UTILIZATION OF GEOTHERMAL ENERGY IN JAPAN

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SUMMARY

Japan, being one of the leading volcanic countries in the world, has very abundant potential reserves of geothermal energy that are reportedly estimated at one TW ($T = 10^{12}$), in terms of power generation output, which is equal to about four times the present total energy demand of the country. On the other hand, the existing scale of geothermal power stations in Japan, including those under construction, is about 220 MW, and multi-purpose utilization is now being applied to bathing, small-scale greenhouse cultivation, etc. From the point of view of energy supply diversification and local community welfare, the implementation of the development of geothermal resources is being strongly demanded.

In view of this situation, the national government, in order to promote the development of geothermal resources, has taken up geothermal energy as part of the Sunshine Project, and is going ahead with efforts toward the establishment of geothermal survey and prospecting techniques, drilling and extraction techniques, techniques for power generation utilizing geothermal hot water, techniques for power generation from volcanoes or hot dry rocks, and techniques for environmental preservation and multi-purpose utilization. At the same time, there are under way surveys, including boring operations, on geothermal areas across the country for the development of geothermal resources, environmental impact surveys to facilitate the planning of geothermal

power station sites, surveys for effective utilization of hot water, commercialization tests, the provision of loans for construction of geothermal power stations, and so forth.

Through these measures, geothermal power generation is expected to supply about 6 GW ($G = 10^9$) by 1990 and about 48 GW by 2000.

I. PRESENT STATUS OF GEOTHERMAL RESOURCES UTILIZATION IN JAPAN

Japan, being one of the leading volcanic countries in the world, has very rich potential reserves of geothermal energy, and depending upon their development, it is possible to cover a considerable proportion of the future energy requirements. Besides, in the sense of utilizing what can be called the only untapped resources, that is expected to contribute toward improving the energy situation in Japan that relies on overseas sources for most of its energy demand.

The country has 65 active volcanoes. Including these, there are more than 200 so-called geothermal areas. It is said that there exists one-tenth of the whole geothermal energy of the world in Japan. As for the reserves of geothermal energy, the Geological Servey of Japan, Agency of Industrial Science and Technology, is conducting a country-wide basic geothermal survey on shallow hydrothermal systems as part of the Sunshine Project, and the G.S.J. tentatively estimates that about 18 GW electric power can be generated through the 30 areas included in the survey. This result, if extended as such to 200 areas across the country, would mean that it is possible to generate about 130 GW.

Survey and prospecting techniques on geothermal energy are still in an initial stage of research and development, and sufficiently accurate supporting data are not available, yet based on the knowledge and information available to date, including other methods of geothermal utilization, the potential reserves of geothermal energy, aggregating shallow hydrothermal system, very deep hydrothermal system, hot dry rocks, volcanic energy, non-volcanic hot water etc., are estimated at about 1 TW, which is equal about to four times the present total energy demand of Japan.

At present, there are five geothermal power stations in operation and two under construction, their power generation output totalling about 220 MW (Table 1).

In a field other than power generation, there is what is called multi-purpose utilization of geothermal resources, and in Japan this is limited, in most cases, to bathing applications (hot spring utilization) where the level of utilization temperature is low.

In power generation, moreover, the great amounts of hot water (temperature level, about 100°C) that flows out are available for multi-purpose utilization, including greenhouse cultivation and fish farming. The multi-purpose utilization of hot water now being practiced or planned in our country is as indicated in the accompanying Table 2 and 3. If geothermal power generation is augmented in the coming years, this multi-purpose utilization will be increased by leaps and bounds, going a long way to the development of local welfare.

II. MEASURES FOR DEVELOPMENT OF GEOTHERMAL RESOURCES

In order to promote the development of geothermal resources, the following measures are being taken:

(1) Geothermal resources development implementation surveys

Various surveys, including surveys on the diffusion of hydrogen sulphide from power station, are under way from the view point of technological needs involved in geothermal resources development.

(2) Geothermal resources development surveys

At present, there are about 200 promising geothermal areas confirmed in our country. These areas have been under basic surveys since 1973, including geochemical surveys and prospecting, natural heat discharge surveys, and seismic prospecting, and those points deemed particularly promising from basic survey results have been under close surveys, centered on boring, since 1974, in order to determine underground structures, the scale of geothermal reservoirs, and other conditions.

(3) Geothermal environment surveys

Geothermal power generation sites tend to be impeded because of the opposition from local inhabitants and other interests caused by environmental problems. To overcome this situation, the sites slated for geothermal development are given environmental survey boring operations by the government to check and make sure that there are no effects on the local plant life, river water, underground water, hot springs, etc., by geothermal steam and hot water, hydrogen sulphide, etc.

(4) Surveys for effective utilization of geothermal hot water

In order to help streamline the planning of geothermal power generation plant sites, multi-purpose utilization feasibility surveys and commercialization tests, with respect to the multi-purpose utilization of hot water flowing out of geothermal power stations, are under way as delegated to the local governments that have jurisdiction over the planned generation sites.

(5) Research and development of geothermal energy technology (Sunshine Project)

In order to promote geothermal energy development, research and development have been under way since 1974 as to techniques for prospecting and extracting geothermal energy, techniques for power generation utilizing hot water, volcanic power generation techniques, and techniques for environmental preservation and multi-purpose utilization (the particulars stated later).

(6) Others

Loans are being provided to aid in the construction of geothermal power generation stations.

In this connection, a chart of the relationships among administrative agencies concerned with geothermal development, etc., is shown in Fig. 1, and the procedure for geothermal resources development, in Fig. 2.

III. PROSPECTS FOR DEVELOPMENT OF GEOTHERMAL RESOURCES

As to prospects for geothermal power generation, a report (Oct. 1969) by the Energy Research Council of the Economic Planning Agency gives its volume as 145 million kW, but refers to 20 GW as that volume which can be economically tapped at existing technological levels.

Estimating the amount of hot water stored underground, the report assumes that it will be extracted continuously during the year 2000.

In estimating that amount of hot water, the report puts the area of the regions covered at 26,000 km^2, the thickness of formations containing hot water at 1.5 km, and the porosity of the formations at 10 per cent.

A report (Jan. 1974) by the Geothermal Subcommittee, Energy Technology Committee, Industrial Technology Council, predicts that power generation utilizing deep geothermal reservoirs, power generation utilizing volcanoes or hot dry rocks, etc., in addition to the system of power generation by shallow geothermal reservoirs which is now in practical service, will have been put into practical operation by 2000, and that, in that case, installed power generation capacity will reach about 48 GW (Table 4).

Meanwhile, a tentative paper (June 1977) on prospects for long-range energy supply and demand, by the Supply and Demand Subcommittee, Advisery Committee for Energy, predicts that geothermal power generation will supply about 6 GW and 330 MW will undergo multi-purpose utilization, by 1990.

IV. RESEARCH AND DEVELOPMENT PROJECT (SUNSHINE PROJECT) OF GEOTHERMAL ENERGY IN JAPAN

(1) Forward

In the face of the energy crisis and environmental pollution, Japan, to which a solution to these problems is of particular importance; must make the development of new energy technology a national project.

"Sunshine Project" is an ambitious national technological development program commenced in 1974 and to be completed by the year 2000.

Through the utilization of inexhaustible, pollution free solar energy, geothermal energy, etc., "Sunshine Project" is expected to alleviate the energy crisis resulting from the exhaustion of petroleum resources, and to give back to the earth its fresh green and lifegiving sunshine. To expedite the project, research and development is to be carried out on a long-term timetable, planned as far as the year 2000 and, at same time, a medium-term schedule.

Energy sources to be treated as the objects of the project from the year 1974 are as follows:

(i) Solar Energy

(ii) Geothermal Energy

(iii) Coal Gasification and Liquefaction

(iv) Hydrogen Energy

(v) Supporting Research

"Sunshine Project" is to be promoted on a national scale with full cooperation from national research institute organs, universities and private enterprise, as well as through international cooperation with projects in other countries.

(2) Outline of Technological Development

a) Technology for exploration and extraction of geothermal energy.

The current exploring techniques largely depend upon those used for petroleum resources exploration, both in method and equipment. However, in order to attain adequate precision in the future, it is necessary that new exploring techniques suited to geothermal prospecting will be developed.

With regard to geothermal well drilling techniques, progress is being made in applying the air drilling method as well as the conventional mud drilling method. In the future, drilling will be made into rocks with even higher temperatures ($300^{\circ} \sim 400^{\circ}C$), therefore, the development of high temperature and corrosion resistant materials is compulsory. Together with a drilling machine, much more severe conditions will be imposed on the well logging instruments, with respect to their heat resistance, pressure resistance, and corrosion resistance; consequently, efforts must be made to improve their performance capacities. In the interests of preventing environmental disruption and reducing heat loss, incline drilling may also be widely adopted.

Consequently, the object of studies is to establish methods for confirming the amount of geothermal deposits and to develop technology for exploring and assessing geothermal resources as well as technology for excavating high-temperature rock in order to reduce the risks involved in development.

b) Technology for power generation utilizing hot water

The power generating system today, is limited to the use of natural steam, but the effective use of hot water associated with natural steam must be developed. For this purpose, the development of binary cycle power generating system using low enthalpy fluids such as Freon or isobutane as the carrier of heat energy, or a combined cycle system combining the former with the natural steam system are expected.

The object of studies is to develop the technology for corrosion-resistive materials, technology for high-efficiency heat exchange, etc., and to develop a high-efficiency binary-cycle power generating system by the late 1980's. Construction is presently being advanced on a 2-system (1MW hot water type, combination hot water and steam type). These systems will be constructed by the end of 1977 and undergo test run.

c) Technology for a volcanic power generating system

The development of hot dry rock fracturing techniques and artificial hot water evolving system for extracting and utilizing thermal energy possessed by hot dry rocks is very important and a challenging theme.

There is a high potential for the development of power generation by extracting thermal energy from volcanoes and hot dry rock utilizing the aforementioned techniques of forming artificial hot water systems.

Therefore, studies are carried out to develop the technology for fracturing into hot dry rock, technology for forming man-made hot water systems, etc., and to develop high-efficiency, large-capacity volcanic and hot dry rock power generating systems by the mid-1990's.

d) Technology for multi-purpose utilization of geothermal energy and environmental preservation

Effective use of hot water associated with geothermal power generation is important in view of reducing power generating costs by allocation and the contribution to regional development. The power generating plant in multi-purpose use of geothermal energy may be called a local welfare type power plant. The multi-purpose use of geothermal energy will also be highly effective in preventing environmental pollution caused by the discharge of hot waste water.

Environmental effects brought on by geothermal fluids must be fully controlled. These include corrosive gases and chemical components discharged from geothermal fluids, as well as hot water and solids, adversely affecting the human organism and the ecological systems. It is imperative that comprehensive techniques for environmental protection be established.

Therefore, studies are carried out to develop technology for transporting geothermal fluids, and to develop geothermal energy utilization systems for regional heating, agriculture, and other purposes.

Furthermore, studies aimed at developing technology for environmental preservation in order to prevent adverse effects on the natural environment and ecosystem from the extraction and utilization of geothermal fluids are being carried out.

Implementation programs of the above-mentioned geothermal energy R & D are shown in Fig. 3.

Table 1. Geothermal Power Stations in Operation or under Construction

Name of company		Name of power station	Output (MW)	Completed and expected completion date	Location
In operation	JMC	Matsukawa	22	Oct. 1963, and operated at 20 MW until April 1973	Iwate Pref.
	KYUDEN	Otake	11	Oct. 1967	Oita Pref.
	M'BISHI METAL	Onuma	7.5 (10)	June 1974, and operated at 6 MW until May 1975	Akita Pref.
	DENPATSU	Onikobe	12.5 (25)	Mar. 1975	Miyagi Pref.
	KYUDEN	Hatchobaru	23 (50)	June 1977	Oita Pref.
Under construction	JMC & TOHOKU	Kakkonda	50	Apr. 1978	Iwate Pref.
	JMC & HOKUDEN	Mori	50	Mar. 1980	Hokkaido

Note: Values in parentheses are planned values.

JMC : Japan Metals & Chemicals Co., Ltd.
KYUDEN : Kyushu Electric Power Co., Inc.
M'BISHI METAL : Mitsubishi Metal Corporation
DENPATSU: Electric Power Development Corp.
TOHOKU: Tohoku Electric Power Co., Inc.
HOKUDEN: Hokkaido Electric Power Co., Inc.

Table 2. Utilization of Geothermal Resources according to Temperature Ranges

180°C	Distillation, ammonia refrigeration, manufacture of papers	
170	Production of heavy water, drying of diatomaceous earth	Electric power generation using natural steam
160	Drying of fish meat, drying of lumber	
150	Manufacture of alumina, air cooling	
140	Drying of agricultural products, canning	
130	Sugar refining	
120	Production of fresh water	
110	Drying of cement	Binary cycle power generation
100	Hay making, processing of foods, cooking, manufacture of salt	
90	Manufacture of dried fish, ice thawing, road snow melting	
80	District heating, green house, poultry farming	
70		
60	Heating cattle sheds, hotbeds, thermostats	
50	Mushroom growing, bathing	
40	Heating the soil	
30	Heated swimming pool, fish farming, sewage treatment	
20	Road snow melting by spraying hot water	

Table 3. Present Status of Multi-Purpose Utilization of Geothermal Hot Water

Power station	Hot water output	Consumer & supply volume	Starting date of supply	Supplier
Matsukawa JMC (in operation)	(Heat exchange of steam and fresh water)	Hachimantai hot spring district, Matsuo Village (5.5 km from power station) -- 1,000 t/min., 75°C	1971	Hachimantai Hot Spring Development Co., Ltd.
		Forest ranger huts & Matsukawa hot spring hotels (3) -- 20 t/hr.	Aug. 1973	JMC
Otake Hatchobaru KYUDEN	Otake 370 t/hr. Hatchobaru 190 t/hr. (200 t/hr. river water heat exchanged to 79°C and supplied, and geothermal hot water totally reinjected into underground)	Private houses (110) Hotels (30) } 209 t/hr.		KYUDEN

Table 3. Present Status of Multi-Purpose Utilization of Geothermal Hot Water (Cont'd)

Power station	Hot water output	Consumer & supply volume	Starting date of supply	Supplier
Onuma M'BISHI METAL	266 t/hr. (15 t/hr. swamp water heat exchanged to 60 - 70°C and supplied, and geothermal hot water totally reinjected into underground).	Lodging facilities in the neighborhood -- 15 t/hr.	1972	Kazuno City
Kakkonda (under planning)	2,000 t/hr.	Morioka City & Shizukuishi Town -- 1,900 t/hr. -- district heating, road snow melting, green house gardening, tourism, industry	1978	

Table 4. Prospects for Geothermal Power Generation Development

(Unit : MW)

