of a stratum, being assumed to have existed before drilling, is estimated. The results of calculation over an each 5 m section are listed in Table 4-2-2 and summarized in Figure 4-2-4. A theoretical equation of the estimation is described at Appendix A.2.4 and an example of estimation curves are

Table 1-2-1 Drilling Scheme

Hole No.	Duration		Depth (m)		Reference a temperature at the bottom (℃)
	from	to	drilled	scheduled	
1	5 Dec. 1983	13 Dec. 1983	101.0	100.0	57.9
2	5 Dec. 1983	20 Dec. 1983	103.0	100.0	74.5
3	14 Dec. 1983	20 Dec. 1983	101.0	100.0	31.4
4	21 Dec. 1983	* ———	24.5	100.0	88.0
5	9 Jan. 1984	23 Jan. 1984	102.0	100.0	30.1
6	18 Jan. 1984	21 Jan. 1984	100.0	100.0	33.5
7	12 Jan. 1984	16 Jan. 1984	105.0	100.0	8.9
9	26 Jan. 1984	27 Feb. 1984	120.0	100.0	77.9
10	6 Apr. 1984	9 Apr. 1984	102.0	100.0	10.5
11	23 Mar. 1984	27 Mar. 1984	102.0	100.0	11.1
12	25 Jan. 1984	6 Mar. 1984	101.0	———	15.0
14	15 Mar. 1984	20 Mar. 1984	101.0	———	37.5
Total	5 Dec. 1983	9 Apr. 1984	1,162.5	1,000.0	———
8	1 Mar. 1984	** 19 Apr. 1984	80.0	400.0	———

* Stopped at the depth of 24.5m due to sharp increase of temperature

** Stopped due to a weather condition, such as snowing and a low temperature down to minus 20℃

Table 4-2-2 Estimated equilibrium temperature

(unit : ℃)

m \ No.	1	2	3	4	5	6	7	9	10	11	12	14
5	11.8	(4^m) 9.0	7.4	(4^m) 65.0	11.0	10.4	8.2	7.3	8.7	8.1	7.9	8.2
10	15.7	9.7	9.0	94.0	12.2	11.8	8.1	7.5	8.2	7.0	7.9	9.1
15	18.5	(14^m) 10.7	9.9	(14^m) 93.7	10.0	13.3	8.2	8.3	8.0	6.8	8.4	10.4
20	21.6	13.3	10.8	89.2	9.5	15.1	8.3	8.1	8.2	6.1	8.9	10.7
25	24.7	(24^m) 15.1	12.0	(24^m) 88.0	10.2	16.7	7.9	8.0	8.1	5.9	9.4	11.9
30	28.1	17.5	13.3		10.2	18.0	7.8	8.3	8.3	6.2	10.0	13.0
35	31.6	(34^m) 19.8	14.4		10.2	19.8	8.0	7.9	8.2	6.2	10.4	14.4
40	35.4	23.2	16.0		10.2	21.4	8.0	8.2	8.2	5.9	10.4	15.6
45	40.0	(44^m) 25.0	17.2		10.2	23.6	8.0	8.4	8.6	5.8	10.3	17.8
50	44.8	27.7	18.6		10.4	25.2	8.0	8.3	8.8	6.1	10.7	19.6
55	49.5	(54^m) 30.5	19.8		12.0	27.3	8.1	8.9	8.8	6.2	11.1	20.4
60	53.2	34.6	21.2		14.0	27.8	8.1	12.4	9.0	6.5	11.6	22.4
65	52.7	(64^m) 38.0	22.7		15.8	29.2	8.2	19.1	9.5	6.4	12.1	24.0
70	51.5	42.6	24.4		17.3	29.9	8.2	29.0	9.8	7.1	12.3	24.9
75	49.5	(74^m) 45.8	26.2		19.6	31.0	8.3	37.3	10.0	7.8	12.8	26.9
80	48.0	53.6	27.9		21.7	31.2	8.5	44.4	10.0	8.7	13.2	29.1
85	47.0	(84^m) 57.9	28.9			32.0	8.5	52.0	10.2	9.5	13.6	31.4
90	47.6	65.3	29.8		25.6	32.6	8.5	57.4	10.2	10.3	14.0	33.6
95	48.6	(94^m) 70.1	30.7			33.5	8.5	60.5	10.5	10.7	14.6	35.5
100	57.9	(98.2^m) 74.5	31.4		30.1		8.9	63.4	10.5	11.1	15.0	37.5
105								67.4				
110								70.1				
115								74.3				
120								77.9				

shown in Figure A-2-4. A distribution map of the equilibrium temperature at the depth of 100 m is attached (See Fig. 4-2-5).

4.2.4 Calculation of Heat Flow

An amount of heat flow, Q is defined by the formula

$$Q = K \cdot dt/dz$$

where K : thermal conductivity of a stratum (cal/cm·sec·°C)

dt/dz : geothermal gradient (°C/cm).

Heat flow Q is calculated from the data within a section where geothermal gradients are rather stable to minimize an effect caused by the existence of water. The results of calculation is obtained from a value observed within an each 5 m interval, using the least squares method.

Geology of each hole is correlated with a stratigraphical succession established in the previous work and a value of thermal conductivity of each stratigraphic unit is deemed to be equivalent to a value obtained from a correlative unit during measurements of physical properties in the second and the third phase surveys.

The results of calculation are shown in Table 4-2-3 and Figures 4-2-6 and 4-2-7.

Table 4-2-3 Geothermal gradient and heat flow

Hole No.	Geothermal gradient ($\times 10^{-3}$ °C/cm)	Thermal conductivity ($\times 10^{-3}$ cal/cm·sec·°C)	Heat flow (HFU)	Range of calculation for geothermal gradient (m)	Stratigraphy for thermal conductivity
1	5.3	2.88	15.3	5–100	V-2
2	11.9	2.88	34.3	74–100	V-2
3	1.8	6.09	11.0	80–100	J-1
4	–	–	–	–	–
5	4.2	2.79	11.7	70–100	V-1
6	1.6	2.79	4.5	55–95	V-1
7	0.2	2.79	0.6	55–100	V-1
9	6.9	4.34	29.9	90–120	T
10	0.3	2.88	0.9	70–100	V-2
11	1.4	2.88	4.0	65–100	V-2
12	0.9	2.79	2.5	45–100	V-1
14	4.3	2.88	12.4	70–100	V-2
Average	3.53	3.27	11.6		

4.2.5 Consideration on Heat Flow Survey

(1) Geology and alteration in holes

i) Geology in holes

The geological logs of twelve holes are illustrated in Fig. 4-2-3.

Four holes (Nos. 1, 2, 10 and 11) were drilled within dacites and related tuff breccias of Quaternary in age. Other four holes (Nos. 3, 7, 8 and 14) entered from the dacite to an underlying succession of Quaternary to Tertiary or Jurassic times. Among remaining four holes, three holes (Nos. 5, 6 and 12) intersected welded tuffs, scoria tuffs and andesitic lavas of Tertiary to Quaternary age. Though a small difference of rocks facies was noticed, these rocks belong to the same geological formation. The last holes (No. 4) remained within andesitic tuff breccias of Jurassic age to a bottom depth of 24.5 m and no change in rock facies was observed.

The dacites are generally pale grey to pinkish white in color and frequently contain obsidian glass. The rocks are occasionally rich in biotite and sporadically contain clasts of shale.

The formation of the Tertiary to Quaternary consists of welded tuffs, scoria tuffs, pumice tuffs, andesite lavas and volcanic breccias. The welded tuffs are made up chiefly of acidic to intermediate glass and are porous. Scorias are almost entirely welded. The rocks frequently contain accidental rock fragments. The scoria tuffs are composed of dacitic to andesitic pyroclastics, bigger than lapilli in size, with a matrix of fine- to coarse-grained volcanic ashes. Scoria are welded in part. The pumice tuffs contain a large amount of pumice which is pale yellowish white. Fine-grained volcanic ashes are frequently included in the rocks. The andesite lavas undergo alteration and are reddish to yellowish brown in color. The andesitic breccias are slightly porous. Older andesites of the Tertiary in the hole No. 14 undergo alteration and are reddish purple to black, varying in color.

The Jurassic formation is correlative with the Chacay Melehue formation and consists of andesitic to basaltic tuff breccias, basaltic andesites and sandstones. The andesitic to basaltic tuff breccias are formed of hard and compact rubbles and a rather soft, sandy to clayey matrix. The basaltic andesites are massive and compact. Interbeded with the tuff breccias are thin beds of hard and compact sandstones, which are dark colored and resemble basaltic andesites.

ii) Alteration in holes

The rocks are slightly altered in general except a case of the Jurassic system intersected in the hole No. 4 at the east of El Humazo, where slightly strong silicification was noticed.

The dacite is generally fresh in appearance and only slight alteration of glass is recognized by a pale yellowish green color in the holes of Nos. 9 and 2. The hole No. 9 is situated between Los Tachos and a fumarole in the east. The hole No.2 is located in the middle of Las Olletas and Los Tachos, but no indication of hot spring is known in the vicinity.

The andesites of the Tertiary are partly altered and bleached with possible sericitization. A degree of alteration is slightly higher than alteration of dacites.

Jurassic system is intersected in the holes Nos. 3 and 4. The rocks in the hole No.4 show the strongest alteration among all holes and are more intensively silicified than the rocks of No.3.

iii) Discussion of geology and alteration in holes

The geology of the holes accords with the surface geology. The same rocks and rock facies occur in the underground and a distribution to the depths does not conflict with a geological structure in the surrounding area.