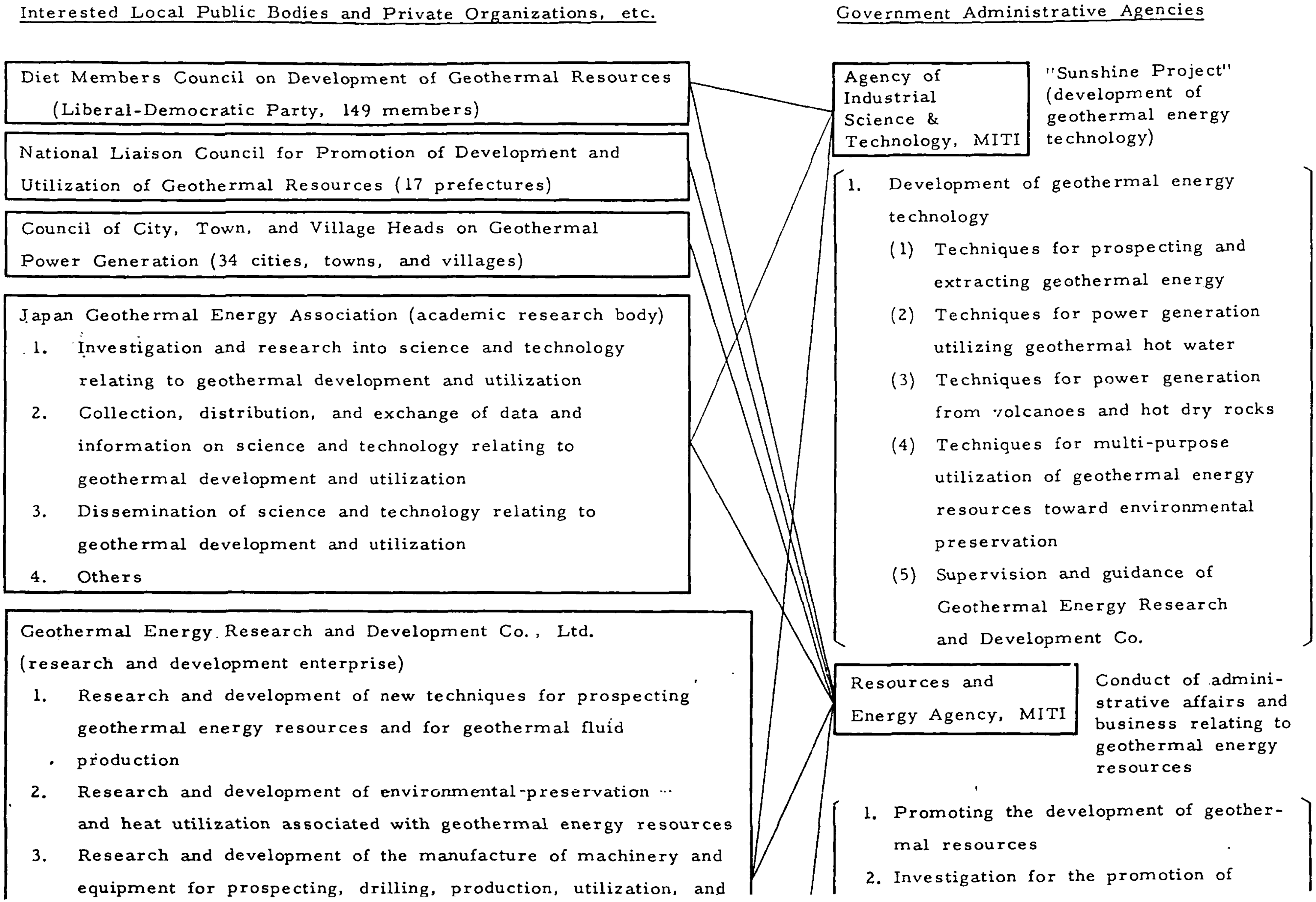
	Power generation utilizing steam from shallow reservoir	Power generation utilizing steam from deep reservoir	Power generation utilizing geothermal hot water	Power generation utilizing volcanoes and hot dry rock	Total
1975	50	-	-	-	55
1980	220	-	2	-	222
1985	500-1,000	200	210	-	910-1,410
1990	3,000	2,150	910	-	6,060
2000	1,950	12,000	11,000	5,500	48,000

1975–1990: Tentative prospects

Conventional technology

New technology (Sunshine Project)

including Administrative Agencies concerned with Geothermal Energy Development



Interested Local Public Bodies and Private Organizations, etc.

Diet Members Council on Development of Geothermal Resources (Liberal-Democratic Party, 149 members)

National Liaison Council for Promotion of Development and Utilization of Geothermal Resources (17 prefectures)

Council of City, Town, and Village Heads on Geothermal Power Generation (34 cities, towns, and villages)

Japan Geothermal Energy Association (academic research body)

1. Investigation and research into science and technology relating to geothermal development and utilization
2. Collection, distribution, and exchange of data and information on science and technology relating to geothermal development and utilization
3. Dissemination of science and technology relating to geothermal development and utilization
4. Others

Geothermal Energy Research and Development Co., Ltd. (research and development enterprise)

1. Research and development of new techniques for prospecting geothermal energy resources and for geothermal fluid production
2. Research and development of environmental-preservation and heat utilization associated with geothermal energy resources
3. Research and development of the manufacture of machinery and equipment for prospecting, drilling, production, utilization, and

Government Administrative Agencies

Agency of Industrial Science & Technology, MITI

"Sunshine Project" (development of geothermal energy technology)

1. Development of geothermal energy technology
   (1) Techniques for prospecting and extracting geothermal energy
   (2) Techniques for power generation utilizing geothermal hot water
   (3) Techniques for power generation from volcanoes and hot dry rocks
   (4) Techniques for multi-purpose utilization of geothermal energy resources toward environmental preservation
   (5) Supervision and guidance of Geothermal Energy Research and Development Co.

Resources and Energy Agency, MITI

Conduct of administrative affairs and business relating to geothermal energy resources

1. Promoting the development of geothermal resources
2. Investigation for the promotion of

equipment for prospecting, drilling, production, utilization, and power generation relating to geothermal energy resources

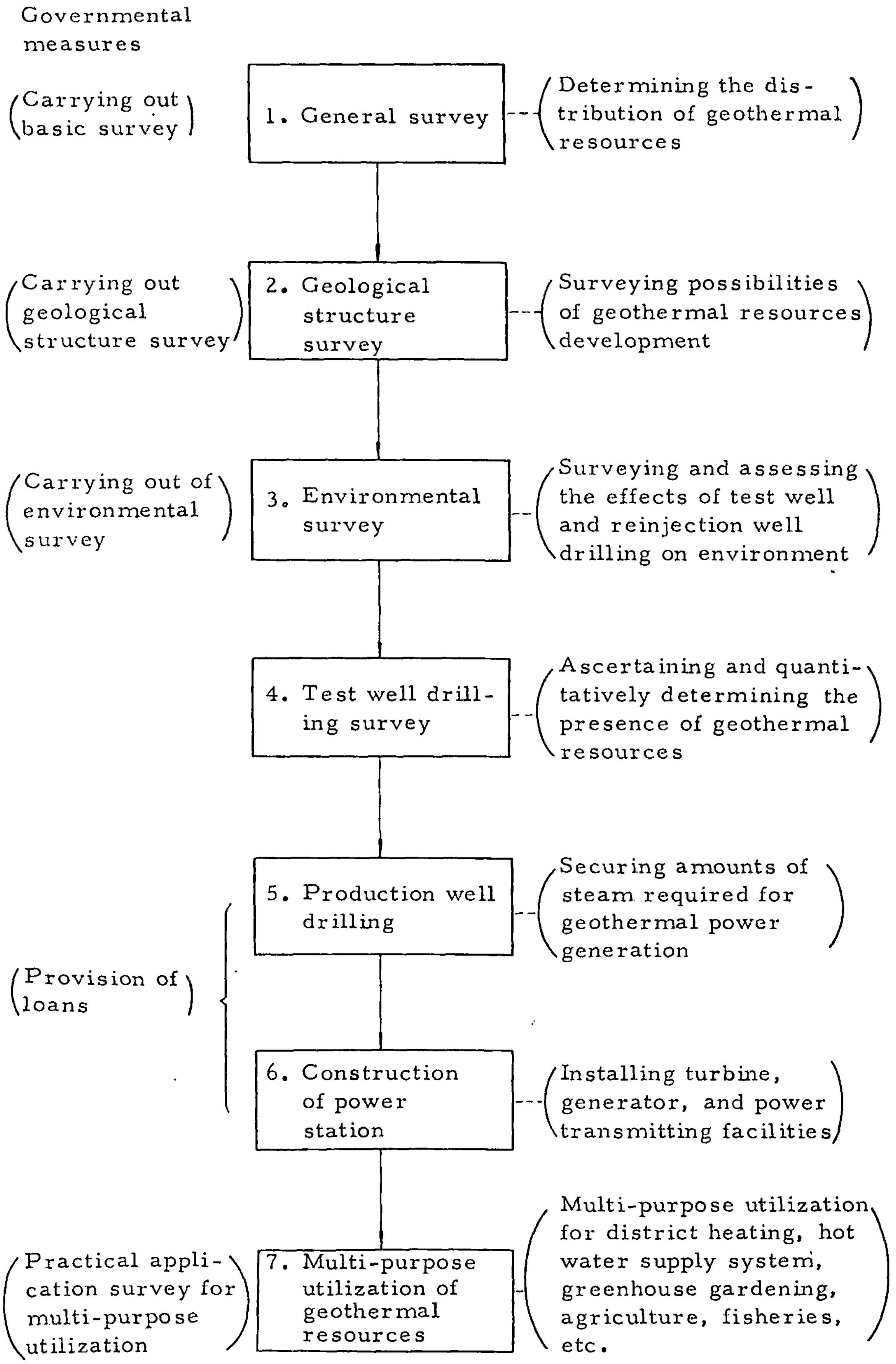
4. Consulting services for the prospecting and production of geothermal energy resources, heat utilization, environmental preservation, etc.
5. Gathering information relating to geothermal energy development and the introduction of geothermal technologies from abroad

Japan Geothermal Energy Development Center (development and utilization promoting body)

1. Investigation and research relating to the development and utilization of geothermal energy resources.
2. Investigation and research relating to the safety of machinery and equipment used for geothermal energy resources development and utilization, and tests involved therein
3. Investigation and research into technological standards relating to the development and utilization of geothermal energy resources
4. Investigation, research, and guidance relating to environmental preservation and pollution control attendant on the development and utilization of geothermal energy resources
5. Securing of liabilities associated with the procurement of funds incurred in modernizing the facilities of geothermal well drilling enterprises
6. Others

2. Investigation for the promotion of geothermal development
3. Investigation for the effective utilization of hot water from geothermal power stations
4. Formulation of long-range programs for the development of geothermal resources
5. Preparation of guidelines relating to environmental preservation and the securing of safety
6. Supervision and guidance of Japan Geothermal Energy Development Center
7. Interchange of technologies with overseas sources
8. Geothermal development investigation
9. Formulation of basic plans for the development of geothermal resources
10. Liaison and coordination with interested government agencies, etc., upon materialization of power station construction plans
11. Guidance and supervision of liabilities securing business
12. Screening business for the provision of loans
13. Assessment and supervision relating to the delivery of drilling subsidies for geothermal test wells

Fig. 2. Procedure for Geothermal Resources Development



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論　文

Hydrothermal Alteration in the Otake Geothermal Area, Kyushu

By Masao HAYASHI*

Abstract Geology of the Otake geothermal area is composed of andesitic effusive rocks belonging to the older Hohi and younger Kujyu volcanic complexes of the Pleistocene age, which cover sediments of the Miocene Kusu group. Various altered rocks have been formed in a thick pile of pyroxene andesites of the Hohi complex, mainly by action of two kinds of hydrothermal solution, acidic and weakly alkaline. The alterations have been studied by microscopic observations, X-ray diffractions and electron probe micro-analyses of minerals, X-ray spectro-analysis of rocks, and atomic absorption spectro-analysis of hydrothermal solutions.

Measured temperatures in the area range up to 267°C at a depth of 800 m, and vapor pressures up to 42 kg/cm² at a well head. The hydrothermal solutions contain 2,000 to 6,000 ppm dissolved solids, primarily Cl, Na, K, SiO_2, SO_4 and HCO_3.

Altered rocks in the area are classified into five types according to essential alteration minerals and pH values of acting solutions. Type I is characterized by the predominant formation of silica minerals, Type II by alunite and its kindred sulfates, Type III by aluminum-silicates with layer structures such as kaolinite, dickite and pyrophyllite, Type IV by aluminosilicates with layer structures such as montmorillonite, chlorite, sericite, etc., and Type V by aluminosilicates with framework structures such as Ca-zeolites, Na-feldspar and K-feldspar.

Each type is further classified into four subtypes according to alteration temperature and pressure. Respective estimated temperature, total pressure and fluid pressure of each alteration subtype are: below 100°C, below 50 atm and below 15 atm for Subtype *a*; 100 to 200°C, below 150 atm and below 30 atm for Subtype *b*; 150 to 250°C, below 250 atm and below 60 atm for Subtype *c*; and above 230°C, above 250 atm and above 50 atm for Subtype *d*.

Chemical conditions of each alteration type are inferred as follows: Type I may be produced by strongly acidic to acidic solution, by a very high chemical potential of SiO_2, and by perfect mobility of all components. In the case of Type II and III, which may have been formed under sulfuric acidic and acidic conditions respectively, three components, SiO_2, Al_2O_3 and TiO_2, are almost immobile. Variations of alteration type may result from differences in chemical potentials of some mobile components in acting solution. In addition to the above three components, Fe_2O_3, CaO and MgO become almost immobile in Types IV and V, which may have been formed under weakly acidic to weakly alkaline conditions. Two alkalis, Na_2O and K_2O, are still mobile even in these types.

I. INTRODUCTION

The Otake geothermal area is located approximately 6 km northwest of Mt. Kujyu (1,787.8 m), the highest mountain in Kyushu (Fig. 1). The area is divided into two fields. The one is the Otake field on the north, where a geothermal power plant of a capacity of 10 MW was built in 1967 by the Kyushu Electric Power Company, and the other is the Hatchobaru field (or Komatsu field) on the south, where a plan of construction of another power plant on a larger scale is in progress.

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[*] Research Institute of Industrial Science, Kyushu University

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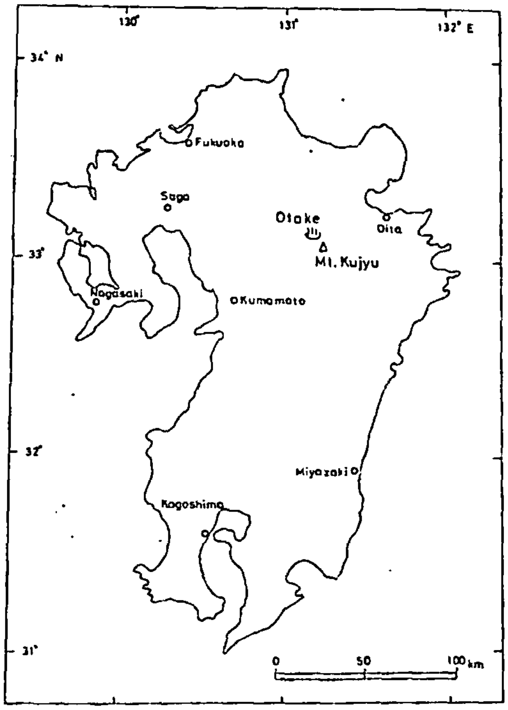
Fig. 1 Location of the Otake geothermal area.



The Otake area not only is an active geothermal area with many hot springs, fumaroles, and altered zones on the surface, but is possessed of many favorable conditions for the study of hydrothermal alteration as follows:

1) The "deep water", which means the hydrothermal solution from depths, shows weak alkalinity of about pH 8 in the Otake field, while two kinds of deep water, acidic and weakly alkaline, are recognized in the Hatchobaru field, and a variety of altered rocks occurs affected by these conditions. In most of the geothermal area in the world, one kind of deep water, either acidic or alkaline, is produced, and co-existence of the both kinds of deep water, as in the Otake area is a very rare case. The Matsukawa area in Tohoku district of Japan (Sumi, 1968) and the Tahuangtsui area in Taiwan (Chen, 1967) produce acidic deep waters, and weakly alkaline deep waters are produced in many other geothermal areas, such as Wairakei (Steiner, 1953 and 1968; Grindley, 1965) and Broadland (Brone, 1970) in New Zealand; Salton Sea and Salton Trough (Muffler and White, 1969), Steamboat Springs (Sigvaldason and White, 1961), Yellowstone (Honda and Muffler, 1970) in U.S.A.; Pauzhetsk (Piip et al., 1963) in Kamchatka; and Hveragerdi (Sigvaldason, 1963) in Iceland.

2) The original rocks of altered zones are mostly pyroxene andesites with almost invariable chemical composition, and consequently, the difference of original rocks does not affect considerably the conditions of alteration.

3) Furthermore, as no silica mineral is contained in the original andestites, all the silica minerals in alterd rocks can be considered to be alteration products.

4) Many production wells and test bores drilled so far have been observed in detail and the cores and cuttings have been preserved well.

5) The locations and sizes of cracks as the passages for deep waters and gases have been confirmed at the time of drilling together with the amount of lost circulation water.

6) Since measurements have been made of the temperatures at different depths in drillholes and of the vapor pressures at well heads, the alteration temperature and pressure can be estimated reasonably.

7) There is an accumulation of analysis data of deep waters and gases produced from the production wells.

In the previous papers (Hayashi and Yamasaki, 1969; Yamasaki and Hayashi, 1970; Yamasaki, Matsumoto and Hayashi, 1970), it was clarified that the following altered zones had been formed from the original rocks of almost invariable chemical composition in the Otake area mainly by the differences in physicochemical properties of acting hydrothermal solutions: the alunite, the kaolin, the pyrophyllite, the montmorillonite, the zeolite and the chlorite zones. This classification is based on the most characteristic alteration mineral in a altered zone. However, in this classification, similarly to the other classifications of alteration, chemical conditions are stressed in some cases and physical

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conditions in the other cases, and it is not a very systematic one.

In the present paper, the writer intends to classify systematically the types of alteration. First, they will be classified according to chemical features of essential alteration minerals and the pH values of hydrothermal solution. Next, each type will be further classified into subtypes by the physical conditions of alteration such as temperature and pressure. This kind of systematic classification is considered to make possible the correspondence between the types of alteration and the physicochemical conditions of acting hydrothermal solutions.

II. EXPERIMENTAL METHODS

About 250 specimens of altered rocks were collected from the surface of the Otake area, and were examined using an X-ray diffractometer. Cores from T-1 and T-2 bores were almost continuously available, but were actually studied every 10m. Cores every 50m and cuttings about every 25m were taken to examine from all the production wells.

(1) X-ray Diffraction

For identification of minerals a Rigaku-denki D3F X-ray diffractometer and a polarized microscope were mainly used. Instrumental settings of the diffractometer were as follows: CuK$_\alpha$ (λ=1.5418Å), 30 KV, 10 mA, Ni-filter, full scale 800 cps, time constant 2 sec., slits 1-1-0.4 mm, scanning speed 2°/min. and chart speed 10 mm/min.

Clay minerals were purified by a centrifugal separator, and examined by the diffractometer on both random and oriented samples. Heated or chemically treated samples were also examined in some cases.

Cell parameters were determined under a slow scanning speed, 0.5°/min., and silicon powder was used as an internal standard. The cell parameters were calculated by the FACOM 230-60 computer of Kyushu University, using a program written by Momoi (unpublished).

(2) X-ray Spectro-analysis

Most of chemical analyses of rocks were performed after the fusion method reported by Norrish and Hutton (1969), using a Rigaku-denki KG-4 X-ray spectrometer. The weight percentage of each component obtained by the procedure will be variable generally within ±3 percent of the correct values. The concentrations of Na_2O and MgO were determined by an atomic absorption spectrometer because of their relatively large errors by that method.

(3) Electron Probe X-ray Micro-analysis

Quantitative chemical analyses on mineral species were carried out using an electron probe X-ray micro-analyser (Japan Electron Optics Laboratory Co., Ltd., Model JXA-5A with take-off angle of 40°).

For common rock-forming minerals such as silicates, the following selected materials were used as standards: Na, natural albite; Mg, synthetic periclase; Al, synthetic corundum; Si, synthetic quartz; Ca, synthetic wollastonite; K, natural orthoclase; Ti, synthetic rutile; Mn, natural manganosite; and Fe, natural magnetite. The accelerating voltage was 15 KV, and the specimen current was 0.015 μA on pure iron. The electron beam diameter was about 10μ through all the measurements.

Counts for the unknown and standard specimens were corrected for dead time and background, and then the relative intensities were calculated. Corrections for absorption, atomic number and fluorescence were made by the method of Sweatman and Long (1969). Calculations of the corrections factors were done by the FACOM 230-60 computer of Kyushu University using a program written by the present writer (unpublished).

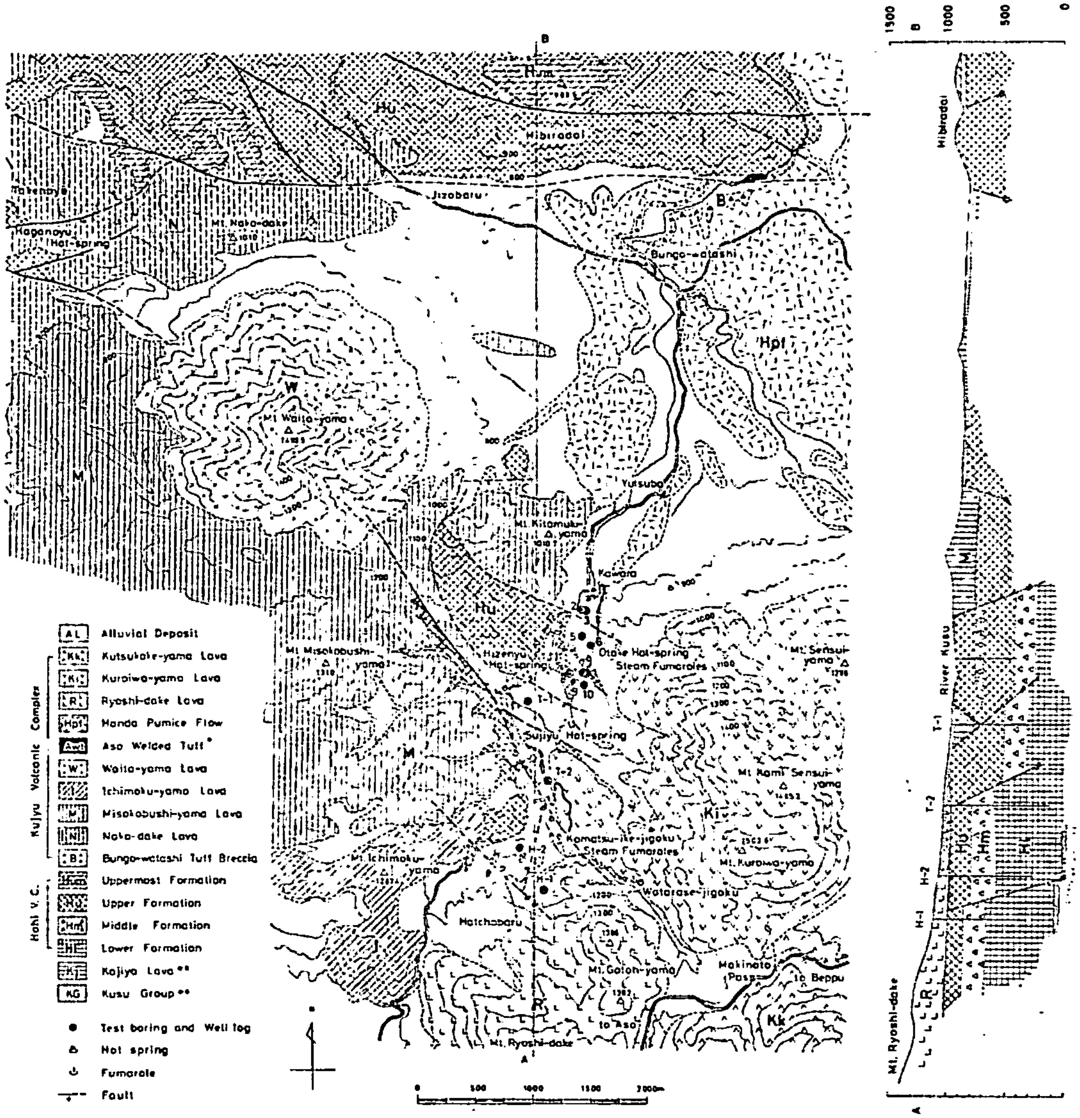
(4) Atomic Absorption Spectro-analysis

Concentrations of cations in deep water from drillholes were measured by a Hitachi 303 atomic absorption spectrometer, but the analyses for sulfur and for chlorine were done by the gravimetry method and the titrimetry method respectively.

III. GEOLOGIC SETTING

The geology of the Otake geothermal

Fig. 2 Geologic map of the Otake geothermal area and its surroundings (Yamasaki, Matsumoto and Hayashi, 1970)



area has already been studied by Yamasaki and Matsumoto (1967), Yamasaki, Matsumoto and Hayashi (1970), Ota, Matsuno and Nishimura (1968) and others. Geologic map and succession of the area are shown in Fig. 2 and Table 1 respectively.

The Otake geothermal area (lat. 33°17′ N, long. 131°12′E) is located in the Kujyu volcanic region, north-central of Kyushu island, covered widely by effusive rocks mostly of the Pleistocene. The gravity survey by Kubotera et al. (1969) confirmed that the Kujyu region showed the characteristics of "low-anormaly type caldera", though the existence of caldera could not be clearly identified from the topographical viewpoint.

The basement rock clarified so far in the area is of the Miocene Kusu group, which is found only at considerable depths in the Hatchobaru field. At the Kusu basin, about 20 km north of the Otake area, it crops out locally consisting of tuffite, pumice tuff and pebble fine sandstone, ofroundings

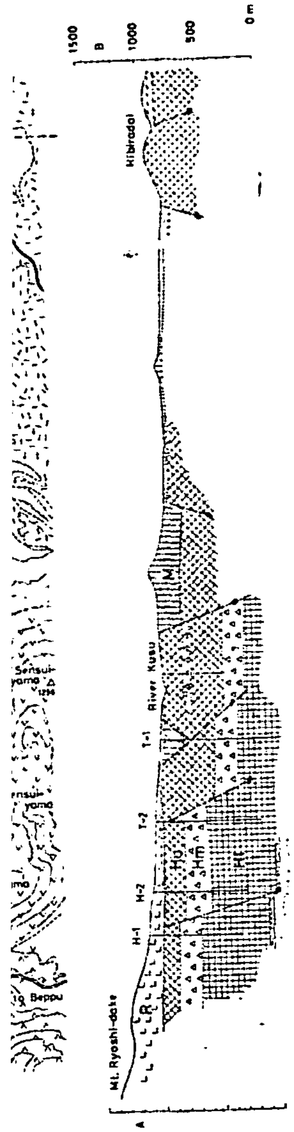


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Table 1 Geologic succession of the Otake geothermal area and its surroundings (Yamasaki, Matsumoto and Hayashi, 1970).

Age		Formation		Rock type
Holocene		Alluvial Deposits		Gravel, Sand, Clay, Volcanic ash.
Pleistocene	J_3	Kujyu Volcanic Complex	Kutsukake-yama lava *	Augite-hypersthene bearing hornblende andesite(VId).
			Kuroiwa-yama lava *	Hypersthene-augite bearing hornblende andesite(VId).
			Ryoshi-dake lava *	Hypersthene-augite bearing hornblende andesite(VId).
			Handa pumice flow	Biotite-augite-hypersthene-quartz bearing hornblende andesitic pumice.
			Aso welded tuff **	Pumiceous tuff breccia, Welded tuff.
	J_2		Waita-yama lava Ichimoku-yama lava]*	Augite-hypersthene-hornblende andesite(VId).
				Quartz bearing hypersthene-augite-hornblende andesite, Biotite-augite-hypersthene bearing hornblende andesite(VId ~ XVId).
	~		Misokobushi-yama lava	Augite-hypersthene bearing hornblende andesite. Quartz-olivine bearing augite hypersthene-hornblende andesite(VId), with tuff breccia.
	J_1		Naka-dake lava	(Quartz) Hypersthene-augite bearing hornblende andesite(VId), with tuff breccia.
			Bungo-watashi tuff breccia	Tuff breccia of ditto.
	I	Hohi V. C.	Uppermost formation	Olivine augite hypersthene andesite(VId).
			Upper formation	Hornblende bearing augite-hypersthene andesite, Augite-hypersthene andesite(VId ~ Vd).
			Middle formation	Mainly of tuff breccias, being transitional type to the upper and lower.
			Lower formation	hornblende bearing augite-hypersthene andesite, Augite-hypersthene andesite(VId ~ Vd).
Miocene	G-F	Kusu group		Tuffite, Sand stone, Mudstone, Diatom earth etc.

Remarks; * Mutual relations are not determined yet.
** Not included in Kujyu Volcanic Complex.
(VId) Rock types are shown according to the classification of volcanic rocks proposed by H. KUNO (1950).

ten intercalated with diatomaceous beds. Cuttings from deeps of the Hatchobaru production wells, however, are entirely altered in most cases, so that it is very difficult to identify their original rocks. It is believed that steam and hot water of the Hatchobaru wells have been going up from the unconformity between the Kusu group and the younger Hohi volcanic complex.

Overlying the Kusu group, the Quaternary volcanic rocks are predominant. They are divided into two complexes, the lower Pleistocene Hohi volcanic complex and the middle to upper Pleistocene Kujyu volcanic complex. The former is characterized by pyroxene andesites and the latter by hornblende andesites.

The Hohi volcanic complex (Matsumoto, 1963) with voluminous and widespread pyroxene andesites has been found at many localities in the north and central Kyushu as a basement of the middle to upper Pleistocene volcanoes. The complex is also distributed widely under the Kujyu volcanic region though it crops out locally in the Otake area as the so-called "fenster" surrounded by the younger Kujyu complex. It has, however, been confirmed by test bores and the Hatchobaru wells that the complex occurs deeply with a thickness of at least 900m as shown in the geologic cross section in Fig. 2. It is composed of alternation of lavas and tuff breccias, mainly of augite-hypersthene andesite and sometimes hornblende bearing augite-hypersthene andesite.

The Hohi complex in the Otake area may be roughly divided into three formations: upper, middle and lower. The upper and lower formations, with thickness of about 250 and 400 m respectively, consist mainly of lavas, intercalating with thin layers of tuff breccias and other tuffaceous rocks. In the middle formation, approximately 150 to 200 m thick, permeable tuff breccias are so predominant that the stratum is considered to coincide with "main reservoir" of geothermal energy which has been utilized by the Otake power plant.

The Kujyu volcanic complex overlies the Hohi complex and forms many lava domes in and around the Otake geothermal area. It is composed of relatively viscous lavas of hornblende andesites, frequently containing augite and hypersthene and sometimes quartz or biotite. It is presumed that the modern hot spring activity of the area has been caused by the post volcanic action of Mt. Kuroiwa which probably erupted last.

There are many faults confirmed or presumed so far in the area, trending generally in a direction of northwest to southeast. Of these, the most prominent is the NW fault which runs near by the T-2 bore. It is revealed by the correlation of T-1 and T-2 bores that the northeast wing of the fault is downthrown about 270 m in height. Most faults, accompanying subfaults, joints and fissures have close relation with the distribution of hot springs, fumaroles, solfataras and altered rocks.

IV. PHYSICAL AND CHEMICAL PROPERTIES OF HYDROTHERMAL SOLUTION AND GAS

IV-1. *General Remarks*

The outline of production wells and test bores is shown in Table 2. All the production wells are 8 inches in diameter. The Otake production wells, which are numberd from No. 6 to No. 10, range from 350 to 600 m in depth, while the Hatchobaru production wells, numbered from H-1 to H-6, go down to 1,200 m in depth. The former wells are entirely within pyroxene andesites of the Hohi volcanic complex, and the latter wells were drilled down to the Kusu formation.

All wells encountered many cracks including small ones as well as large ones (geologic columns in Figs. 12a to 12j). Their water tables were found between the depths of 90 to 225 m.

They have been producing a mixture of vapor and water, of which water is predominant. With respect to No. 8 well, however, vapor was the only product from the well until 1967 when it was made deeper to 154 m. Then the well began to discharge water in quantity about equal to vapor as shown in Fig. 3.

The figure indicates variation in the quantities of vapor and water flow from the Otake production wells since drilling was terminated. It is worthy of note that No. 7 well had been producing the largest quantity of vapor and water, though it was the shallowest, and that the quantity has gradually decreased, and at present is smaller than that of Nos. 9 and 10.

Table 2 Outline of production wells and test bores (mainly after Hayashi and Ejima, 1970).