Alteration of rocks in the holes are generally weak, similar to alteration in the surface. The alteration is confined in the vicinity of the geothermal manifestations, and decreases sharply its intensity toward the outside. This may be of the characteristic of the geothermal systems in the investigation area.

(2) Relation between geology and temperature in holes

An equilibrium temperature and a geothermal gradient of a 5 m section are attached in Fig. 4-2-3. The dotted line in the figure denotes the geothermal gradient used in calculation of heat flow.

Eleven holes were drilled to the depths of 100 m and the shallow parts among these five holes (Nos. 5, 7, 9, 10 and 11) showed the geothermal gradient at zero reflecting the effect of surface water and the migration of ground water. The geological succession in which the geothermal gradient stands at zero, consist of dacitic lavas of the Tertiary, welded tuffs and pumice tuffs of Tertiary to Quaternary in age. Pumice tuffs may obviously be permeable. Dacitic lavas and welded tuffs vary from 2 to 12% in the effective porosity and, in the field these rocks may or may not be permeable depending on their locality.

The Tertiary and underlying beds were penetrated in four holes. A change in the geothermal gradient is noticed even within the same bed, indicating movability of fluids in these beds. Among these rocks, andesitic lavas gave a rather constant geothermal gradient (e.g. andesitic lavas of Tertiary age in the hole No. 12 and andesitic lavas of Tertiary age in holes Nos. 9 and 14), but cannot necessarilly be deemed to be imprevious due to the limitation of a number of drill holes which penetrated the andesitic lavas.

(3) Temperature in the drilled holes (Fig. 4-2-4)

Generally, the geothermal gradient of the superficial parts remains low, probably due to cooling by surface water depending on the high permeability of the stratum. Especially, no increase of temperature was recorded in the hole No. 7. At the depth of 100 m, seven holes out of eleven exceeded 30°C in temperature and within these seven, three holes recorded anomalous values beyond 50°C.

For reference, an annual average of temperature on the surface is estimated at some 8°C from the curve of ground temperature.

(4) Temperature at the 100 m depth (Fig. 4-2-5)

The area which exceeds 30°C in temperature lies between the A° Manchana Covunco and the A° Covunco and extends eastwards. An anomalous values beyond 50°C are located around the drill holes Nos. 1 and 2 at the central part and around the drill holes Nos. 4 and 9 at the eastern part of the surveyed area.

(5) Geothermal gradient (Fig. 4-2-6)

The anomalous values exceeding 40°C/100 m were recorded in five holes. The maximum gradient of 119°C/100 m was observed in the hole No. 2.

(6) Heat flow (Fig. 4-2-7)

The values, exceeding 10 HFU (x10^{-6} cal/cm^2·sec), seven times larger the world average of 1.5 HFU, are located in the central and the eastern parts extending towards east between the A° Manchana Covunco and the A° Covunco. The zone of anomaly which exceeds 15 HFU, trends northwest-westerly. The maximum value of 34.3 HFU, more than twenty times of the world average was observed at the site of No. 2. In the area of some 40 Km^2, surrounded by the holes Nos. 6, 10, 9 and 12, the amount of heat discharge by heat conduction is calculated to be 4.5 x 10^5 cal/sec and the heat flow to average 11.3 HFU.

4.2.6 Summary on Heat Flow Survey

a) Three holes gave the anomalies above the 50 degrees and seven holes out of eleven gave the high values beyond 30°C, at the depths of 100 meters.

b) The area of high values, above 30°C in temperature at 100 m depth and 10 HFU of heat flow, lies between the A° Manchana Covunco and the A° Covunco and extends to the east.

c) In the area of some 40 Km^2, the amount of heat discharge by heat conduction is 4.5 x 10^5 cal/sec and the value of heat flow averages 11.3 HFU, indicating the presence of a high geothermal potential.

4.3 Electrical Prospecting

4.3.1 Purpose of Electrical Prospecting

Rocks have the specified electrical resistivities depending on their porosity and the water contents. The resistivity method makes use of these properties to clarify a geological structure of an area under investigation. The method is broadly used to detect an anomalous area where rocks are generally conductive due to the existence of geothermal fluid in a field of geothermal exploration.

In the second phase of the present study, the zones of alteration and the precipitates of hot springs were investigated. This was followed by the implementation of the electrical resistivity survey in the third phase using the Schlumberger array to delineate the structure of geothermal fluids and the related zones of geothermal alteration in the depths.

4.3.2 Method of Electrical Prospecting

(1) Line setting

The lines surveyed were almost the same of the seismic prospecting and an extension of the lines was set using a compass. The arrangement of the lines is shown in Fig. 4-1.

(2) Measurement

On a line, the survey points are spaced at an interval of 500 m each and a distance of current electrodes A & B is increased to the maximum of 1,000 to 4,000 m. At the points of Nos. 230, 250 and 270 on the Line E, the separation of 200 m was adopted. The details are given in Table 4-3-1. The theory, instruments and arrangements of field procedures are attached in Appendix A.3.

Table 4-3-1 Scheme of electrical prospecting

Line	Line length (km)	No. of station	Maximum distance of current electrode AB (m)			
			1,000	2,000	3,000	4,000
A	9.0	17	2	2	2	11
B	4.0	7	2	2	2	1
C	4.0	7	2	2	2	1
D	4.5	8	2	2	2	2
E	5.0	10	2	2	2	5
Total	26.5	50	10	10	10	20

4.3.3 Analyses of Electrical Prospecting

(1) Physical properties

The Figure 4-3-1 gives the resistivity and the effective porosity of the rock specimens obtained in the 2nd and the 3rd phase surveys.

Basement rocks are highest in the resistivity and are followed by volcanic rocks. Sediments and pyroclastic rocks are relatively less resistive. Basement rocks are of above 700Ω-m, and the most rocks retain the rather higher resistivities being of above 250Ω-m, except the cases of scoria tuffs, andesitic breccia tuffs of the Tertiary to Quaternary and andesites and andesitic breccia tuffs of the Tertiary, in which the rocks range from 35 to 150Ω-m in resistivity.

The effective porosity has the negative correlation with the resistivity, and ranges from less than 3% in the basement rocks to more than 20% in scoria-tuffs and andesitic breccia tuffs of Tertiary to Quaternary in age.

Measurements of physical properties were conducted with fresh rock specimen or drilled cores. If an extremely lower value than in the laboratory is obtained in the field, such a value may indicate an effect of geothermal alteration or a state of a high temperature.

(2) Cross-section of apparent resistivity

A brief explanation of Figs. 4-3-2(i) ~ 4-3-2(ii) and 4-3-3 are given hereafter.

a) Line A

Between the points Nos. 50 and 550, the equi-resistivity lines run in parallel with a topography, indicating a stable layered structure, the shallow layer having a moderate to higher resistivity of 100 to 500Ω-m, the middle layer being of a low resistivity of less than

25Ω-m and the lower layer having a moderate resistivity of 25 to 100Ω-m.

A zone of low resistivity of less than 10Ω-m was located in a shallow depth between Nos. 100 and 150 at the western end of the Line. At the eastern end, two zones of a low resistivity of less than 25Ω-m were detected in a depth between Nos. 650 and 750, under a thick succession of high resistivities. Due to the fact that a zone of a low resistivity remains in a shallow depth between Nos. 800 and 850, a section between Nos. 650 and 750 seems to have been remarkably sunk to a depth.

b) Line B

Similarly to the Line A, a layered structure is observed between Nos. 100 and 200, being of a moderate to high resistivity of 100 to 250Ω-m in a shallow, less resistive in a middle and of a higher resistivity in a deep zone. At the intersection with the Line A, a zone of a low resistivity was detected between Nos. 150 and 200, being of less than 10Ω-m, similarly to the Line A. Between Nos. 200 and 250, an existence of a fault was assumed because the northern side had a narrower zone of a low resistivity, and being more than 50Ω-m in a middle depth, in contrast with the south side.

c) Line C

A zone of a low resistivity was found in a middle depth between Nos. 100 and 200, being of less than 25Ω-m. The zone increases its resistivity towards north. Between the Nos. 50 and 100, a fault is assumed to exist, due to an abrupt change of resistivity. At the point of No. 50, the measurements consistently recorded the values of more than 100Ω-m.

d) Line D

The southern half of the line, between Nos. 50 and 200, provides a thick sequence of high resistivity of more than 500Ω-m in a shallow depth which is underlain by a zone of a low resistivity. A distinct difference in geological structures were assumed between the points No. 200 and No. 250, because a zone of a low resistivity less than 25Ω-m was detected in a shallow depth, to the north of No. 250.

e) Line E

A complicated pattern was delineated in the Line E, compared with the others.

A low-resistivity zone in the depths between Nos. 230 and 250 indicates a local subsidence and related hydrothermal alteration. The zone becomes shallower eastwards and less resistive being below the 25Ω-m near the surface between Nos. 400 and 450.

(3) Distribution of apparent resistivity

The apparent resistivity is shown in Figs. 4-3-4(i) ~ 4-3-4(iv) over the different electrode intervals ($\overline{AB}/2$ = 250, 500, 1,000, 1,500 m).

a) $\overline{AB}/2$ = 250 m

The zones of a low resistivity below 50Ω-m were found in

i) the western to central area at the western halves of the Lines A and B.

ii) the north-eastern area surrounding the hole No.4, and

iii) the south-eastern area near the east end of the Line A.

The altered zones which were located on the surface were situated within these areas. From this, the shallow depths of these areas are supposed to have undergone a hydrothermal alteration.

The moderate to high resistive zone above 250Ω-m is centered by the hole No. 8 at the south-eastern area and extends towards the holes Nos. 4 and 3.

The trends of tectonic lines assumed by resistivity were E – W at the southwest, N – S at the southeast and NW – SE at the northwest of the areas.

b) $\overline{AB}/2 = 500$ m

The western to central area becomes less resistive. The zones of a low resistivity at the northeast and the southeast areas seem to join each other.

c) $\overline{AB}/2 = 1{,}000$ m

The zone of a low resistivity below 50Ω-m dominates and the zones below 25Ω-m are noted at the western to central area and in the vicinity of holes Nos. 8 and 3.

d) $\overline{AB}/2 = 1{,}500$ m

The zones below 500Ω-m were recognized at the west and the area between the holes Nos. 3 and 8.

A complicated structure is presumable on the Line E, due to intense changes of resistivity.

(4) Cross-section of resistivity

The results of the VES curve analysis are given in Fig. A-3-4 and the sections are shown in Figs. 4-3-5(i), 4-3-5(ii). The method is described in Appendix A.3.4.

a) Line A

The subsurface of the Line A is roughly divided into three layers as follows.

The upper layer of a moderate to high resistivity. – The thickness of the layer ranges from 10's to 100 m at the west of point No. 600, and increases to some 200 m between Nos. 650 and 750. The values of the resistivity ranges from 100 to 6,000Ω-m, being 1,000 to 6,500Ω-m near the surface between No. 650 and No. 750.

The layer is correlated with dacites of the Quaternary at the east of No. 150 and with welded tuffs of the Tertiary to Quaternary at the west of No. 100.

The middle layer of a low resistivity from 2 to 15Ω-m. – To the west of No. 700, the layer can be correlated with pumice- and scoria-tuffs of the Tertiary to Quaternary in age. An effect of hydrothermal alteration throughout the field is possibly apparent, because being less resistive than the values obtained in the laboratory. The very low resistivity was recorded being at 2 to 6Ω-m in the vicinity of No. 150 where the hot spring of Aguas Calientes gushes out. The zones of a low resistivity are probably formed by a hydrothermal alteration in places of tuffs, overlying and underlying dacites, welded tuffs and the basement of grandiorites. The layer of a low resistivity situated to the east of No. 750 is assumed to be correlative with andesitic breccia tuffs which underwent a hydrothermal alteration.

The deep layer of a high resistivity. – The layer is correlative with the basement of granodiorites at the west of No. 750. Several faults are assumed from the difference in altitudes of basements being at 100 to 200 m below the surface between Nos. 100 and 150, and being at 600 to 800 m below the surface between No. 650 and 700 and on the No. 250.

b) Line B

The shallow layer of a moderate to high resistivity ranges from 30 to 80 m in thickness and is correlated with dacites of the Quaternary and welded tuffs, andesites and a part of pumice tuffs of Tertiary age. Outcroping on the surface and being dry, pumice tuffs seem to be resistive, though these rocks are generally more conductive in a depth.

The layer of low resistivity in a middle depth is made up of scoria tuffs with overlying and underlying beds.

The basements on this line are shallow in depths being of some 300 m, except at the point No. 50 where the basements were probably sunk to a depth which exceeded an effective penetration of the method.

c) Line C

Between the point Nos. 150 and 300, the shallow layer of moderate to high resistivity corresponds to the Quaternary dacite, the middle layer of a low resistivity to the Tertiary to Quaternary pumice tuffs and the deep layer of a high resistivity to the basements of granodiorites. The highly resistive basements increase their depth to the north. At the both ends of the line, the layer of a low resistivity has not been detected indicating a lack of hydrothermal alteration, although the separation of the electrodes was not wide enough to confirm the phenomenon.

d) Line D

Two different patterns of a resistivity structure are noted being separated between Nos. 200 and 250.

At the south, the subsurface is divided into three layers similarly with the Line A.

At the north, the resistivity remains within a low range throughout the succession in which it reaches to a value of 40 to 200Ω-m at the bottom. The low resistivity at the shallow depth probably represents the effect of hydrothermal alteration in the Tertiary andesites and the Mesozoic sediments. The idea is supported by the existence of anomalies in temperature at a depth of 1 m, and of the altered zones on the surface. The underlying zone of 40 to 60Ω-m is assumed to be correlative with the lower-Jurassic beds, probably being altered and of a high temperature, of which an assumption is drawn from the physical properties observed in the laboratory.

e) Line E

The most complicated structure in resistivity is seen on this line.

At the points Nos. 230 and 250, the depths of the basements exceed more than 1,000 m. The resistivity at the middle depth ranges from 10 to 20Ω-m and indicate the existence of alteration. The faults of large throws seem to exist.

The eastern part of No. 300 has not a zone of a high resistivity and consists of a shallow layer of 10 to 20Ω-m and an underlying layer of 30 to 150Ω-m, similarly with the north of the Line D.

(5) Structure of the resistivity basement

The Fig. 4-3-6 shows the depths of the upper surface of the highly resistive bed and faults inferred from the electrical prospecting.

i) The depth of the resistivity basement ranges dominantly from 200 to 600 m.

ii) Found are the places where the depths of the highly resistive basement exceed 800 m, between No. 650 and No. 700 of the Line A. Nos. 50 and 200 of the Line D and Nos. 230 and 270 of the Line E at the south of El Humazo.

iii) The highly resistive basement has not been delineated at the intersection of the Lines D and E.

4.3.4 Summary on Electrical Prospecting

a) The subsurface generally consists of the shallow layer of a moderate to high resistivity, the middle layer of a low resistivity and the highly resistive basements at the depth, except some places such as the vicinity of the intersection of the Lines D and E or the eastern end of the Line A.

b) The shallow layer of a moderate to high resistivity ranges from 20 to 200 m in thickness and is correlative with dacites of the Quaternary and welded tuffs and andesites of the Tertiary to Quaternary in age.

c) The middle layer of a low resistivity is correlated mainly with scoria tuffs and pumice tuffs of the Tertiary to Quaternary, being presumably hydrothermally altered or in the state of a high temperature as indicated by the values of less than 20Ω-m.

At the intersection of the Lines A and B, a low value of 2 to 4 Ω-m at the shallow depth is correlative with a source of hot spring at Aguas Calientes.

d) The high resistivity of more than 500Ω-m at the depths of deeper than 200 m is correlative mainly with granodiorites in the basements. The geological structures seem to be deeper in the vicinity of No. 200, in the section between Nos. 650 and 700 of the Line A and in the section between Nos. 230 and 270 on the Line E.

e) In the vicinity of intersection of the Lines D and E and at the eastern end of the Line A, the subsurface consists of the layer of a low resistivity at a shallow depth and of the layer of a low to moderate resistivity at the deep. Both of the layers may be correlative with the Mesozoic sediments which underwent a hydrothermal alteration or are possibly in a state of high temperature at the depths.

f) The faults or tectonic lines are dominated in the vicinity of No. 200 of the Line A, at the intersection of the Lines A and D, and in the vicinity between Nos. 230 and 250 of the Line E. These areas can be deemed to be promising for a development of geothermal energy, from the point of view of the thermo-structure where the basements are faulted to the depths.

4.4 Seismic Prospecting

4.4.1 Purpose of Seismic Prospecting

During a course of geothermal investigation, it is essential to find out a geothermal reservoir or a possible passage of fluid which is indicated by a fracture system or a crushed zone. The general concepts of the basement structure and the fracture system have been obtained from the previous surveys, such as the gravity method, etc. In the third phase survey, the seismic prospecting was employed to disclose the details of the structures which might exist in the Mesozoic sediments or the basements under the coverings of volcanic rocks of later ages. As the depths of the basements are estimated to remain in a shallow range, the Mini-Sosie method, an effective seismic reflection prospecting, was introduced.

4.4.2 Field Procedure of Seismic Prospecting

(1) Point setting

The most of the lines are in common with the lines laid for the electrical prospecting. The base points were surveyed by the Argentine party using the tellurometer CA 1,000 and the transit Wild T-2, and intermediate points were traversed by the Japanese party using a pocket compass. The lines were pegged by every 10 m of horizontal distance.

The arrangement of the lines are shown in Fig. 4-1.

The altitude of the bench mark, 300 m west of the base camps at 1,874 m A.S.L., was reduced by 67 m, similarly to the case of gravity survey in the second phase survey. From this point, the leveling was implemented by the Japanese party using the automatic level, Sokkisha Autolevel B-2, with an accuracy of $D \leq \pm 100\sqrt{S}$, where D is an error in mm in a closed traverse and S is a horizontal distance of the traverse expressed in Km.

(2) Measurement

Prior to the data acquisition, field parameters were chosen as given in Table 4-4-1 from the noise, filter and number of pops tests between the points Nos. 400 and 450 on the Line A at the central area. The methods of the test and measurement with the specifications of instruments are described in Appendix A.4.2 ~ A.4.4.