Well No.	6	7	8	9	10	T-1	T-2	H-1	H-2	H-3	H-4
Drilling started	Dec. 6,1963	Mar.21,1964	Oct.10,1964	Jan.18,1965	Jan.12,1966	Aug.27,1964	Oct.26,1965	Aug.24,1968	Mar. 6,1969	Mar.22,1970	Jul.26,1970
Drilling finished	Feb.23,1964	Apr.28,1964	Dec. 1,1964	Mar. 7,1965	Mar.29,1966	Mar. 1,1966	Nov.12,1966	Feb. 1,1969	Jun. 2,1962	Jun.16,1970	Oct.13,1970
Bore diameter (in)	8	8	8	8	8	3	3	8	8	8	8
Bore depth (m)	500	350	346	550	600	1,000	900	785	764	1,175	1,084
Casing diameter (in)	8	8	8	8	8	97mm	4	8	8	8	8
Casing depth (m)	250	235	250	250	250	420	442	560	600	600	600
Depth of water table (m)	133	100	-	130	225	90	90.5	155	130	150	220
Ejected substance	vapor and water	vapor and water	vapor	vapor and water	vapor and water	none	vapor and water	vapor and water	vapor and water	vapor and water	vapor and water
Max. temperature measured (°C)	202	161	195	150	183	220	267	216	175	220	212
Well characteristics											
shut-in pressure (Kg/cm²G)	4.3	11.3	4.6	8.0	5.8	–	28	6.3	2.8	5.0	–
max. shut-in pressure (ditto)	10.0	17.8	7.0	15.0	7.0	–	–	22	7	18	42
Mass output											
separator pressure (ditto)	2.1	2.1	2.1	2.1	2.1	–	1.3	2.5	2.5	2.5	–
vapor flow (t/h)	19	53	17	29	30	–	19	42	20	46	–
water flow	187	193	0	61	135	–	33	107	50	143	–
total	206	246	17	90	165	–	52	149	70	189	–

No. 6 well began to decrease rapidly in its

roduction wells and
mainly after Hayashi
1970).

Depth of water table (m)	133	100	—								
Ejected substance	vapor and water	vapor and water	vapor	vapor and water	vapor and water	none	vapor and water	water	water		
Max. temperature measured (°C)	202	161	195	150	183	220	267	216	175	220	212
Well characteristics											
shut-in pressure (Kg/cm²G)	4.3	11.3	4.6	8.0	5.8	—	28	6.3	2.8	5.0	—
max. shut-in pressure (ditto)	10.0	17.8	7.0	15.0	7.0	—	—	22	7	18	42
Mass output											
separator pressure (ditto)	2.1	2.1	2.1	2.1	2.1	—	1.3	2.5	2.5	2.5	—
vapor flow (t/h)	19	53	17	29	30	—	19	42	20	46	—
water flow	187	193	0	61	135	—	33	107	50	143	—
total	206	246	17	90	165	—	52	149	70	189	—

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ıat of Nos. 9 and 10.
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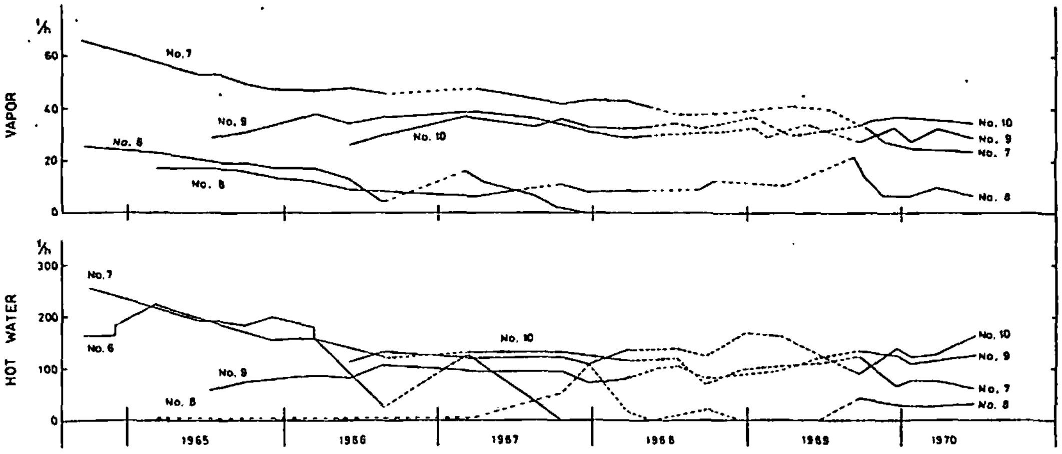
Fig. 3 Variations of amount of vapor and hot water discharged from the Otake production wells (Hayashida, 1970).



flow after twenty months of operation probably caused by the formation of scale, and finally stopped to discharge in 1967. The scale of the well is almost entirely composed of $CaCO_3$ in contrast to other wells which precipitate scales of SiO_2.

IV-2. *Temperature and Vapor Pressure*

The temperatures in Table 2 were measured in the course of drilling or within several hours after having been drilled in most cases, therefore they may be somewhat lowered by the cooling effect of drilling. Among them, the temperatures of Nos. 6 and 8 and T-2 will be close to real values, because these were measured many hours after drilling. The highest temperature so far measured is 267°C at a depth of 800 m in T-2 bore.

The estimated temperatures in Table 3 were calculated by the chemical methods which depend upon solubility of quartz (Morey et al., 1962) and/or the Na/K ratio (Ellis, 1967). When the method using quartz solubility was applied for the temperature estimation, the quantities of vapor plus water in Fig. 3 were used. The reason is that the solutions were concentrated by flashing in proportion with the ratio of water to vapor. On the contrary, the Na/K ratio would not change during the flashing. The estimated temperatures are in good accordance with those measured many hours after drilling. These estimations revealed that the Hatchobaru wells had higher temperatures in scores of degrees than those of the Otake wells.

As well as the temperature, the measured pressures in Table 2 will be lower than vapor pressures in the underground reservoir on account of pressure loss by frictional resistance during flowing and by other factors. The Otake production wells have shut-in pressures ranging from 4.3 to 11.3 kg/cm²G, and the maximum shut-in pressures from 7.0 to 17.8 kg/cm²G. These values are lower than those of the Hatchobaru production wells, of which the highest pressures so far measured is 42 kg/cm²G at H-4 well.

A shut-in pressure is measured just at the time when the flowing of vapor and water have been stopped by closing a valve at the well head. After that, the pressure gradually increases for some time. The maximum shut-in pressure is the maximum value after the flowing has been stopped. Therefore, it is considered to be closer to underground fluid pressure than the shut-in pressure. However, it is troublesome to keep the valve closed for a long time due to possible damage to the well.

The estimated fluid pressures in Table 3 could be evaluated from some of the drilling data; for example, the depth of reservoir, the depth of water table, the maximum temperature measured or estimated and so on. The estimation method is as follows: if a well dose not gush out water or vapor when the drilling is finished, then the pressure is considered to be less than that induced by the water column between the water table and the reservoir. And, the pressure must be higher than both of the maximum shut-in pressure and a saturate pressure, latter of which corresponds to the maximum temperature of solutions.

IV-3. *Chemical Properties of Hydrothermal Solution and Gas*

Table 3 shows chemical composition, pH value and electric conductivity of hydrothermal solutions and gases from the drill holes (Koga, 1970; Hayashida and Ejima, 1970; Hayashi, unpublished data). The deep waters from all the Otake production wells are neutral to weakly alkaline in pH

Table 3 Chemical composition of hydrothermal solutions and gases (mainly after Koga, 1970; and Hayashida and Ejima, 1970).

Well No.	6	7	8	9	10	T-2	H-1	H-2	H-3	H-4	H-5	H-6
Estimated depth of occurrence (m)	260～350	300～340	250～350	250～320	310～420	560～830	–	–	1,050～ 1,100	1,000～ 1,070	1,250～ 1,400	1,200～ 1,230
Estimated temperature (°C)	190～220	200～225	200～215	220～240	205～245	–	260～280	240～270	260～280	290	–	250～260
Estimated pressure (Kg/cm²G)	10～15	20～30	10～13	15～25	10～15	30～40	20～30	15～20	20～30	>50?	–	15～20
Solution												
pH (25°C)	8.4	8.4	8.4	8.15	8.4	4.6	8.15	3.4	4.3	7.4	–	8.4
Electric conductivity (μv/cm)	2,750	3,510	2,500	3,500	5,100	3,810	5,400	7,100	6,950	8,000	–	–
SiO$_2$ (ppm)	414	427	510	605	624	–	1,076	636	960	390?	–	
Li	–	4.50	4.35	5.15	5.68	–	11.1	7.03	–	–	–	749
K	70	105	108	131	143	–	289	228	238	320	–	270
Na	670	846	805	936	1,098	–	1,396	1,186	1,204	1,550	–	1,523
NH$_4$	–	0.11	0.05	0.06	0.15	–	0.11	0.41	–	–	–	–
Ca	15.0	9.9	19.8	12.3	20.1	–	9.9	15.0	–	–	–	–
Mg	4.817	0.025	0.055	0.190	0.010	–	0.158	0.467	–	–	–	–
Fe	3.57	0.05	0.05	0.03	0.06	–	0.15	32.35	–	–	–	0.8
Al	–	0.09	0.02	0.03	0.09	–	0.09	6.64	–	–	–	0.11
Mn	–	0.00	0.00	0.01	0.00	–	0.00	0.69	–	–	–	–
F	–	3.80	4.18	4.65	4.20	–	4.95	1.48	–	–	–	–
Cl	1,010	1,219	1,243	1,474	1,753	2,300	2,327	1,941	2,200	2,325	–	–
Br	–	2.48	2.82	3.40	4.15	–	6.28	5.58	–	–	–	–
I	–	0.26	0.22	0.26	0.33	–	0.51	0.37	–	–	–	–
B	–	32	28	32	40	–	31.6	35.8	–	–	–	–
HPO$_4$	–	0.90	1.23	1.06	0.77	–	0.22	2.6	–	–	–	–
HCO$_3$	–	78.1	66.8	56.4	76.9	–	58	0.0	–	–	–	–
SO$_4$	200	214	202	136	112	168	98	318	43	40	–	–
HS	–	2.76	2.41	2.09	2.26	–	–	1.5	–	–	–	–
OH	–	0.043	0.043	0.024	0.043	–	0.02	0.00	–	–	–	–
Total solid	2,390	2,950	3,000	3,460	3,880		5,300	4,400	4,900	6,080	–	–
Gas												
pH	5.0	5.1	5.7	5.0	5.3	4.3	4.3	3.9	4.3	–	–	–
Vapor (wt.%)	99.54	99.75	99.70	99.56	99.95	99.84	99.77	99.93	99.95	–	–	99.87
Noncondensable gas (wt.%)	0.46	0.25	0.30	0.44	0.05	0.16	0.23	0.07	0.05	–	–	0.13
CO$_2$ (wt.%)	95.03	99.65	93.48	96.02	93.00	85	94.3	90.0	85.0	–	–	98.5
H$_2$S (wt.%)	0.57	0.65	2.02	1.38	1.00	3	0.1	0.4	4.3	–	–	0.9
O,N ,others (wt.%)	4.40	2.70	4.50	2.60	6.00	12	5.6	9.6	10.7	–	–	0.5

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Total solid	2,300	2,950	3,000	3,400								
Gas												
pH	5.0	5.1	5.7	5.0	5.3	4.3	4.3	3.9	4.3	—	—	—
Vapor (wt.%)	99.54	99.75	99.70	99.56	99.95	99.84	99.77	99.93	99.95	—	—	99.87
Non-condensable gas (wt.%)	0.46	0.25	0.30	0.44	0.05	0.16	0.23	0.07	0.05	—	—	0.13
CO_2 (wt.%)	95.03	96.65	93.48	96.02	93.00	85	94.3	90.0	85.0	—	—	98.5
H_2S (wt.%)	0.57	0.65	2.02	1.38	1.00	3	0.1	0.4	4.3	—	—	0.9
H_2, N_2 others (wt.%)	4.40	2.70	4.50	2.60	6.00	12	5.6	9.6	10.7	—	—	0.5

Fig. 4a Variations of concentration of Cl, Na and SiO_2 in hot water from the Otake production wells.

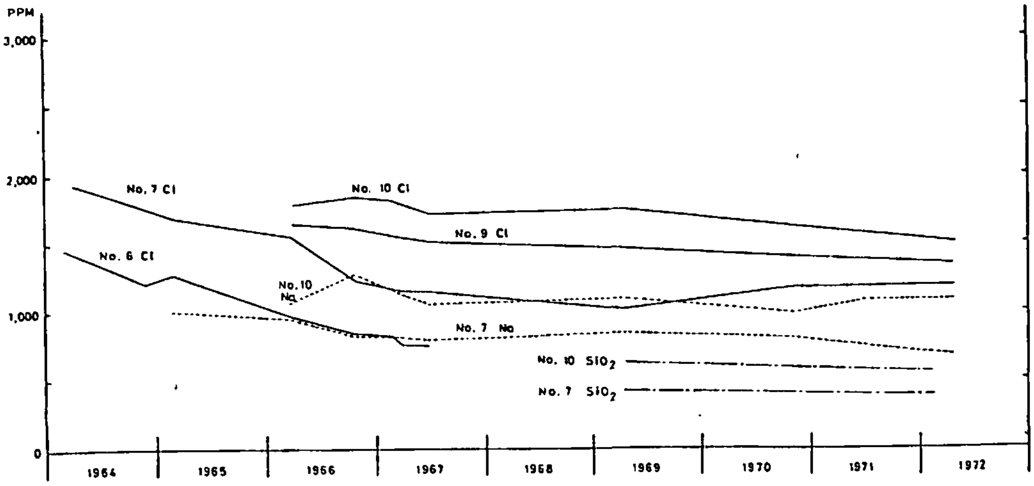
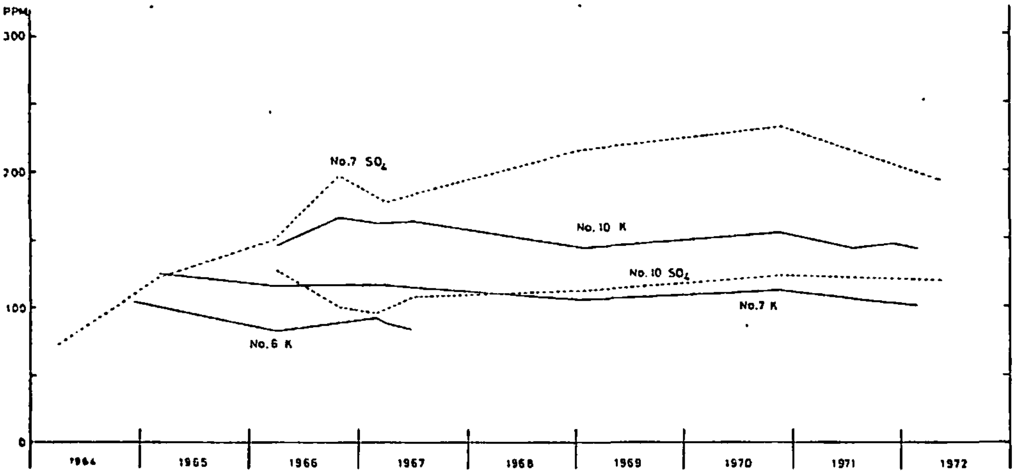


Fig. 4b Variations of concentration of K and SO_4 in hot water from the Otake ·roduction wells.

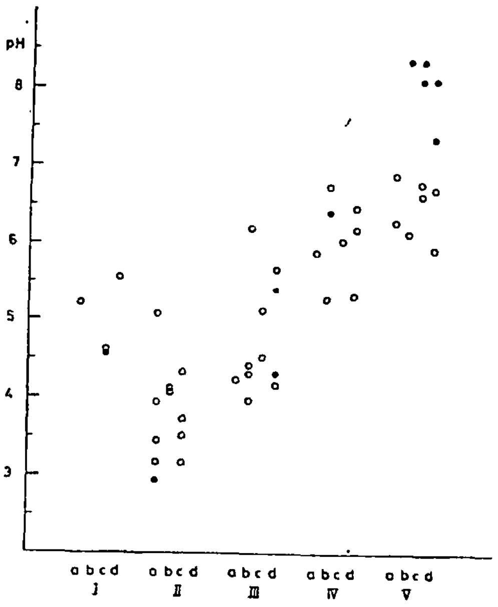


value, but those from Nos. 8 and 9 were once temporarily weakly acidic. In the Hatchobaru field there are some drill holes which have been producing acidic deep waters ranging from 3.4 to 4.6 in pH value, namely T-2, H-2 and H-3.

Electric conductivity of the deep waters is in a range from 2,500 to 5,100 μv/cm for the Otake wells, and in a higher range from 5,400 to 8,000 μv/cm for the Hatchobaru wells.