Table 4-4-1 Seismic field parameters

Number of pops	2,000 pops
Number of channels	24 channel
Shooting interval	20 m
Station interval	20 m
Number of fold	12-fold
Spread	Inline-offset
Offset	30~490 m
Record length	1.0 sec
Sample rate	1 msec
Grouping	20 m (1.2 m x 18 pcs)
Filter	Low cut 30 Hz 24 dB/oct. Notch out High cut 250 Hz 24 dB/oct.

The scheme of seismic prospecting is given in Table 4-4-2.

Table 4-4-2 Scheme of seismic prospecting

Line	Shooting points	Number of shooting	Geophone stations	Line length
A	Nos. 146~900	378	Nos. 97~897	8,020 m
B	Nos. 0~188, 192~366	183	Nos. 3 ~399	3,980
C	Nos. 8~62, 62, 74~318	152	Nos. 11~351	3,420
D	Nos. 20~240	111	Nos. 23~289	2,680
E	Nos. 50~400	176	Nos. 1~397	3,980
Total		1,000		22,080 m

4.4.3 Data Processing of Seismic Prospecting

The processing of the seismic data requires the special processors and programmes. The data were processed by Horizon Interstate Co., Ltd. During the processing, a specialist was dispatched to the processing center to examine, the method and results of processing. The results are illustrated in a form of record section. A method of data processing is attached in Appendix A.4.5.

4.4.4. Analyses of Seismic Prospecting

(1) Method

On the time sections of the record, reflections are discriminated and possible faults are detected. A phantom horizon can be traced with a continuation of a group of reflections. The indications of faulting are

i) abrupt discontinuity of reflections

ii) time lags within reflections

iii) sharp change of gradient of reflections.

The time sections are then converted to the depth sections (see Figs. 4-4-1 and 4-4-2(i) to 4-4-2(ii)).

The relationships between two way time and depth on the each line are shown in Fig. A-4-6.

(2) Results

A series of clear reflections was detected through the area ranging from 100 to 600 m in depths, except a place in the vicinity of the drilled hole No. 8 where two lines of A and D intersect each other. The phantom horizon delineated by reflections is correlative with the upper faces of lower Mesozoic sediments or the basements in which the elastic wave velocity is higher.

(a) Depth sections (Figs. 4-4-2(i) ~ 4-4-2(ii))

a) Line A

An existence of a fault, dipping to the west with a throw of more than 200 m, is assumed in the vicinity of No. 470. To the west, a series of clear reflections is noted in the depths of 300 to 500 m. Several discontinuities in the series indicate the existence of faults with small throws.

From No. 600 to No. 750, only weak reflections of poor continuity are observed to a depth of 1,200 m.

To the east of No. 800, a series of clear reflections is located in a shallow depth.

b) Line B

A series of clear reflections is recognized in a depth ranging from 300 to 600 m. Upheavals are delineated between Nos. 50 and 180, and to the north of No. 350, with possible faults at the boundaries of blocks.

c) Line C

A series of clear reflections is seen in a depth of 300 to 600 m, similarly to the Line B.

The general structure of the line comprises upheavals in the middle and downthrows at the both ends. A pattern with a downthrow between Nos. 10 and 47 and with a upheaval in the vicinity of No. 60 at the south end of the line is similar with a pattern observed at the south end of the Line B, indicating a structural continuity of geology with in the both lines.

d) Line D

Sporadically clear reflections in a shallow depth to the north of No. 210 and less continuous reflections in the depths of 1,000 to 1,500 m were recorded.

To the south of No. 210, a pattern of downthrows resembles one of the section between Nos. 600 and 750 of the intersecting Line A. Within these depressions, an existence of faults is possible, although it has not been confirmed due to poor reflections. The clear reflections at the shallow depth to the north of No. 210 is correlative with the upper face of the lower-Mesozoic sediments.

e) Line E

A series of clear reflections is noticed at the depths of 100 to 600 m, which deepens to the west. A local depression exists in the vicinity of No. 240 with an association of possible faults.

A series of clear reflections in the east of No. 290 is presumably correlative with the upper boundary of the lower Mesozoic sediments.

(b) Structure of the basements (Fig. 4-4-3)

The Fig. 4-4-3 shows the depths of the phantom horizon which is deemed to be the upper boundary of the Mesozoic sediments or the basements, and the projections of faults inferred within these sediments and the basements.

The undulations in the central and the western parts of the area are small, being of 300 to 600 m deep.

In the eastern area, a depression of a large scale is assumed around the intersection of Lines A and D. Apart from this depression, the throws of faulting range in general from 50 to 200 m.

4.4.5 Summary on Seismic Prospecting

a) A series of clear reflections was observed at the depths of 100 to 600 m, and assumed to be the responses of the upper boundaries of the lower Mesozoic sediments or the basements.

b) A deep depression is inferred to exist in the vicinity of the drilled hole No. 8 at the intersection of Lines A and D, where less continuous reflections of low amplitude were recorded at the depths of 1,000 to 1,500 m.

c) The local displacements of the reflections indicate the existence of faults with throws of some 200 m, except the faults around the depression mentioned above.

4.5 Isotopic Investigation

4.5.1 Isotopic Characteristics of Hydrogen and Oxygen in Hot Spring Water

The chemical components of the hydrogen isotope and the oxygen isotope in water from hot springs and a spring in the survey area are shown on the Hoefs (1980) diagram in Figs. 4-5-1 and 4-5-2.

The measured values fall into the category of meteoric water origin as indicated by the value of δ^{18} O.

The correlation diagram of oxygen and hydrogen isotopes is shown in Fig. 4-5-3. In the diagram, the line of Meteoric Water is expressed in the formula,

$\delta D = 8 \cdot \delta^{18}O + 10$, precipitation of the Pacific side (Craigi 1961).

Water from hot springs in the area is plotted in the vicinity of the Meteoric Water line and is assumed to be of meteoric origin with reference to Figs. 4-5-1 and 4-5-2. The most samples indicate the slight isotope exchanges which took place with oxygen in rocks when water was heated during the circulation. The values of the Sample ⑦ from La Bramadora and the Sample ③ of spring water in the Vertiente Fria Los Tachos lie on the line of Meteoric Water.

The amount of dissolved chlorine ion (mg/l) in hot spring water is correlated with the isotopic component of oxygen in Fig. 4-5-4. Water from La Bramadora ⑦is low in chlorine contents and resembles to meteoric water in the area, as illustrated in Fig. 4-5-3. Spring water of Vertiente Fria Los Tachos ③ has also a similar character. Hot spring water from Los Tachos Grandes①, Aguas Calientes ④and Lincón de Las Papas ⑤ varies in chlorine content from 780 to 970 mg/l and in δ^{18}O from -13 to -15‰.Water from Los Tachos Chicos②, Las Olletas ⑥ and El Humazo ⑧ is high in temperature and in salinity and ranges in Cl^- content from 1,500 to 2,000 mg/l. The value of δ^{18}Ois about -14 ‰. Although a number of samples is limited and the value fluctuates, the positive correlation relationship between the concentration of Cl^- and the value of δ^{18}O indicates that hot spring water is common in origin and is differentiated in the course of common process.

4.5.2 Isotopic Characteristics of Sulphur in Hot Spring Water

The chemical components of sulphur in hot springs in the investigated area are shown on the Hoefs diagram in Fig. 4-5-5.

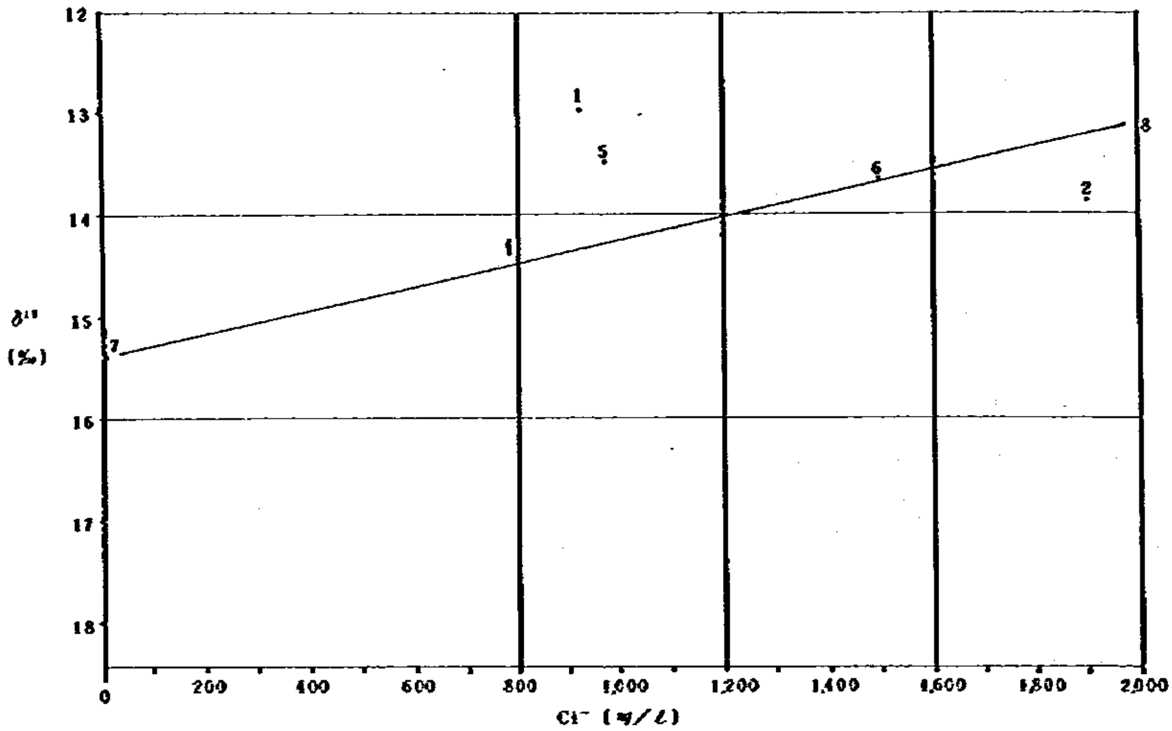


Fig. 4-5-4 Correlation between $\delta^{18}O$ and Cl^-

The contents of $\delta^{34}S$ are constant in seawater being about +20‰ in general. It varies in rocks ranging from 0 to 10‰ in granite of magnetite series (Sakai & Ishihara, 1979) from −10 to 0‰ in granite of ilmenite series and being at +4.4 ± 2.1‰ (Ueda & Sakai) in Quaternary volcanic rocks. The value in volcanic gas is being estimated to be of less than several ‰ to 10‰, although the value varies depending on each volcano. The value of $\delta^{34}S$ in hot spring waters of the area is comparatively stable ranging from 11.9 to 14.9‰. No difference is discriminated in origin of sulphur. The hot spring water was probably formed of underground water which was meteoric in origin and heated by water steam with hydrogen sulphide gas.