The deep waters contain 2,000 to 6,000 ppm of dissolved solids, primarily Cl, Na, SiO_2, SO_4 and HCO_3, plus a host of minor constituents. The concentration in Table 3, however, does not represent the true values of deep waters in reservior, since all constituents must have been concentrated by flashing in proportion to the vapor-water ratio. The correction coefficients to multiply are 0.80 for No. 6, 0.82 for No. 7, 0.78 for No. 9, 0.81 for No. 10, 0.62 for H-1 and 0.73 for H-2, respectively. The underground waters, therefore, will contain 900~1,500ppm of Cl, 500~900ppm of Na, 60~180ppm of K, 350~700ppm of SiO_2, 90~300 ppm of SO_4 and 40~60 ppm of HCO_3. Such bases as Ca, Mg, Fe and

Fig. 5 pH values of deep water from drillholes and of distilled water in which rock powder of each type was immersed. Solid circles for deep water from drillholes and open circles for the immersed solution.



Al, which are abundant in mother rocks, are very poor in the waters.

As a matter of course the major constituent of gases is composed of vapor, which is over 99.5 in weight percent. The remains, noncondensable gases, are composed of CO_2, H_2S, O_2, N_2 and others. The content of H_2S is generally high in the gases from the wells which have been producing acidic waters. The pH values of the condenced waters range from 3.5 to 5.7.

Figs. 4a and 4b show the variations of concentration of major elements in the deep waters from the Otake production wells. When the amount of production decreases, the concentration of Cl is gradually decreases. On the contrary, SO_4 increases as in Nos. 6 and 7 wells. The deep waters from the wells, whose production did not show a considerable change in amount, are unchanged in chemical composition from the begining of the first flow.

Fig. 5 presents pH values of solutions of 50cc of distilled water in which 5 grams of rock powder have been immersed for 1 hour. The pH values of deep waters from bore holes are also plotted in the figure.

Except for Type* I, their pH values increase in order of Types II, III, IV and V. Moreover, it is interesting that the pH values of the solutions are roughly in accord with those of the deep waters from the corresponding zone. But the Type V solutions are weakly acidic and is in opposition to the deep waters from the corresponding zones which are weakly alkaline.

Fig. 6 illustrates the changes of pH of two kinds of deep waters which have been oxidized by introducing air. After 10 hours duration of this operation, the acidic waters were gradually oxidized from pH value 5.9 to 3.8. But, the pH value of the weakly alkaline waters barely changed.

V. HYDROTHERMAL ALTERATION

V-1. *General Remarks*

Conspicuous hydrothermal alteration has been recognized in the sediments of Kusu group, in the pyroxene andesites of the Hohi volcanic complex, and also in the lowermost hornblende andesites of the Kujyu volcanic complex. Most materials for the study of alteration came from the Hohi complex since it is widely distributed underground in the Otake area with a thickness of about 900 m. Although the Hohi complex is a thick stratum, the pyroxene andesites from various depths are similar in their chemical composition to one another. In addition, the original andesites contain no silica mineral. All silica minerals in altered rocks, therefore, are obviously alteration products. Thus the Otake geothermal area is possessed of good conditions for the study of hydrothermal alteration.

V-2. *Mineral Identification*

Alteration minerals were identified using both an X-ray diffractometer and an electron probe X-ray micro-analyser. Each mineral will be described below.

(1) Silica minerals

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* As to the description of types of alteration, refer to the chapter V-3.

been immersed for 1
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otted in the figure.
, their pH values in-
Types II, III, IV and
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MAL ALTERATION

marks

othermal alteration has
the sediments of Kusu
ne andesites of the Hohi
nd also in the lower-
desites of the Kujyu vol-
t materials for the study
from the Hohi complex
listributed underground
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hs are similar in their
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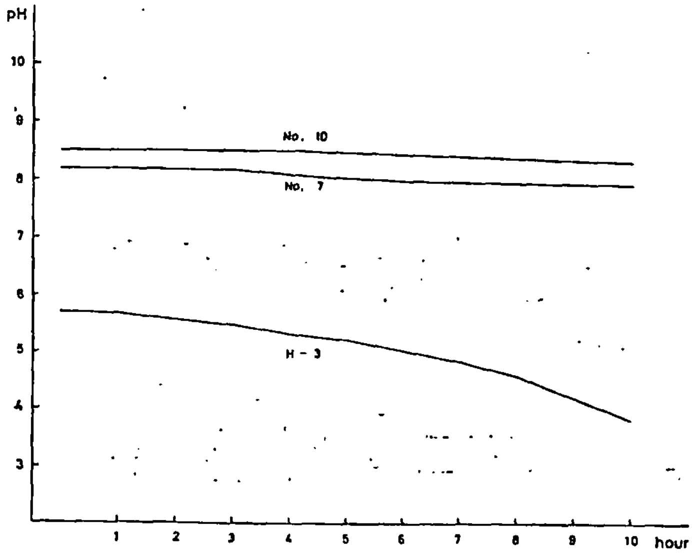
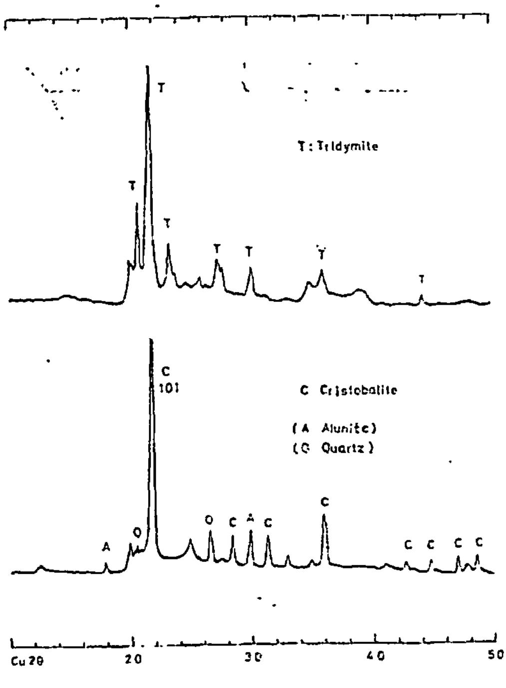
Fig. 6 Changes of pH values of two kinds of deep waters by oxidation.



area has several weak peaks in addition to the strongest one (010). The pattern of the tridymite in the figure shows that it is probably mixed with a little amounts of cristobalite since the strongest peak is too high.

Dennen and Blackburn (1970) pointed out that a trace aluminum content in quartz varied linearly and exclusively with its temperature of crystallization. However, the results of semi-quantitative analyses of the aluminum in quartz from the Otake area do not show such clear relationship between its content and alteration subtypes as shown in Table 4a.

Fig. 7a X-ray diffraction patterns of tridymite and cristobalite.



In almost all of altered rocks from the Otake area, one or more silica minerals are formed as alteration products. They are low-quartz, low-cristobalite, amorphous silica and a little amount of low-tridymite.

As shown in Fig. 7a, the X-ray diffraction pattern of the cristobalite from this

Table 4a Semi-quantitative analysis of Al in quartz (ppm)

subtype \ type	I	II	III	IV
b	30 ~ 100	80 ~ 170	100 ~ 230	40 ~ 70
c	50 ~ 120	50 ~ 140	50 ~ 90	70 ~ 110
d	40 ~ 80	—	30 ~ 60	60 ~ 140

(2) Alunite

Fig. 7b shows the X-ray diffraction pattern of alunite from this area. The chemical compositions of alunites in Table 4b show that it contains Na_2O ranging from 0.71 to 2.26 in weight percent, which decreases with a rise of alteration temperature. The present writer already reported

Fig. 7b X-ray diffraction pattern of alunite.

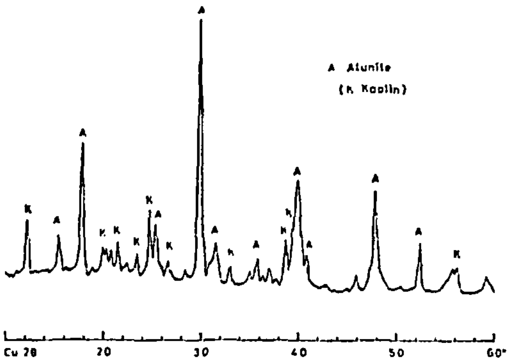


Table 4b Chemical composition of alunite.

	1	2	3
SiO_2	0.18	0.28	0.16
Al_2O_3	36.19	36.54	36.21
Fe_2O_3	0.14	0.21	0.08
CaO	0.15	1.00	0.30
Na_2O	2.26	1.74	0.71
K_2O	8.12	7.53	9.33
SO_3	38.12	37.55	37.55
H_2O+*	(13.15)	(13.17)	(13.12)
Total	(98.31)	(98.02)	(97.46)

* Calculated value using the chemical formulas below.

(1) Alunite in alunite-cristobalite rock at the surface in the Otake field (*Subzone IIa*).
$(K_{0.72}Na_{0.31}Ca_{0.01})_{1.04}(Al_{2.98}Fe_{0.01}Si_{0.01})_{3.00}S_{2.00}O_8(OH)_6$

(2) Alunite in alunite-kaolinite-quartz-pyrite rock (T2-220 m) from Subzone IIb.
$(K_{0.67}Na_{0.24}Ca_{0.08})_{0.99}(Al_{2.99}Fe_{0.01}Si_{0.02})_{3.02}S_{1.98}O_8(OH)_6$

(3) Alunite in alunite-pyrophyllite-kaolinite-quartz-pyrite rock (T2-350 m) from Subzone IIc.
$(K_{0.84}Na_{0.10}Ca_{0.03})_{0.97}(Al_{3.01}Fe_{0.004}Si_{0.01})_{3.02}S_{1.99}O_8(OH)_6$

the same relationship between Na content and the temperature for the alunites from fumaroles in the Unzen hot springs area (Yoshimura, Hayashi and Seki, 1968).

(3) Kaolin-Pyrophyllite-Diaspore

Fig. 7c shows the X-ray diffraction patterns of dickite and pyrophyllite from this area. Judging from the powder pattern, the dickite in the figure is almost pure. The pyrophyllite, which gives the sharpest diffraction pattern in the Otake area, is obviously monoclinic type referred to the powder data by Brindley and Wardle(1970). Most of the other specimens show disordered patterns as those of disordered kaolinite.

Fig. 7c X-ray diffraction patterns of dickite and pyrophyllite.

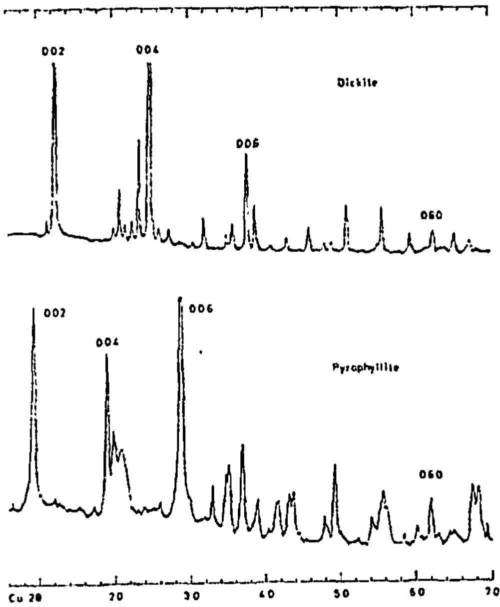


Table 4c Chemical composition of kaolinite, dickite, pyrophyllite and diaspore.

	1	2	3	4	5
SiO_2	46.76	46.24	66.21	0.44	0.41
Al_2O_3	39.61	38.89	28.19	84.88	84.45
Fe_2O_3	n.d.	n.d.	n.d.	0.21	0.11
H_2O+*	(13.96)	(13.96)	(5.00)	(15.01)	(15.01)
Total	(100.33)	(99.09)	(99.40)	(100.54)	(99.98)

* Calculated value using the chemical formulas below.

(1) Kaolinite in kaolinite-quartz-pyrite rock (T2-260 m) from Subzone IIIb.
$Al_{2.00}[Si_{2.00}O_5](OH)_4$

(2) Dickite in dickite-anhydrite-quartz-pyrite rock (T2-660 m) from Subzone IIIc.
$Al_{2.01}[Si_{1.99}O_5](OH)_4$

(3) Pyrophyllite in pyrophyllite-diaspore-quartz-pyrite rock (T2-830 m) from Subzone IIId.
$Al_{2.01}[Si_{3.99}O_{10}](OH)_2$

(4) Diaspore in diaspore-dickite bearing silicified rock (T2-720 m) from Subzone IIIc.
$(Al_{0.993}Si_{0.004}Fe_{0.002})_{1.00}O(OH)$

(5) Diaspore in pyrophyllite-diaspore-quartz-pyrite rock (T2-830 m) from Subzone IIId.
$(Al_{0.994}Si_{0.004}Fe_{0.001})_{1.00}O(OH)$

The chemical compositions of kaolinite, dickite, pyrophyllite and diaspore from this area are very close to the ideal formulas, as shown in Table 4c.

(4) Zeolites

Fig. 7d shows the X-ray diffraction patterns of Ca-zeolites, laumontite and wairakite from this area. The X-ray powder data of laumontite had already been reported by the present writer in some detail, though it was partially dehydrated to leonhardite (Hayashi and Yamasaki, 1971).

Wairakite with monoclinic structure is

Fig. 7d X-ray diffraction patterns of laumontite and wairakite.

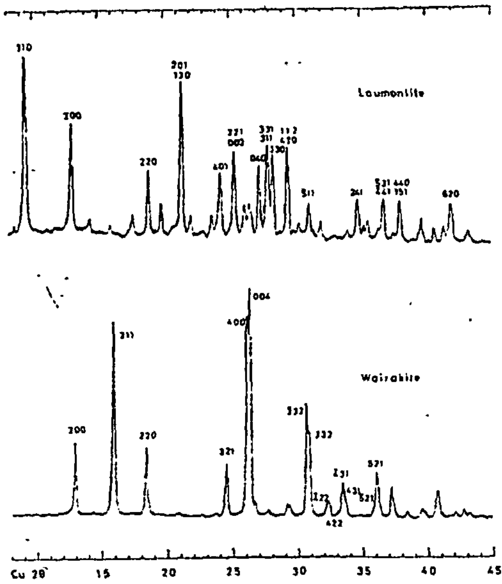


Fig. 7e X-ray diffraction patterns of montmorillonite, sericite/montmorillonite, and sericite (oriented samples).

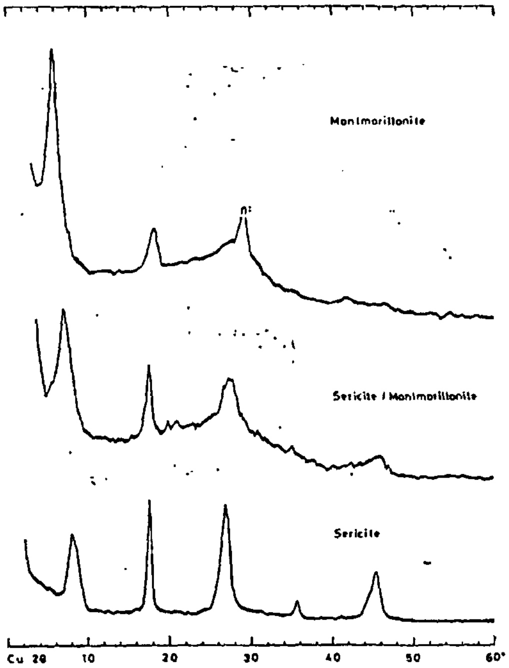
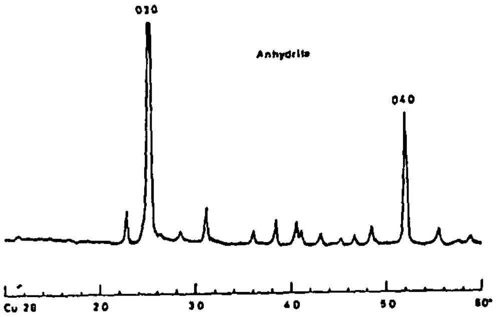


Fig. 7f X-ray diffraction pattern of anhydrite.



distinguishable from its disordered phase, as shown by Seki (1968):

1) sharp appearance of the 200 reflection;
2) clear separation of 004 reflection from that of 400; and
3) paired reflections of $\bar{3}32$, 332; $\bar{4}22$, 422; $\bar{4}31$, 431; and $\bar{5}21$, 521.

The pattern of wairakite in the figure has these characteristics, though some of the paired reflections cannot be clearly observed. The calculation of the qualified reflections yeilded the following cell parameters: $a_0=13.67$ Å, $b_0=13.65$ Å, $c_0=13.63$ Å and $\beta=90°20'$.

The chemical compositions of heulandite, laumontite and wairakite from this area are subject to a little fluctuation as shown in Table 4d. Among them the wairakite in 6th column in the table is noticeable that it contains 1.80 percent of Na_2O, which corresponds to 25 percent of analcime molecule. It is worthy of note that the content of Na is generally higher in wairakite than in laumontite, whereas that of K

Table 4d Chemical composition of Ca-zeolites.

	1	2	3	4	5	6
SiO_2	57.61	53.34	52.97	53.23	54.83	55.42
Al_2O_3	16.62	22.01	21.36	22.73	23.48	23.51
CaO	7.80	11.60	11.31	12.63	12.30	9.32
Na_2O	0.26	0.36	0.10	0.04	0.43	1.80
K_2O	0.64	0.13	0.30	0.02	0.06	0.22
H_2O+*	(14.80)	(11.97)	(11.97)	(8.85)	(8.30)	(8.94)
Total	(97.73)	(99.41)	(98.01)	(99.50)	(99.40)	(99.21)

* Calculated value using the chemical formulas below.

(1) Heulandite in heulandite-montmorillonite-calcite-cristobalite-pyrite rock (No. 7-22 m) from Subzone Va.
$(Ca_{0.87}Na_{0.05}K_{0.08})_{1.00}[(Si_{6.00}Al_{2.04})_{8.00}O_{16}]5H_2O$.

(2) Laumontite in laumontite-chlorite-calcite-quartz-pyrite rock (No. 9-290 m) from Subzone Vb.
$(Ca_{0.94}Na_{0.05}K_{0.01})_{1.00}[(Si_{4.04}Al_{1.96})_{6.00}O_{12}]3H_2O$

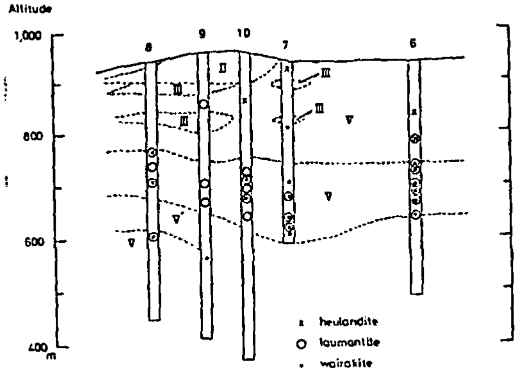
(3) Laumontite in laumontite-wairakite-montmorillonite-calcite-quartz-pyrite rock (No. 10-280 m) from Subzone Vb.
$(Ca_{0.93}Na_{0.02}K_{0.03})_{0.98}[(Si_{4.07}Al_{1.94})_{6.01}O_{12}]3H_2O$

(4) Wairakite in wairakite-chlorite-calcite-quartz-pyrite rock (No. 7-335 m) from Subzone Vb.
$(Ca_{0.99}Na_{0.005}K_{0.002})_{1.00}[(Si_{4.04}Al_{0.96})_{6.00}O_{12}]2H_2O$

(5) Wairakite in wairakite-laumontite-chlorite-calcite-quartz-pyrite rock (No. 6-270 m) from Subzone Vb.
$(Ca_{0.96}Na_{0.06}K_{0.005})_{1.03}[(Si_{3.99}Al_{2.01})_{4.00}O_{12}]2H_2O$

(6) Wairakite in wairakite-sericite/montmorillonite-chlorite-calcite-quartz-pyrite rock (No. 9-335 m) from Subzone Vb.
$(Ca_{0.73}Na_{0.25}K_{0.02})_{1.00}[(Si_{4.03}Al_{2.01})_{4.04}O_{12}]2H_2O$

Fig. 8 Distribution of Ca-zeolites in the Otake field.



is higher in laumontite.

Fig. 8 indicates the spacial distribution of the Ca-zeolites in the Otake field. No clear zonal arrangement is recognized.

(5) Feldsper

Na- and K-feldspars are recognized as alteration products as shown in Table 4e. Albite contains about 1.6 percent of CaO corresponding 8 percent of anorthite molecule. Adularia contains only a little amount of Na_2O.

Table 4e Chemical composition of feldspars.

	1	2	3
SiO_2	67.43	66.49	64.55
Al_2O_3	19.49	20.55	18.37
CaO	1.63	1.64	0.10
Na_2O	10.89	10.13	0.84
K_2O	0.07	0.31	14.54
Total	99.51	99.12	98.40

(1) Albite in laumontite-albite-chlorite-calcite-quartz-pyrite rock (No. 10-312 m) from Subzone Vb.
$(Na_{0.93}K_{0.004}Ca_{0.08})_{1.01}[(Si_{2.97}Al_{1.01})_{3.98}O_8]$

(2) Albite in albite-chlorite-sericite/montmorillonite-calcite-quartz-pyrite rock (No. 6-492 m) from Subzone Vc.
$(Na_{0.89}K_{0.02}Ca_{0.08})_{0.99}[(Si_{2.94}Al_{1.07})_{4.01}O_8]$

(3) Adularia in adularia-chlorite-epidote-anhydrite-quartz-pyrite rock (T1-994 m) from Subzone Vd.
$(Na_{0.08}K_{0.86}Ca_{0.005})_{0.95}[(Si_{3.01}Al_{1.01})_{4.02}O_8]$

6) Epidote

The chemical compositions of epidote from this area are listed in Table 4f, which shows that there are considerable variations among grains of epidote as well as zonings in a single grain.

Table 4f Chemical composition of epidote.

	1	2	3	4
SiO_2	38.81	37.09	37.66	37.93
Al_2O_3	26.04	22.81	26.55	22.61
Fe_2O_3	9.09	14.50	11.50	14.53
MnO	0.41	0.43	0.27	0.44
MgO	0.06	0.00	0.09	0.01
CaO	23.28	23.57	21.83	21.98
H_2O+*	(1.92)	(1.87)	(1.91)	(1.88)
Total	(99.61)	(100.27)	(99.81)	(99.38)

* Calculated value using the chemical formulas below.

(1) Epidote in epidote-chlorite-albite-calcite-quartz-pyrite rock (T1-726 m) from Subzone Vc.
$(Ca_{1.96}Mn_{0.03}Mg_{0.01})_{2.00}(Fe_{0.54}Si_{0.05}Al_{2.41})_{3.00}Si_{3.00}O_{12}(OH)$

(2) Ditto.
$(Ca_{2.01}Mn_{0.03})_{2.04}(Fe_{0.87}Al_{2.11})_{2.98}(Si_{2.96}Al_{0.04})_{3.00}O_{12}(OH)$

(3) Epidote in epidote-aduralia-chlorite-anhydrite-quartz-pyrite rock (T1-994 m) from Subzone Vd.
$(Ca_{1.84}Fe_{0.10}Mn_{0.02}Mg_{0.01})_{1.97}(Fe_{0.58}Al_{2.42})_{3.00}(Si_{2.96}Al_{0.04})_{3.00}O_{12}(OH)$

(4) Ditto.
$(Ca_{1.89}Fe_{0.01}Mn_{0.03}Mg_{0.001})_{1.93}(Fe_{0.87}Al_{2.13})_{3.00}Si_{3.03}O_{12}(OH)$

7) Sericite-Montmorillonite

Fig. 7e gives the X-ray diffraction patterns of montmorillonite, a randomly interstratified sericite-montmorillonite, and sericite from this area. The pattern of the interstratified mineral in the figure indicates that it is rich in montmorillonite component in accord with the results of chemical analysis. The sericite in the figure may also contain a little montmorillonite component judging from the rather broad line profiles. No regularly interstratified mineral was found. The results of semi-quantitative analysis of these minerals are shown in Table 4g.

Table 4g Chemical composition of sericite-montmorillonite.

	1	2	3
SiO_2	52.1	43.7	51.8
Al_2O_3	19.3	28.8	32.1
Fe_2O_3	3.9	1.6	1.4
MgO	2.9	4.0	1.1
CaO	2.0	0.9	0.2
Na_2O	0.4	0.1	0.1
K_2O	0.4	5.7	8.3
Total	(81.0)	(84.8)	(95.0)

(1) Montmorillonite in montmorillonite-cristobalite-pyrite rock (No. 6-65 m) from Subzone IVa.

(2) Sericite-montmorillonite interstratified mineral in a rock (T1-140 m) from Subzone IVb.

(3) Sericite in sericite-anhydrite-quartz-pyrite rock (T2-900 m) from the Subzone IVd.

8) Chlorite

The chemical compositions of chlorite from this area are shown in Table 4h. They are Fe-Mg chlorites slightly decreasing in FeO content with a rise of alteration temperature.

9) Anhydrite

nposition of epidote.

3	4
37.66	37.93
26.55	22.61
11.50	14.53
0.27	0.44
0.09	0.01
21.83	21.98
(1.91)	(1.88)
(99.81)	(99.38)

chemical formulas below.
-albite-calcite-quartz-pyrite
ie Vc.
$'_{0.54}Si_{0.05}Al_{2.41})_{3.00}Si_{3.00}O_{12}$

$_{2.11})_{2.98}(Si_{2.96}Al_{0.04})_{3.00}O_{12}$

ı-chlorite-anhydrite-quartz-
s Subzone Vd.
$_{1.97}(Fe_{0.58}Al_{2.42})_{3.00}(Si_{2.96}$

$)_{1.93}(Fe_{0.87}Al_{2.13})_{3.00}Si_{3.03}O_{12}$

:a. The pattern of the
ıl in the figure indi-
ı montmorillonite com-
th the results of chemi-
sericite in the figure
ı little montmorillonite
from the rather broad
regularly interstratified
The results of semi-
s of these minerals are
.

composition of sericite-
illonite.

2	3
43.7	51.8
28.8	32.1
1.6	1.4
4.0	1.1
0.9	0.2
0.1	0.1
5.7	8.3
(84.8)	(95.0)

ontmorillonite-cristobalite-pyrite
om Subzone IVa.
nite interstratified mineral in a
Subzone IVb.
-anhydrite-quartz-pyrite rock (T2-
one IVd.

compositions of chlorite
are shown in Table 4h.
chlorites slightly decreas-
ːnt with a rise of altera-

Table 4h Chemical composition of chlorite.

	1	2	3
SiO_2	28.46	28.68	27.51
Al_2O_3	16.21	16.90	19 17
FeO	23.95	23.71	19.86
MgO	18.17	17.85	20.46
CaO	0.19	0.26	0.18
H_2O+*	(11.58)	(11.61)	(11.80)
Total	(98.56)	(99.01)	(98.98)

* Calculated value using the chemical formulas below.

(1) Chlorite in wairakite-chlorite-calcite-quartz-pyrite rock (No. 7-335 m) from Subzone Vb.
$(Mg_{2.85}Fe_{2.11}Ca_{0.02}Al_{1.01})_{5.99}[(Si_{3.00}Al_{1.00})_{4.00}O_{10}](OH)_8$

(2) Chlorite in albite-chlorite-calcite-quartz-pyrite rock (No. 6-492 m) from Subzone Vc.
$(Mg_{2.78}Fe_{2.07}Ca_{0.03}Al_{1.08})_{5.96}[(Si_{3.00}Al_{1.00})_{4.00}O_{10}](OH)_8$

(3) Chlorite in adularia-chlorite-anhydrite-quartz-pyrite rock (T1-994 m) from Subzone Vd.
$(Mg_{3.14}Fe_{1.71}Ca_{0.02}Al_{1.15})_{6.02}[(Si_{2.83}Al_{1.17})_{4.00}O_{10}](OH)_8$

The X-ray diffraction pattern of anhydrite from this area is shown in Fig. 7f.

10) Other minerals

In addition to the above-mentioned minerals, the following minerals were found in the Otake area: a randomly interstratified chlorite-montmorillonite, jarosite, melanterite, hallotrichite, gypsum, calcite, rutile and native sulfur.

V-3. *Mineral Association and Classification of Types of Hydrothermal Alteration*

Table 5a Mineral association in altered rocks from the surface.

Sample No. \ Mineral	montmorillonite	kaolinite	halloysite	alunite	pyrite	calcite	rutile	quartz	cristobalite	tridymite	amorphous silica	(relic pyroxene)	(relic feldspar)	others
K1				◎				×	◎					
K4					×				○		◎			
K7				◎	×				○		×			S
K22		×		○			×	×	◎					
K36				◎	×				◎					
K62		×		◎					○	○				
K72		○		○			×	○						
K50		○						×	◎					
K52		◎			×		×	○	○					S
K75		○							○		○			
K144		○			○		×	×	◎					
K154		◎							○					
K168			◎											
K175			◎						○					
K24	○				×		×		◎					
K28	○				×								○	
K81	○					×			○				×	
K120	◎								○					
K126	○				×	×		○					○	
K131	○							×				×	○	
K160	◎				×				○					

◎ : predominant S : native sulfur
○ : common
× : rare

The mineral associations of altered rocks from the surface, and cores or cuttings of some selected wells are listed in Tables 5a to 5h. The locality of the rock specimens is shown in Fig. 9.

Many kinds of alteration minerals have been detected in the Otake area. Of these,

Table 5b Mineral association in cores and cuttings from No. 6 production well.

Depth (m) \ Mineral	chl-mont*1	ser-mont*2	montmorillonite	chlorite	kaolinite	alunite	pyrite	calcite	heulandite	laumontite	wairakite	Na-feldspar	quartz	cristobalite	(relic feldspar)	(relic pyroxene)	others
66			◎				×	×						○			
99			○				×	×	×				○			○	
118			○				×	○					○				
172			○				×						○			×	
186	?		○					×					○			○	
200			×				×	○		×	○		○				
212			×				×	○		×	×		○				
225			◎				×						○				
234			×				○			×			○				
250			○				×	×		×	×		○				
264		×		○			×	×		×	×		○				
300		○		×			×						◎				
325				○				×					○			○	
349		×		○			×	×				×	○			○	
390	○	×					○	×				○	×				
455				×			×						◎				
500		◎		○			×	×				×	○			×	Ru

Ru : rutile
*1 : irregular interstratified chlorite-montmorillonite
*2 : irregular interstratified sericite-montmorillonite

Table 5c Mineral association in cores and cuttings from No. 7 production well.

Depth (m) \ Mineral	chl-mont*1	ser-mont*2	montmorillonite	chlorite	kaolinite	alunite	pyrite	calcite	heulandite	laumontite	wairakite	Na-feldspar	quartz	cristobalite	(relic feldspar)	(relic pyroxene)	others
15			○				×							○		○	
22			○				×							○		×	
40					○		×						◎				
46					○		○						◎				Gy
60			○				×						○			○	
86			◎				○						○				
100			○				×						○		×	○	
114					◎		×						○				
120			○				×	×					○				
130			○				×	×					◎				
140			○				×						◎				
149	×		○				×						○				
160	○						×	×					◎				
176			○				×						◎				
184			○										○			○	
197					◎		×						○				
203					○		○						○				
210		○					×						◎				
217		○					×						◎				
231		○					×						◎				
245		○	?				×	×			○		○				
260		○		○			×	×		×	×		○				
270				○				×					○			○	
284	○						×	×		×	×		○				
295				○			×	×					○			○	
301				○			×	○		×	×		○				
332				○			×	○					○				
335				○			×	×			○		○				

Gy : gypsum

Table 5d *Mineral association in cores and cuttings from No. 8 production well.*

Mineral / Depth (m)	chl-mont*1	ser-mont*2	montmorillonite	chlorite	kaolinite	alunite	pyrite	calcite	heulandite	laumontite	wairakite	Na-feldspar	quartz	cristobalite	(relic feldspar)	(relic pyroxene)	others
25						◎								◎			
50					O		X							◎			
76		X	◎				X	X					◎				
89		X	O				X	O					◎				
100					O		O						◎				
120			O				X	X					◎				
141		O					X						◎				
146		O					X						◎				
174	O	O					X	X		X	X		◎				
186		O						O					X				
200			O				X	X		X			◎			X	
213			O				X	X		X	X		◎			X	
226			O				X	X		X			◎			X	
239			O				X	X		X	O		◎				
246		O					O						◎				
250				O			X	X					◎			X	
272	X	O	O				X						◎				Ah
292				O			X	X					O			O	
311		X		O			X	X				X	O			O	
330	O	O		O			X	O					O				

Ah : anhydrite

Table 5e Mineral association in cores and cuttings from No. 9 production well.