4.5.3. Isotopic Characteristics of Carbon in Hot Spring Water

The isotopic components of carbon in water from hot springs and a spring in the investigated area are shown on the Hoefs diagram in Fig. 4-5-6.

The value of $\delta^{13}C$ ranges broadly from −5.0 to −24.0 ‰ and a small difference in origin of carbon is indicated. If such a difference is interpreted to represent a difference of rocks from which spa water flows out or a difference of rocks which form a geothermal reservoir, the following explanation can be made. The high value ranging from −5.9 to −5.0‰ in water from the Lincón de Las Papas ⑤ and La Bramadora ⑦ suggests that the

Table 4-5-1 Isotopic analyses of hot water in Domuyo

No.	Hot spring	Elevation	δD (SMOW)‰	$\delta^{18}O$ (SMOW)‰	$\delta^{13}C$ (PDB) ‰	$\delta^{34}S$ (CD) ‰	3H TR	Date of sampling	Temperature Air (℃) / Water (℃)	pH
1	Los Tachos Grandes	2,350 (m)	−100	−13.0	−28.2	12.1	1.0	13−3−84	11.5 / 93.5	6.2
2	Los Tachos Chicos	2,250	−111	−13.9	−13.2	12.0	1.1	〃	18.0 / 93.0	7.4
3	Vertiente Fría Los Tachos	1,900	−106	−14.5	−16.4		2.3	〃	12.5 / 12.5	7.1
4	Aguas Calientes	1,800	−109	−14.4	−13.3	12.0	1.1	〃	22.5 / 67.0	7.1
5	Lincón de Las Papas	2,300	−112	−13.5	− 5.9	13.0	1.0	〃	20.0 / 40.0	6.9
6	Las Olletas	2,150	−110	−13.7	−18.3	12.0	1.0	〃	18.5 / 90.0	8.0
7	La Bramadora	3,250	−113	−15.4	− 5.0	14.9	1.8	〃	7.5 / 52.5	6.6
8	El Humazo	2,200	−110	−13.3	−24.0	11.9	1.7	〃	18.0 / 93.0	7.4

water derived from Jurassic limestones has experienced an isotope exchange of carbon with geothermal water.

On the other hand, the low value ranging from –24.0 to –28.2‰ in water from Los Tachos Grandes ① and El Humazo ⑧ indicates that carbon is originated from organic sediments. But the geology of Los Tachos Grandes ① consists of, from the depth to the surface, granites, Jurassic andesitic tuff breccias and Quaternary dacitic tuff breccias. The site of El Humazo ① is underlain by granites in deep and hornfels on top. Among hot springs with an intermediate value of $\delta^{13}C$ ranging from –13.2 to –18.6‰, the geology of Los Tachas Chicos ② is similar to the geology of Los Tachos Grandes ①, and the site of Aguas Calientes ④ and Las Olletas ⑥ are underlain by granites which are covered by Quaternary andesites and associated scorias. These phenomena suggest that a difference in contents of isotopic carbon cannot be explained simply by a difference of geological condition.

The variation in contents of $\delta^{13}C$ depends not only on the difference of geology but also on the mechanism, by which water of hot springs is yielded. Water from Los Tachos Grandes ① and El Humazo ⑧ is not almost free from an effect of deep geothermal water, and is created by heating of underground water with steam and accompanied hydrogen sulphide gas. The contents of $\delta^{13}C$ are low at –24.0 to –23.2‰. Water from Los Tachos Chicos ②, Aguas Calientes ④and Las Olletas ⑥ reflects the effect of deep geothermal water and has relatively high contents of $\delta^{13}C$ ranging from –13.2 to –18.6‰. The highest values of $\delta^{13}C$ obtained from Lincón de Las Papas ⑤ and La Bramadora ⑦ indicate, on the contrary, the geological conditions rather than the mechanism of generation.

4.5.4 Isotopic Characteristics of Tritium in Hot Spring Water

The concentration of tritium in precipitation, which is a source of geothermal water, reflects a characteristic of a mass of air flow and varies by ±50‰ of the annual average depending on a place, a time and a season of precipitation. Since, large quantities of tritium entered the hydrological cycle as a result of atmospheric testing of thermonuclear bombs. A half-life period of tritium stands at about 12.3 years and a concentration of tritium in a year 30 years before is thus estimated to be of 2.4 fold of the present concentration. But underground water is of various origins and mined with meteoric water in various ratios. A method or standard to estimate the residence times has been proposed as follows:

a) If ground water contains tritium at concentration levels of less than 1TR, it must have originated prior to 1953. A large fraction of water has a long residence time.

b) Measurements of the tritium content rest between 1TR and 5TR, the co-existence of ground water prior to 1952 with contaminated water derived from precipitation is supposed.

c) In case the tritium content exceeds 10TR, water originates from precipitation which contains tritium produced by thermonuclear bombs and has a short residence time.

Based upon these criteria, examination of the tritium concentration in hot spring water proves that all water falls in the criterion b). Rain water of later than the year 1952, has been mixed in groundwater but a large fraction of hot spring water comes from ground water, precipitated prior to 1952 and developed in a ground.

The tritium content of geothermal water ranges generally from 1 to 2TR in the depth of about 1,500 m, and is assumed to decrease to be of 0.1 to 0.4TR in the depth of about 3,000 m. The spring water in the Vertiente Fria Los Tachos ③ includes a large amount of effluence of groundwater which has a short residence time. The content of tritium stands at 2.3TR. This is followed by 1.8TR of La Bramadora ⑦ and 1.7TR of El Humazo ⑧. These examples account for generation of groundwater in relative recent years. Other hot spring water can be deemed to have originated in groundwater of a long residence time.

The mechanism of generation among hot spring waters of a comparatively long residence time has been discriminated. The isotopic characteristics of hot spring waters are shown in Table 4-5-2.

Waters of Los Tachos Grandes ① and El Humazo ⑧ have been heated by hot steam with hydrogen sulphide gas. Hot spring waters of the Lincôn de Las Papas ⑤ and La Bramadora ⑦ have experienced the isotope exchange of carbon between limestones and geothermal water in the ground. A large amount of groundwater resembling with hot spring water.

4.5.5 Summary on Isotopic Investigation

a) The most of hot spring waters investigated is assumed to be meteoric in origin, and during circulation, a minor isotopic exchange of oxygen between water and rocks took place when heated. The positive correlation between the value of $\delta^{18}O$ and the concentration of chlorine indicates that hot spring waters in the area are common in origin and are developed in common processes.

b) The value of $\delta^{34}S$ in hot spring waters is comparatively stable and no discrimination in origin of sulphur is made. Hot spring water is considered to have originated from precipitation and have been heated by steam with hydrogen sulphide gas during its circulation in the ground.

c) Based on the value of $\delta^{13}C$, it is assumed that, hot spring waters from Los Tachos Grandes ① and El Humazo ⑧ are free from an effect of deep geothermal water and are of groundwater heated by steam with hydrogen sulphide gas, and that, on the contrary, waters from Los Tachos Chicos ②, Aguas Calientes ④ and Las Olletas ⑥ are largely affected by deep geothermal water.

d) The value of tritium concentration indicates that the most hot spring waters in the area are originated from groundwater developed from precipitation prior to 1952, although newly generated groundwater is mixed in.

Table 4-5-2 Isotopic characteristics of samples

Sample No.	Temp. (°C) air / water	pH	δD (SMOW)	$\delta^{18}O$ (SMOW)	$\delta^{34}S$ (CD)	$\delta^{13}C$ (PDB)	^{3}H	Summary
①	11.5 / 93.5	6.2	-100 ‰ Mixture of ground water with geothermal water	-13.0 ‰	12.1 ‰ (Somewhat below the value of dissolved SO_4^{2-} (+20 ±1 ‰). Deep ground water has been heated by hot steam. No discrimination is possible in origin of sulphur contained in geothermal water.)	-28.2 ‰ Heated by steam and gas of H_2S, etc.	1.0^{TR} Ground water from the depths of about 1,500m.	Heating of deep groundwater by hot steam
②	18.0 / 93.0	7.4	-111 ‰ Mixing of geothermal water developed in a long residence time	-13.9 ‰	12.0 ‰	-13.2 ‰ (Participation of deep geothermal water)	1.1^{TR} Water prior to 1952 is included	Rich in geothermal water of a long residence time
③	12.5 / 12.5	7.1	-106 ‰ River water derived from precipitation	-14.5 ‰	—	-16.4 ‰	2.3^{TR} Effluence of modern water	Mixture of modern ground water with rain water
④	22.5 / 67.0	7.1	-109 ‰ Mixture of ground water with geothermal water	-14.4 ‰	12.0 ‰	-13.3 ‰	1.1^{TR} Groundwater from the depths of about 1,500m.	Mixing of groundwater with geothermal water of a long residence time.
⑤	20.0 / 40.0	6.9	-112 ‰ Mixing of geothermal water developed in a long residence time	-13.5 ‰	13.0 ‰	-5.9 ‰ Isotopic exchange with limestones	1.0^{TR} Water pior to 1952 is included	Isotopic exchange between limestones and groundwater of a long residence time. Temperature decrease due to dilution.
⑥	18.5 / 90.0	8.0	-110 ‰ Mixing of geothermal water developed in a long residence time	-13.7 ‰	12.0 ‰	-18.3 ‰ Participation of deep geothermal water	1.0^{TR}	Rich in geothermal water of a long residence time.
⑦	7.5 / 52.5	6.6	-113 ‰ Similar to meteoric water	-15.4 ‰	14.9 ‰	-5.0 ‰ Isotopic exchange with limestones	1.8^{TR} Groundwater from somewhat a shallow depth.	Isotopic exchange between limestones and geothermal water. Dilution by precipitation
⑧	18.0 / 93.0	7.4	-110 ‰ Mixing of geothermal water developed in a long residence time	-13.3 ‰	11.9 ‰	-24.0 ‰ Heated by steam and gas of H_2S, etc.	1.7^{TR} Water prior to 1952 is included	Heating of groundwater by hot steam

5. Integrated Analyses

5. Integrated Analyses

A model of the geothermal system has been presented at the completion of the second phase survey over an area of 200 Km^2. A combined analysis is made on the area of some 40 Km^2 in the third phase of the present survey, to select the promising areas for the geothermal exploitation.

The integrated analytical sections are illustrated in Figs. 5-1(i) and 5-1(ii) on each line surveyed by the electrical and the seismic methods. These sections are made up of 1) a distribution of the resistivity in the electrical prospecting and faults inferred, 2) the reflections in the seismic prospecting and faults inferred, and 3) an analytic cross-section of a two-layered structure in the gravity survey based on a balance of density of $\Delta\rho$=0.4.

The integrated analytical plan illustrates, 1) a distribution of the Bouguer anomalies (ρ=2.30 g/cm^3), 2) a distribution of the short-wave Bouguer anomalies, 3) the boundary between the blocks of the water•vapor-mixed type (Type II) and of the water-dominated type (Type III), these three being from the second phase, and 4) the isotherm at 30°C in the depth of 100 m, 5) the localities of the fracture systems inferred from the seismic prospecting, 6) the range of the areas where a depth of the upper surface of the highly resitive layer in the electrical prospecting exceeds 800 m in deep, those three being from the third stage, and 7) the locations of hot-springs and fumaroles.

In the gravity profiles of Figs. 5-1(i) and 5-2(ii), the control points are placed on the granodiorites which form the basement and crop out in rivers. The correction of the gravity trend was made to the north and to the east directions, with the rate at +0.8 mgal/Km and at +0.4 mgal/Km respectively, on the lines concerned.

The elastic wave velocity, the density and the electric resistivity of rocks are illustrated on the schematic column in Fig. 5-3.

5.1 Geothermal System in the Investigation Area

The geological structure of the area in the second phase survey was devided into two blocks. In the western block, the basements are in a shallow depth and are covered by a succession of volcanic rocks of Cenozoic age. In the eastern block, the basements are deep-seated and overlain by a succession of the Mesozoic, the Tertiary formations and volcanic rocks of the Cenozoic. The western block corresponds to a zone of high gravity anomaly (the area A in Fig. 3-3-3), whereas the eastern block to a zone of low gravity anomaly (the area C). A transitional zone (the area B) extends in the north-south direction between the two blocks.

The target area of the third phase lies between the A° Manchana Covunco and the A° Covunco on the western slope of the Co. Domo, and is situated in the high and the transitional zones of the gravity survey, being tentatively called as a Domuyo Triangle Zone. The area of the present interest is subdivided into three zones, namely, the Western, the Transitional and the Eastern Zones, owing to the characteristics in the geothermal systems delineated during the investigations in the past three years (Table 5-1).

(1) Western Zone

The Western Zone refers to a zone on the western side of a line which connects the point No. 600 on the Line A with No. 215 on the Line E. The geothermal manifestations such as hot springs and fumaroles have been known at Las Olletas, Aguas Calientes, Baños del Agua Caliente and Los Tachos Chicos, and are dominantly of water-dominated type of a temperature below 200°C, with a concomitance of the water•vapor-mixed type of a geochemical temperature above 200°C. Except at the case of the western end, the temperature of a depth of 100 m in holes normally exceeded 30°C and reached at 76.3°C in the hole No. 2 on the center of the Zone. The most part of the Zone is situated within a zone surrounded by the isogal contour of -135 mgal in Fig. 5-2, corresponding to the area of a local low in a zone of high gravity anomaly.

The Zone is further divided into two horizons depending on geology and physical properties.

The lower horizon is correlative with granodiorites in the basements, and is of a high density and of a high resistivity, and has a high elastic wave velocity. Those which coincide in a shallow depth ranging from 200 to 700 m deep are an analytic depth of the gravitational basement on a balance of density at $\Delta\rho$=0.4, an altitude of the upper face of the highly resistive bed in the electrical prospecting, and a depth of the upper face of a series of strong reflection, although the correspondence between them is not always exact.

The electrical method separates the upper horizon into two layers. The layer of the moderate to high resistivity at a shallow depth of 0 to 150 m is correlative with a succession of welded tuffs and andesites of Tertiary to Quaternary age and dacites of the Quaternary. The layer of the low resistivity at a middle depth is correlative with scoria- and pumice-tuffs, which are high in the effective porosity, of Tertiary to Quaternary age. The value ranging several to several 10'Ω-m indicates an undergoing of hydrothermal alteration or a state of a high temperature in rock saturated with water.

Faults inferred from the electrical and seismic prospectings are spaced at an interval of 300 to 1,000 m and their throws do not exceed a range of 200 m in general.

(2) Transitional Zone

In the Transitional Zone, a temperature at a depth of 100 m is usually above 30°C. The Zone falls in the field of the water•vapor-mixed type, being above 200°C of the geochemical geothermometer. There exist the geothermal manifestations with active fumaroles at El Humazo and Los Tachos.

The northern part, being between Nos. 215 and 285 of the Line E, belongs to the area A-2 of the high gravity where El Humazo is located. The southern part, being between Nos. 600 and 750 on the Line A, and between Nos. 100 to 225 on the Line D, is situated in the area B of the transitional zone in gravity where Los Tachos is located.

Both the northern and the southern parts of the Zone are divided into two horizons in common with the Western Zone in view point of rock properties, but a depth of the basements of the lower horizon is larger, indicating an existence of collapses, and varies from 800 to 1,500 m deep in the gravity survey, from 800 to 1,200 m in the electrical prospecting and

Table 5-1 Geothermal system of the Domuyo area

Western Zone	Area	The western side of the line connecting the points of No.600 on the LineA and of No.215 on the Line B		
	Geothermal manifestation	Las Olletas, Águas Calientes, Baños del Agua Caliente, Los Tachos Chicos		
	Type of hot spring	mainly water-dominated (Type II)		
	Temperature at the 100m depth	mainly over 30℃		
	Depth (m)	0~150		200~700
	Lithology	Quaternary Dacite Quaternary Weldedtuff ~Tertiary Andesite	Quaternary Scoria tuff ~Tertiary Pumice tuff	Basement Granodiorite
	Resistivity	medium~high	low	high
	Depth of gravimetric basement (m)	100~700		
	Depth of seismic basement (m)	200~600		
Transitional Zone	Area	Transitional zone		
	Geothermal manifestation	El Humazo, Los Tachos		
	Type of hot spring	water・vapor-mixed (Type I)		
	Temperature at the 100m depth	over 30℃		
	Depth (m)	150~200		800~1,500
	Lithology	Tertiary, Jurassic rocks		Basement Granodiorite?
	Resistivity	medium~high	low	high
	Depth of gravimetric basement (m)	800~1,500		
	Depth of seismic basement (m)	500~1,200		
Eastern Zone	Area	The eastern side of the line connecting the points of No.750 on the LineA and of No.285 on the LineE		
	Geothermal manifestation			
	Type of hot spring	Water・vapor-mixed (Type I)		
	Temperature at the 100m depth	over 50℃		
	Depth (m)	50~200		
	Lithology	Tertiary, Jurassic rocks		
	Resistivity	low	medium	
	Depth of gravimetric basement (m)	200~1,200		
	Depth of seismic basement (m)	100~300		

from 500 to 1,200 m in the seismic prospecting.

Similarly to the Western Zone, the upper horizon is divided into two layers. The low resistivity in the deep layer indicates an undergoing of hydrothermal alteration or a state of a high temperature accompanied by geothermal fluid.