Mineral / Depth (m)	chl-mont*1	ser-mont*2	montmorillonite	chlorite	kaolinite	alunite	pyrite	calcite	heulandite	laumontite	wairakite	Na-feldspar	quartz	cristobalite	(relic feldspar)	(relic pyroxene)	others
21						O							O	◎			
30						◎							O	O			
37						◎							O	O			
43						O							O	X			
50						O							◎				
56						O							◎				
82					◎		X						◎				
89					◎		O						◎				Ha
100			◎				X	X					◎				
121					O	X	X						◎	?			
127					O		X						◎	?			
147					◎		O						◎				
161		O					X						O				
167			O				X						◎				
183		◎					X						◎				Gp
250	O	O					X	X		X			◎				
260			O				X						◎				
270				O			X			?			O			O	
290				O			X	X		O			◎				
395		O		X			X				X		◎				
434	O	O		O			X	O				?	◎				Ah
460				O			X	X				X	O			X	Ah
480	O			X			O	X					◎				Ah
512	O						X					X	◎				Ah
550		O		X			X	X				X	◎				Ah

Ah : anhydrite
Gp : gypsum
Ha : hallotrichite

Table 5f Mineral association in cores and cuttings from No. 10 production well.

Mineral / Depth (m)	chl-mont*1	ser-mont*1	montmorillonite	chlorite	kaolinite	alunite	pyrite	calcite	heulandite	laumontite	wairakite	Na-feldspar	quartz	cristobalite	(relic feldspar)	(relic pyroxene)	others
14						O								◎			
29						O								◎			
36						O							O	O			
50						O								◎			
76			◎					X					X	O			
89			O				X						O	O			
103			O				X						O			O	
115			X										O			O	
129			O										O			O	
140			O										O			O	
168			X				X						O			◎	
180			X				X						O			◎	
206			O				X	X					O			O	
227			X				X	X		/			O			X	
240		O	O				X	O		X			O				
250		O	O				X	O		X	X		O				
280	X		O				X	X		X	X		O				
290			O					X		X			O			O	
304			O				X	X			X		O				
312		X		O			X	X		X		X	O		X	O	Ru

Ru : rutile

Table 5g Mineral association in cores from T-1 bore.

Mineral / Depth (m)	chl-mont*1	ser-mont*2	montmorillonite	chlorite	sericite	pyrophyllite	kaolinite	dickite	gypsum	anhydrite	alunite	pyrite	calcite	diaspore	rutile	epidote	Na-feldspar	K-feldspar	quartz	cristobalite	(relic feldspar)	(relic pyroxene)	others
42			O	X								X	X								O		
70			O									O							O	X	X		
100		◎										X							◎				
130		◎										X	O		X				◎				
140							O					O							◎				
200			◎									X	O						O		X		
220		O										O							O				
250			X	O									X						O		O	X	
280						O	O					O							◎				
300							◎					X							◎				
325				O								X	O						O		O		
338		O										O							O				
360							O			X		X							◎				
380				X									X						X		◎	X	
400		O							X	O		X							O				
417			◎									X	O		X				O				
439				O									X						O		O		
460				O								X							X		◎	X	
470		O								O		X							O				
480			◎	X						O		X	X						O				
505							◎		X	◎													
550		O								O		X			X				O				
590							O					O							◎				
625		O								O		X			X				O				
657		O							X	O		X					O		O				
700		O		O						O		X					X		O				
720				O									O			O			O		X		
727				O	?								O				O		O				
750		X		O						X		X					O		O				
780				O													O		O				L(vein)
800		X		X								X	X				X		O				
840				X						O									X		◎	X	
865				O								X				O	O		X				
886				O												O	O		O				
900	X			O					X	O						X			O				
920				X						O		X							O		O	X	
955					O					O		X							◎				
968				O								X	X			O			O				
994	X			O	X								X		X	O		O	O				
1000				O									O			O		O	O				

L(vein) : laumontite in veins

characteristic minerals which infer chemical conditions, mainly pH values, of acting hydrothermal solutions can be divided into the following five groups.

1) Silica minerals: are conspicuously enriched around the conduits of the hydrothermal solutions being strongly acidic to acidic, though it is contained in almost all altered rocks.

2) Alunite and its kindred sulfates: occur in the strongly altered rocks which

ociation in cores and
om No. 10 production

utile

ssociation in cores from

: laumontite in veins

it is contained in almost

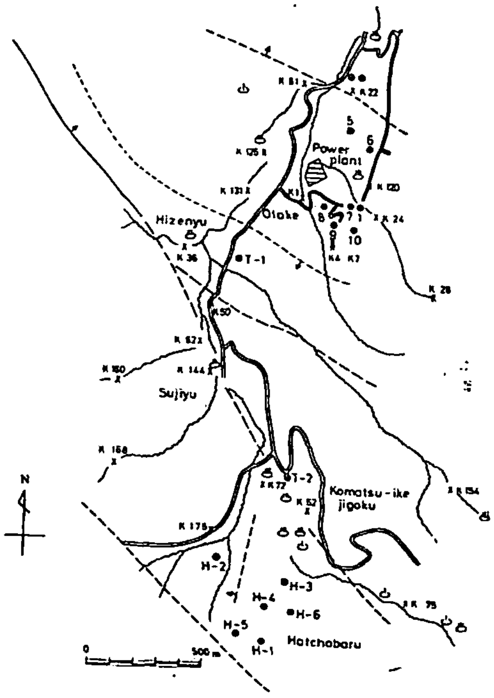
d its kindred sulfates: oc-
ngly altered rocks which

Table 5h Mineral association in cores from T-2 bore.

Depth (m) \ Mineral	chl-mont*1	ser-mont*2	montmorillonite	chlorite	sericite	pyrophyllite	kaolinite	dickite	gypsum	anhydrite	alunite	pyrite	calcite	diaspore	rutile	epidote	Na-feldspar	K-feldspar	quartz	cristobalite	(relic feldspar)	(relic pyroxene)	others
70							○													○			J
80											○									◉			Tr
100			○									×	○								○		
120			○						×			×							○	○			
140							○				○	×							×	◉			
180		×	○							×									○				
185			×																×		○	×	
200			◉									○							○				
225							○				○	×			×				◉				
270							◉					×							◉				S
320						○	○				○	×							○				
350						○	○		×			×			×				○				
380			○									×							○				
410			×			○	○					×							◉				
440		○					○					○							○				
470						×	○			○		×							○				
510			◉				×			○		×							○				
550		○							×	○		○		×					◉				
560												×		×					◉				
580		×		○						○			×						○				
600								○		○		×		×					◉				
640		○						×		○		×							○				
660								◉		○		○							○				
680		×					○			○		○							○				
710						○		○		○									○				
720								×				×		×	×				◉				
750		×					○			○		×							○				
780				×						×									×		◉		
800		◉								×		×		×					◉				
808					×									×					◉				
830						○						○		×	×				◉				
860					×	○				○		×							○				
880						○								○					◉				
900					○					○		×			×				◉				

J : jarosite
S : native sulfur
Tr: tridymite

Fig. 9 Locality of altered rocks.



have been formed under the conditions with strong sulfuric acid. Anhydrite, which is well-developed in the Otake area, is not included in this group because it may be formed under both conditions, acidic and alkaline.

3) Aluminum-silicates with layer structures such as kaolinite, dickite and pyrophyllite: occur in the strongly altered to intermediately altered rocks which have been formed under acidic conditions. These characteristic silicates are conspicuous by the absence of bases except for aluminum.

4) Aluminosilicates with layer structures such as montmorillonite, chlorite, sericite, etc.: occur in the intermediately to weakly altered rocks which have been formed under weakly acidic to neutral conditions.

5) Aluminosilicates with framework structures such as Ca-zeolites, Na- and K-feldspars: occur in the weakly altered rocks which have been formed under neutral to weakly alkaline conditions. The characteristic minerals are aluminosilicates containing only alkalis or alkaline earths as major elements. They are usually accompanied with the minerals of the group 4.

To state clearly the physicochemical conditions of various kinds of altered rocks which have been formed in the Otake area, the writer proposes a systematic classification as shown in Table 6a and 6b. First, the altered rocks are classified into five types based upon the mineral groups abovementioned. Next, each type is further classified into four subtypes in order of temperature and pressure of alteration which resulted in progressive changes of essential mineral associations as shown in Figs. 10a to 10e. Consequently each subtype may denote sufficiently both chemical and physical conditions of hydrothermal alteration.

Type I is characterized by the predominant formation of silica minerals. Therefore, this type corresponds to so-called "silicification". Of four subtypes, Subtype Ia can be easily distinguished from the others, but it is often difficult to identify the other three subtypes. In such cases, the mineral associations of surrounding

Table 6a Classification of types of hydrothermal alteration in the Otake geothermal area.

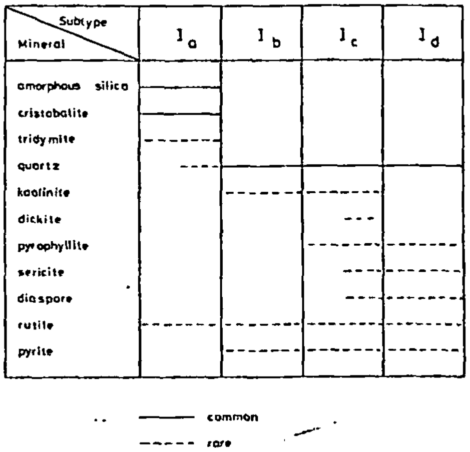
Alteration type	Acting hydrothermal solution	Characteristic alteration mineral	Subtype	Important mineral association
Type I	strongly acidic～acidic	silica minerals	Ia	C
			Ib～Id	Q
Type II	strongly sulfuric acidic	alunite	IIa	A + C
			IIb～IId	A + Q
Type III	acidic	kaolinite dickite pyrophyllite	IIIa	K + C
			IIIb	K + Q
			IIIc	D + P + Q
			IIId	P + Q
Type IV	weakly acidic ～ neutral	montmorillonite chlorite sericite	IVa	M + C
			IVb	M + S/M + Q
			IVc	Ch + S/M + Q
			IVd	S + Q
Type V	neutral ～ weakly alkaline	heulandite laumontite wairakite albite adularia	Va	H + C
			Vb	L + W + Q
			Vc	Ab + Q
			Vd	Ad + Q

A, alunite; Ab, albite; Ad, adularia, C, cristobalite; Ch, chlorite; D, dickite, H, heulandite; K, kaolinite; L, laumontite, M, montmorillonite; P, pyrophyllite; Q, quartz; S, sericite; S/M, sericite-montmorillonite; W, wairakite

Table 6b Estimated temperature and pressures of each alteration subtype

Subtype	Temperature	Total Pressure	Fluid Pressure
a	below 100°C	below 50 atm	below 15 atm
b	100～200°C	below 150 atm	below 30 atm
c	150～250°C	below 250 atm	below 60 atm
d	above 230°C	above 250 atm	above 50 atm

Fig. 10a Progressive alteration of Type I.



rocks may be useful for the identification.

Type II is characterized by the appearance of alunite including other kindred sulfates. Jarosite, melanterite and hallotrichite are sometimes formed. This type generally accompanies the formation of the aluminum-silicates of Type III, but never the aluminosilicates of Types IV and V. Except for Subtype IIa, the other three cannot always be identified mineralogically as in the case of Type I. Although

Fig. 10b Progressive alteration of Type II.

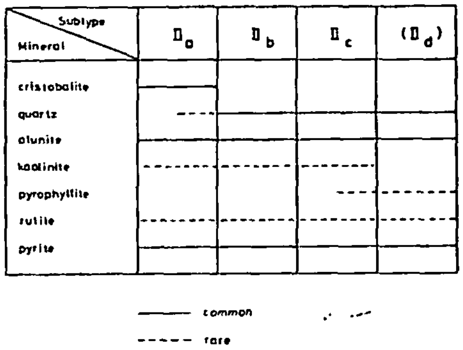


Fig. 10c Progressive alteration of Type III.

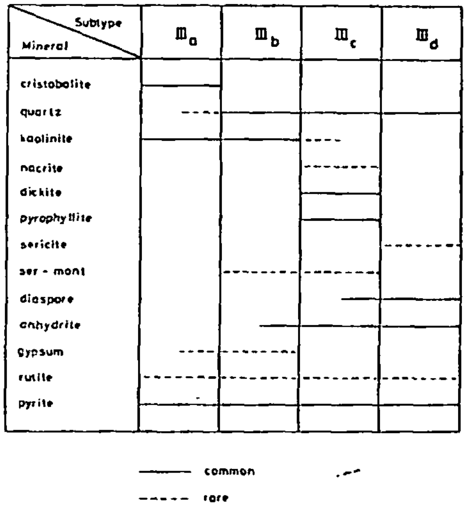
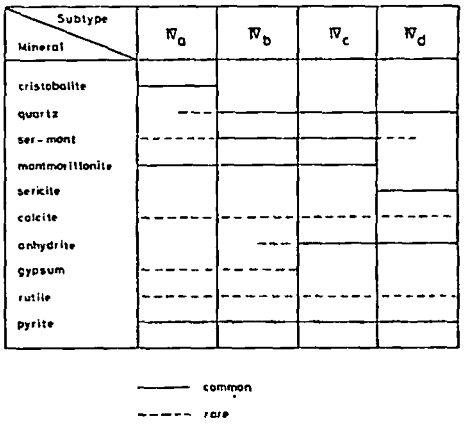
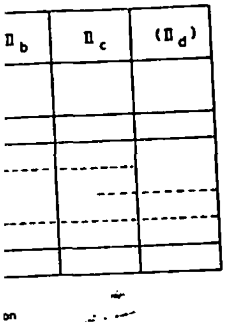


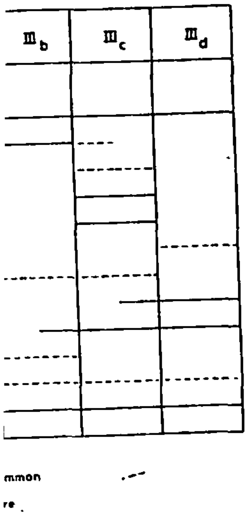
Fig. 10d Progressive alteration of Type IV.



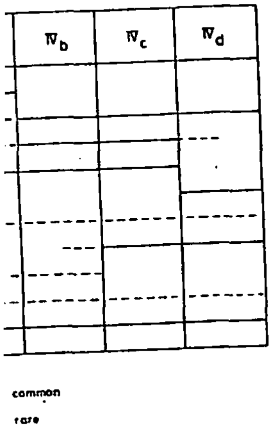
lteration of Type II.



alteration of Type III.

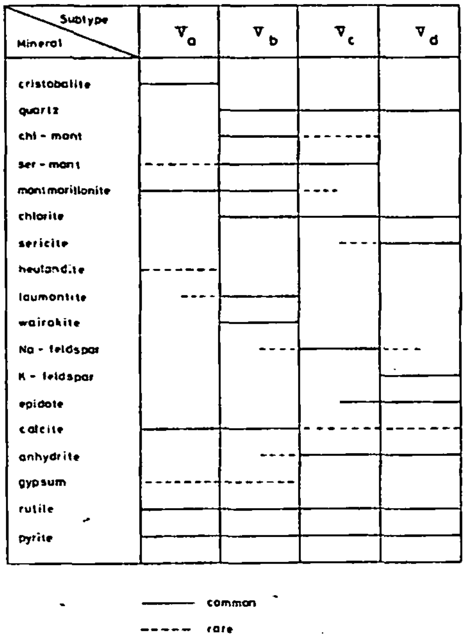


e alteration of Type IV.



nies the formation of the
of Type III, but never
es of Types IV and V.
pe IIa, the other three
identified mineralogically
ɔf Type I. Although

Fig. 10e Progressive alteration of Type V.