The Zone is covered by a sequence of dacites of the Quaternary to a depth of several ten's meters. The zone of the low resistivity in the electrical method at the deep is correlated with the Jurassic formation in the northern part and with a succession of Tertiary and pre-Tertiary formations in the southern part.

(3) Eastern Zone

The Eastern Zone refers to the east side of the lines connecting the points No. 750 on the Line A, No. 225 of the Line D and No. 285 of the Line E. The Zone is situated in an area of the water•vapor-mixed type, with a geochemical temperature above 200°C, and located within the transitional zone B of the gravity survey. The temperature in the depth of 100 m consistently exceeded 50°C and reached at 94°C in a depth of 10 m of the hole No. 4. The heat potential in the Eastern Zone is assumed to be high in comparison with the Western and Transitional Zones.

The Zone is further divided into the northern part where the hole No. 4 is located and the southern part where the hole No. 9 is situated. Zones of alteration are widespread in the northern part and are observed in places of the southern part.

The geology of the northern part consists of the Jurassic formation. The southern part is underlain by a thick succession of the pre-Tertiary and the Tertiary with a cover of dacites of Quaternary age. In the Zone, the relationship of the responses of the geophysical prospectings is not clear. The analytic depth of the basement in the gravity survey varies from 200 to 700 m in the northern part, and from 1,000 to 1,200 m in the southern part. The depth of the reflections in the seismic prospecting ranges from 100 to 300 m through the Zone. In the electrical method, the low resistivity in a shallow (50 to 200 m) is assumed to indicate a regional existence of an altered zone, correlative with a zone of alteration delineated on the surface. The moderate resistivity in a middle to a deep is supposed to indicate an undergoing of alteration or a state of a high temperature in rocks with the low effective porosity, not saturated by an enough amount of geothermal fluid, as suggested by the values of the resistivity.

(4) Summary of the analyses of the geothermal system

The results of the third phase survey substantiate the results of the second phase and are summarized as follows.

(a) Faults and fracture systems

According to the results of the electrical and seismic prospectings, faults and fractures in the pre-Tertiary rocks are spaced at an interval of 300 to 1,000 m, and have a throw which reaches up to 200 m at its maximum in the Western Zone. A greater throw is assumed on the boundary of or within the Transitional Zone.

(b) Heat flow structure

A semi-dome structure with an axis trending in the direction of east-west was indicated by the distributions of geothermal activity of a hydrothermal alteration, of geothermal manifestations such as hot springs and fumaroles, and of the ground temperature at a depth of 100 m. The temperature increases toward east suggesting that the eastern side is high in heat potential and that a heat source may be located in a depth at the east of the area of the third phase survey.

(c) Circulation mechanism of geothermal fluid

The isotopic study of hot-spring waters shows that waters in the area are common in meteoric origin and were differentiated and developed in common processes. Most waters have a life in excess of 30 years originated in prior to 1952 of the thermonuclear explosion. But waters from Aguas Calientes, Las Olletas and Los Tachos Chicos of the Western Zone are assumed to have a longer residence time.

The assumed circulation mechanism of the geothermal fluid in the area can be presented as follows. The precipitation to the east of the transitional zone in the gravity is infiltrated to a depth and heated by a heat source. The water traverses in the ground and comes out through faults or crushed zones to gush out on the surface.

In the Western Zone, a slight modification of a system is possible. The water in the transitional zone of gravity or in the west of the zone, comes up through fractures or crushed zones and flows toward the west in the middle layer, which is represented by a layer of a low resistivity in the electrical prospecting. Then, the water and vapor will spout out or blow off on the surface.

5.2 The Promising Area

Consequently, the Transitional Zone of the present investigation is selected as the most promising area for geothermal development.

In the Western Zone, the depths of the basements and of the possible reservoir are shallow and the heat potential falls behind the above. Although the heat potential in the Eastern Zone is high, the geophysical prospectings indicate that the depth of a reservoir would be great.

The Transitional Zone forms a local low of gravity anomalies. The depth of the layer of a low resistivity exceeds 800 m. Within the Zone, the existence of faults, crushed zones or collapses of the basements is assumed. The temperature at a depth of 100 m stands at the above of 30°C. The Zone is adjacent to the geothermal manifestations of hot-springs and fumaroles of the water-vapor-mixed type.

The Zone is subdivided into two parts.

(a) Area Ⓐ

The southern part of the Transitional Zone is referred as the Area Ⓐ which covers a space of about 2.5 Km^2, being of 2.5 Km north-south and 1.0 Km east-west, over an area between the points Nos. 625 and 750 on the Line A and Nos. 100 and 225 on the Line D.

The Area is situated on the transitional zone B of gravity where the depth of the basements increases sharply toward the east and where the gravity anomaly of local low is delineated. Within the Area, a large collapse of the basements and overlying beds is assumed possibly to exist, in which these rocks, medium to high in density and low to moderate in porosity, were intensively crushed and hydrothermally altered to reduce their density.

In the holes No. 9 in the southeast and No. 14 in the northwest, Tertiary formations were intersected at the depths of 68 and 60 m, respectively. The possible reservoir will be in a succession of andesitic to dacitic tuffs of the Tertiary, which are low to medium in density and moderate to high in effective porosity.

A circulation mechanism of geothermal fluid is assumed as follows.

The water precipitated to the east of the gravitational transition zone is infiltrated to a depth where the water is heated. The water comes up and remains in a storage of a depth ranging from 300 m to 1,200 m. A part of water spouts out and blows off as the manifestations at Los Tachos in the south.

(b) Area Ⓑ

The northern part of the Transitional Zone is referred as the Area Ⓑ which covers an area of 0.6 Km² being 1.2 Km north-south and 0.5 Km east-west where the points between Nos. 215 and 285 on the Line E are situated.

The Area lies in the south of the geothermal manifestation at El Humazo and in the gravity anomaly of local low in a zone of high gravity anomaly. A structural continuation between the Area and El Humazo is supposed to exist.

The lower Mesozoic formations were intersected in the hole No. 3 on the southwest at a depth of 35 m and in the mouth of the hole No. 4 on the northeast. An expected geothermal reservoir will be found in the lower Mesozoic formations or the basements. Being high in density and low in effective porosity, these rocks are generally not able to be deemed as a geothermal reservoir. But the existence of active manifestation at El Humazo, formation of the gravity anomaly of local low, and the possible existence of many faults and fractures indicate that the rocks have been crushed and hydrothermally altered to an intensive extent. Therefore, the geothermal reservoir in the Area is assumed to have a vertical structure composed mainly of a fracture system.

6. Summary

6. Summary

6.1 Purpose and Circumstances of the Project

The survey on 'the Geothermal Development Project of the Northern Part of the Province of Neuquén, Angentine' is implemented in conformity to the Scope of Work signed on the day of 25th, February 1982 between the Government of Japan and the Government of the Argentine Republic.

The first phase survey was carried out in February and March of 1982. It consists of the interpretations of the satellite (LANDSAT) images covering an area of 15,000 Km^2 and the aerial photographs covering an area of 5,000 Km^2 in the northern part of the Province of Neuquén, and the reconnaissance field survey with the analyses and the compilation of existing bibliographies. As the result of the survey, a target area for geothermal development was narrowed down to an extent of 200 Km^2, which was to be investigated in the second phase.

The second phase survey was initiated by the topographic mapping prior to the field investigations during a period from November 1982 to March 1983. The investigations comprise surveys of geology, petrology, alteration, geochemistry and hydrology with a gravity survey. Measurements of the ground temperature at a 1-m depth and reseaches on hot-springs and fumaroles were also implemented in conjunction with the laboratory investigation of rock properties. In consequence of the field investigations, the geology, the geological and the heat flow structures and a circulation mechanism of geothermal fluid were elucidated and models of a geological structure, an areal and a cross-sectional heat flow structures, generation and circulation of geothermal fluid, and a geothermal fluid reservoir structure were presented.

On account of a high potential of geothermal development, the third phase of the survey was recommended to be implemented and a selection was made over an area of about 40 Km^2 to be investigated.

The field survey of the third phase was commenced in November 1983 and completed in March 1984. The scheme of the survey consists of electrical and seismic prospectings, measurement of a heat flow in holes of a 100 m depth, and investigations of isotopes and rock properties.

Consequently, the geothermal system has been clarified and two promising areas have been selected by an overall analyses in areal and longitudinal examinations of the results obtained in the study through the first to the third phases.

Recommended are the measures which will be necessitated in an exploitation survey in the future over the area pointed out.

6.2 Summary of the Third Phase

(1) Heat flow survey

The amount of the heat discharge in the area of 40 Km^2 in the third phase of the survey stands at 4.5×10^5 cal/sec, and the value of the heat flow averages 11.3 HFU, indicating that a heat flow potential of the area is extremely high.

A zone of high temperature above 30°C at the depth of 100 m and a zone of high heat-flow over 10 HFU were delineated between A° Manchana Covunco and A° Covunco. A semi-dome structure of high temperature, with an axis trending east-west and a spread toward the east, was indicated.

(2) Electrical prospecting

a) Western Zone

The western side of a line connecting El Humazo with Los Tachos can be divided into three layers.

The upper layer of the moderate to high resistivity is correlated with welded tuffs, andesites and dacites. The middle layer of the low resistivity is correlative with scoria tuffs and pumice tuffs which are, probably, hydrothermally altered or in a state of high temperature with an association of water, as indicated by the resistivity (1's to 10's Ω-m) observed, in comparison of physical properties obtained in the laboratory. All these rocks are of Cenozoic age. The lower layer is of the high resistivity (beyond 500 Ω-m) and located at a comparatively shallow depth ranging from 200 to 700 m. This layer is correlative with the basement rocks in the area.

b) Transitional Zone

The Transitional Zone is situated at the south of El Humazo and the north of Los Tachos centered by the hole No. 8. Also, the three-layered structure was inferred, but the depths of the highly resistive layer exceeds 800 m from the surface, indicating an existence of a large collapse in geology.

The middle layer of low resistivity is correlated chiefly with Tertiary and Mesozoic formations which are hydrothermally altered or in a state of high temperature with associating water.

c) Eastern Zone

The Eastern Zone covers an area where the holes Nos. 4 and 9 are situated. The zone is separated into two layers, the shallow layer being low and the deep layer being moderate in resistivity. Both of the layers are correlative with Tertiary and Mesozoic formations. An intensive hydrothermal alteration is noticed, at least, in a shallow depth as indicated by occurrences of alteration zones and distributions of the ground temperature at a 1-m depth and geochemical anomalies.

(3) Seismic prospecting

a) On the west and the middle of the surveyed area, the depth of the basement rocks is rather small, ranging from 100 to 600 m from the surface.

b) In the vicinity of the hole No.8, the depth of the basements is probably not less than 1,000 m.

c) Faults and fractures in the basements are spaced at an interval of 300 to 1,000 m. The throws of these faults are generally less than 200 m, but in the vicinity of the hole No.8 a greater throw is forecasted.

(4) Isotopic investigation

The most waters of hot-springs and fumaroles are meteoric in origin and are differentiated and developed in common processes. The residence time of the waters is, at least, not less than 30 years.

The hot-spring waters from Aguas Calientes, Las Olletas and Los Tachos Chicos on the west have probably a longer residence time.

(5) Synthetic interpretation

The area of the present interest is divided into three zones.

a) Western Zone

The Zone refers to an area where the geothermal manifestations of Las Olletas, Aguas Calientes, Baños del Agua Caliente and Los Tachos Chicos, etc. are situated. These are of the water-dominated type of geothermal systems, being below 200°C in geothermometers and rarely accompanied with fumarolic gases.

The basements lies in a shallow depth ranging from 200 to 700 m and throws of faults or fractures are within a range less than 200 m.

The middle layer, which is correlative with scoria tuffs and pumice tuffs of Tertiary to Quaternary age, has probably undergone a hydrothermal alteration or is at a high temperature with an association of water.

The Zone is deemed to be rather far away from a heat source.

b) Transitional Zone

The Transitional Zone covers an area of active geothermal manifestations of emitting gases at El Humazo and Los Tachos, where the water·vapor-mixed type with a temperature beyond 200°C in geothermometers is dominant.

The depth of the basements is in excess of 800 m, indicating the existence of a collapsed structure with the development of associated fractures. The section between 200 and 800 m in deep is correlative with Tertiary and pre-Tertiary formations accompanied with faults and fractures. This section is assumed to be hydrothermally altered and to be at a high temperature as indicated by geophysical investigations.

c) Eastern Zone

The highest heat potential is delineated in the Eastern Zone where the water·vapor-mixed type with a geothermometer temperature beyond 200°C predominates and the temperatures at the depth of 100 m consistently exceed 50°C.

The Zone is underlain by a thick succession of Tertiary and Mesozoic formations. The basements are latent in deep. Hydrothermal alteration in shallow portion of the Zone is indicated by the distributions of altered zone on the surface and of the temperatures in the depth of 1-m with the distribution of geochemical anomalies.

6.3 The Promising Areas

Two promising areas, for the geothermal development, labelled Ⓐ and Ⓑ, have been selected in the Transitional Zone, being adjacent to the prominent geothermal manifestations. The existence of geothermal fluid at a high temperature beyond 200°C is expected. Many fracture systems are accompanied and a depth of the basements exceeds more than 800 m in these areas.

a) Area Ⓐ

The Area Ⓐ is situated on the north of Los Tachos, being 2.5 Km north-south and 1.0 Km east-west and covering an area of about 2.5 Km^2. The andesitic to decitic tuffs of the Tertiary to upper Mesozoic are expected to be a layer of the reservoir, on account of a low to moderate density and a moderate to high effective porosity. The geophysical prospectings have indicated an existence of a collapse in the basements and of developed fractures. The possible geothermal fluid reservoir will extend not only to the lateral directions but also to the vertical direction.

b) Area Ⓑ

The Area Ⓑ is on the south of El Humazo and covers a space of 0.6 Km^2, being 1.2 Km in north-south and 0.5 Km in east-west. A structural continuation between the Area Ⓑ and El Humazo is presumed.

The lower Mesozoic formations and the basement rocks of a high density and a low effective porosity, are assumable to have been intensively crushed by many fracture systems. A vertical structure is anticipated to extend to a depth as a possible geothermal fluid reservoir in the Area.

6.4 Measures for Exploitation Survey in the Future.

(1) The area of the best priority .

The both Areas Ⓐ and Ⓑ offer the potential occurrences of geothermal fluid. Although an intensive anticipation is held over these areas, the best priority is given to the Area Ⓐ where an investigation well shall be drilled.

In comparison with the Area Ⓑ, the Area Ⓐ has more suitable rock assemblages and a larger spread in the geothermal structure for a reservoir.

The basements stand at the depth ranging from 800 to 1,200 m and the overlying rocks will have a reservoir structure which extends laterally and vertically, and is accompanied by faults and fractures. Consequently, a depth of 1,500 m should be covered by an investigation well.

A selection of the site of the well was made on the bases of dense concentration of fractures delineated by the various geophysical surveys, the continuation of anomalies in mercury of soils and the concentrations in gasses which display an active movement of geothermal fluid. The site has been placed in the vicinity of the boundary of a collapsed structure in the present assumption.

After the completion of the field surveys in 1984, a hole was opened in the Area Ⓐ to be drilled to a depth of 400 m for the measurements of ground temperature. The hole was suspended on its way, but has been reported to be re-opened to provide more detailed information. Re-examinations of a site and a depth of the proposed investigation well depend on the forthcoming information.

(2) Investigations required in the future

The geothermal investigations and exploitations consist of, in general, the following process in stages: –

I. Stage of Potential Evaluation I-1 Reconnaissance Survey I-2 Basic Survey (1) Surface investigation
(2) Well logging at the first stage I-3 Pre-feasibility Study
II. Stage of Reservoir Evaluation II-1 Exploitation Survey (1) Well logging at the second stage (2) Construction of Test Plant II-2 Feasibility Study
III. Stage of Exploitation III-1 Sinking of Production Wells III-2 Designing of Production Plant III-3 Construction of Production Plant

The present survey has resulted in finding of a great interest and completed a step of surface investigation in the process. If one moves toward the direction of exploitation, a strong possibility of an occurrence of geothermal reservoir should be confirmed, in conjunction with the evaluations of a geothermal potential, a contribution and an efffect on the district which will be brought in by the introduction of exploitation. In addition, the possibilities of completing the potential evaluation stage and of implementing the coming stage should be examined. For this purpose, the following investigations by steps are considered to be necessary.

a) Re-opening the hole of a 400 m deep and measuring the temperatures

The hole, which was suspended due to the seasonal and weather conditions, should be continued to be drilled and the measurement of the ground temperatures should be performed to a depth of a 400 m to provide the data in details, enabling a depth of reservoir to be forecasted with accuracy.

b) Sinking of an investigation well of a 1,500 m deep

Sinking of the investigation well of a 1,500 m deep in proposed to delineate a reservoir. The results of the present survey have indicated a possibility that the well may penetrate the reservoir or a layer of a high temperature in a comparatively shallow depth. A full measure should be taken for safety, such as an installation of a prevender, etc. in the course of a drilling operation. Information required for the measure will be provided by the data obtainable in the 400 m-hole. The scheme of the investigation well is presented as follows.

Number of well	:	1
Inclination	:	vertical
Well diameter	:	HQ (97.5 m/m) at the bottom
Method	:	all coring
Accomplishment	:	The hole should be cased with a full hole cementing. Strainers are installed at necessary positions.

c) Research of rock properties

The density, effective porosity, magnetic susceptibility, electric resistivity, thermal conductivity, elastic wave velocity, etc. are measured on the cores obtained in the investigation well. The X-ray analysis of alteration minerals and the microscopic observation will be made. These data provide the basic information required for various loggings in the investigation well.

d) Loggings in the investigation well

The temperature and the electrical loggings will delineate a vertical extent and physical conditions of the reservoir and provide the data for re-analysis of the project in conjunction with the data so far obtained.

e) Blowout test

The blowout characteristics are delineated and analysed through the static and the dynamic tests, for verifying the production capacity of the geothermal reservoir.

f) Overall re-analysis

Re-assessment of the promising area will be performed and the accuracy of the presumed structure of the geothermal reservoir will be increased through an overall analysis of the data mentioned above.

g) Pre-feasibility study of economic and social potential

An economic and a social contribution and effects on the northern part of the Province of Neuquén, which is one of the under-developed and less-populated area in the country, should be assessed. The overall evaluation of the project will determine the direction and the measures of the exploitation investigation at the next stage.