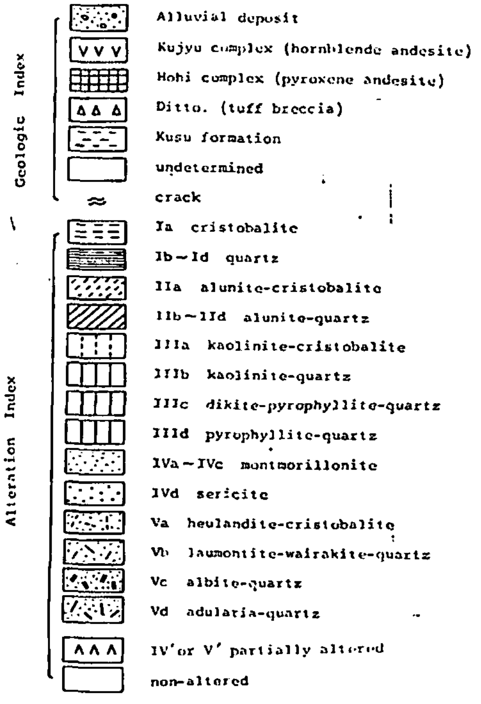
Subtype IId has not been detected in the area, an expected mineral association for this subtype is shown in Fig. 10b.

Type III is characterized by the formation of aluminum-silicates such as kaolinite, dickite and pyrophyllite, with an accessory formation of diaspore. This type can coexist with both Types of II and IV, but not with Type V which contains zeolite or feldspar as characteristic minerals. Diaspore occurs in Subtypes IIIc and IIId.

Type IV is characterized by the formation of aluminosilicates such as montmorillonite, chlorite, sericite, etc., but lacks in zeolite or feldspar. Interstratified minerals of sericite and montmorillonite persist through the whole of altered rocks of this type.

Type V is characterized by the formation of aluminosilicates such as Ca-zeolites and Na- and K-feldspars, always being accompanied by the formation of clay minerals of Type IV. Ca-zeolites, such as heulandite, laumontite and wairakite occur at low temperature parts, Na-feldspar tends to appear with increasing temperature, and finally K-feldspar occurs at the highest temperature parts.

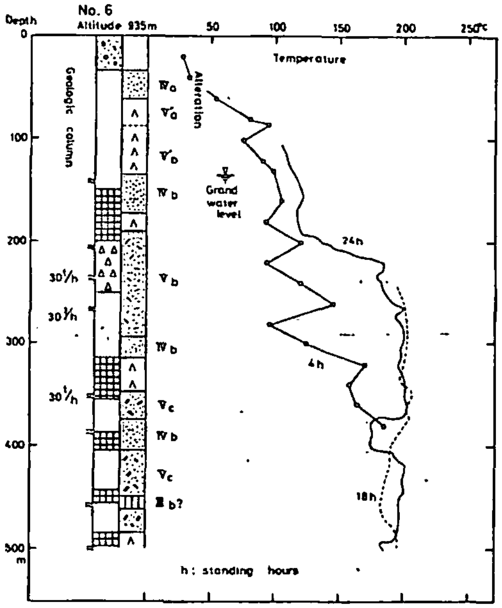
Fig. 11 Geologic and alteration indexes for the figures 12a to 12j.



V-4. *Spacial Distribution of Altered Zones in Relation to Temperature*

Stratigraphy, alteration types and mea-

Fig. 12a Stratigraphy and alteration types of No. 6 well.



sured temperatures of the selected ten drill holes are shown in Figs. 12a to 12j.

Fig. 12b Stratigraphy and alteration types of No. 7 well.

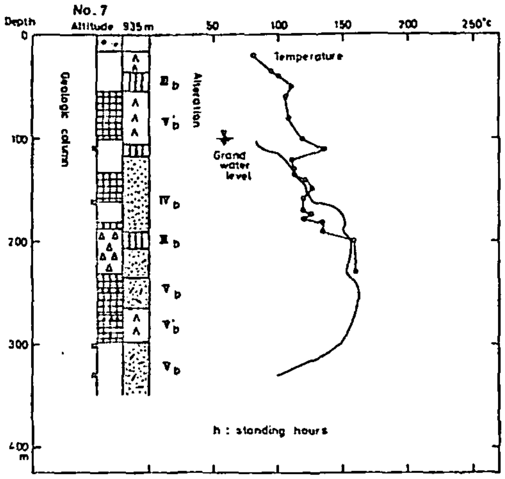


Fig. 12c Stratigraphy and alteration types of No. 8 well.

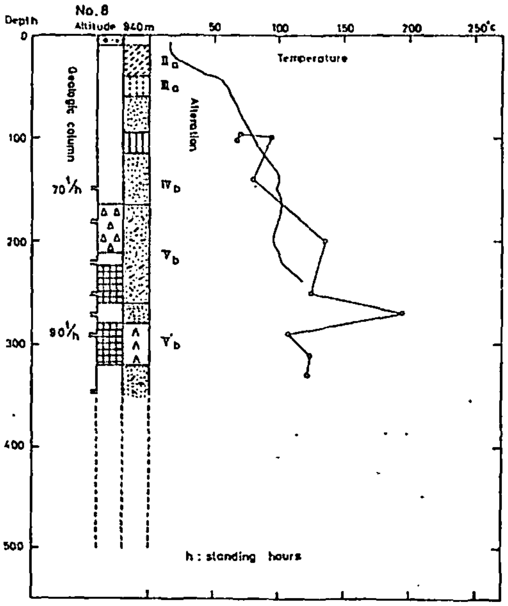


Fig. 12d Stratigraphy and alteration types of No. 9 well.

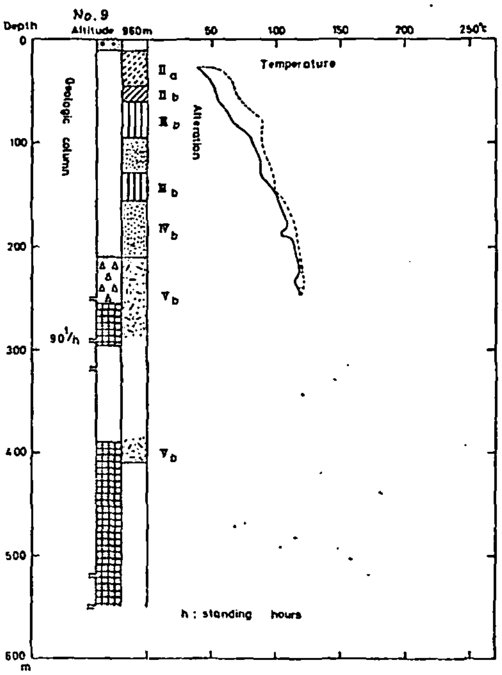
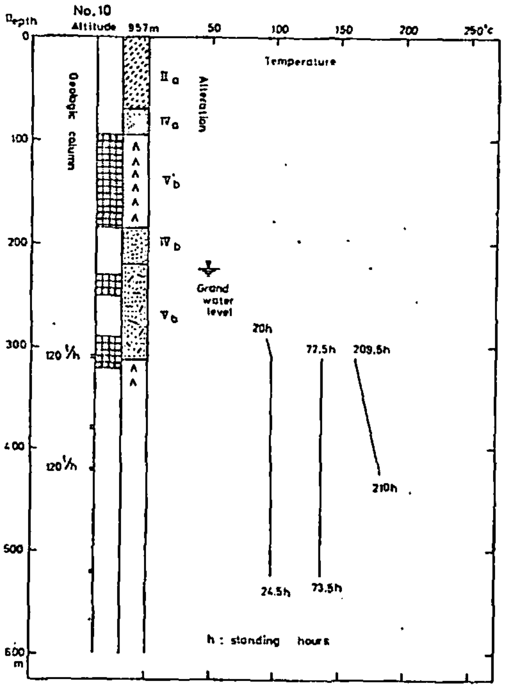
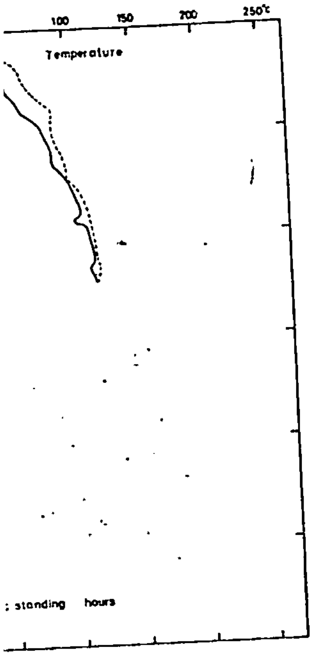


Fig. 12e Stratigraphy and alteration types of No. 10 well.

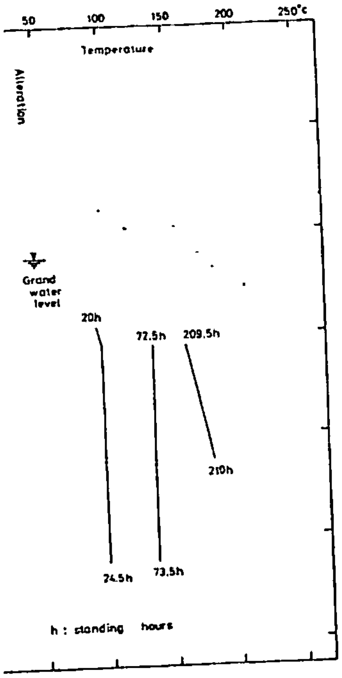


During drilling, all wells ecountered many cracks including small ones as well as large ones, some of which might be the conduits of hydrothermal solutions and gases. The size of those cracks could be roughly estimated by the amount of the lost circulation water indicated in tons per hour in the figures. According to the results of calculation of permeability, such cracks seldom exceed 1 cm in width if they extend

hy and alteration types
well.



graphy and alteration types
. 10 well.



of permeability, such cracks
d 1 cm in width if they extend

Fig. 12f Stratigraphy and alteration types of T-1 bore.

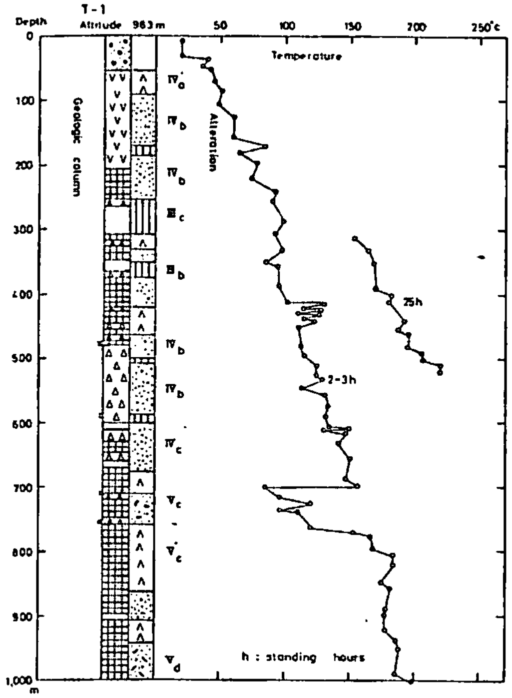


Fig. 12g Stratigraphy and alteration types of T-2 bore.

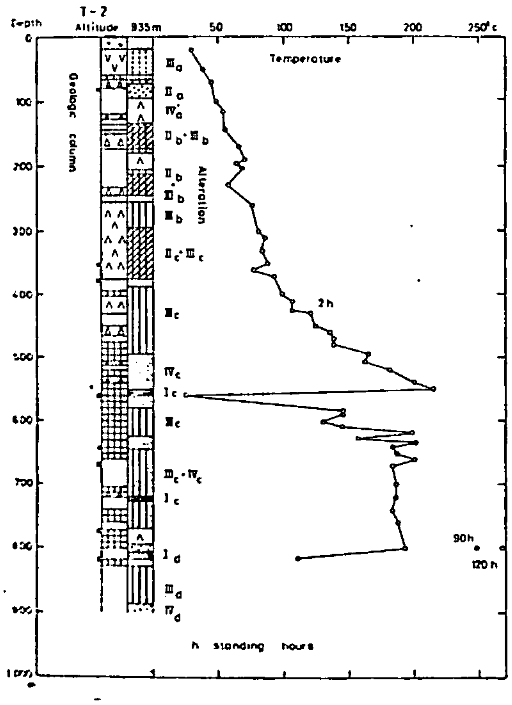


Fig. 12h Stratigraphy and alteration types of H-3 well.

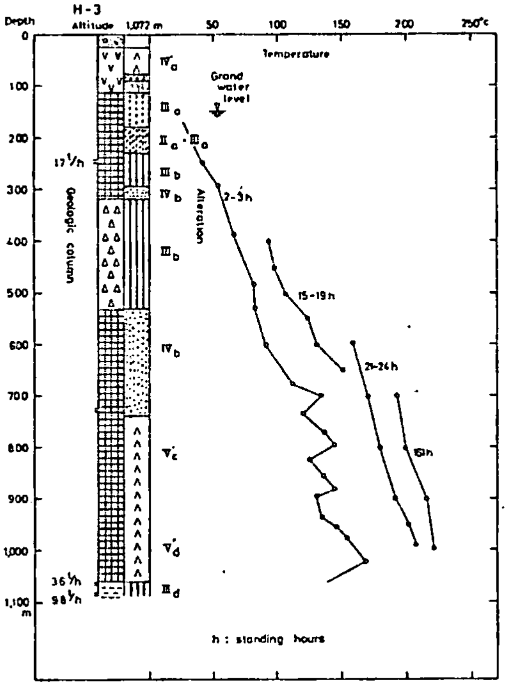
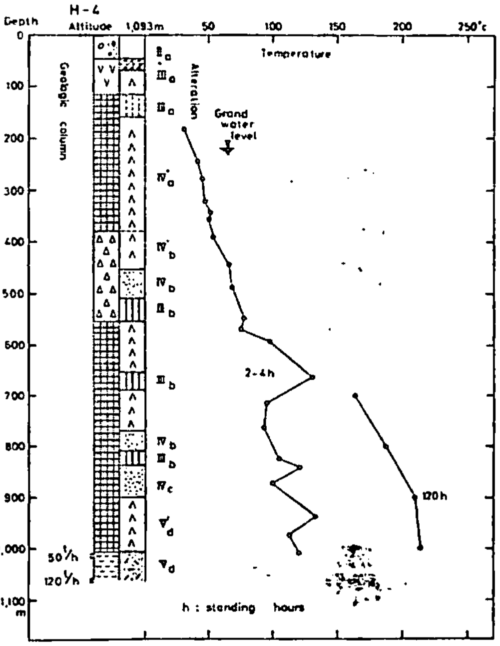
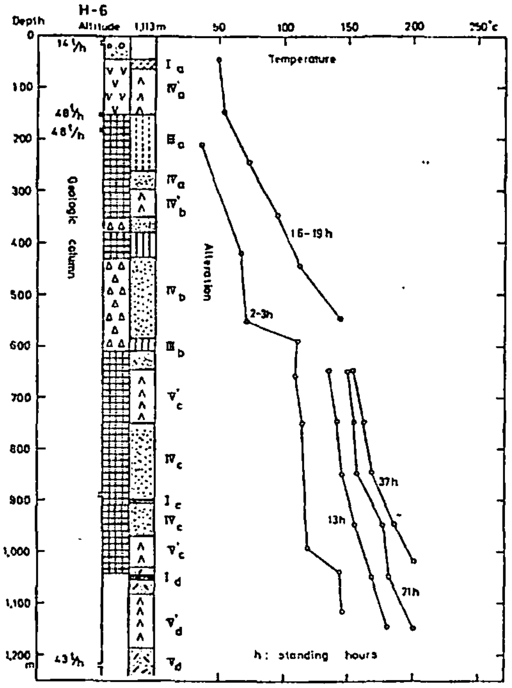


Fig. 12i Stratigraphy and alteration types of H-4 well.



infinitely (Ejima, personal communication). However, there is a record of a cavity 80 cm across at a depth of 560 m in T-2 bore

Fig. 12j Stratigraphy and alteration types of H-6 well.



(Yamasaki, Matsumoto and Soejima, 1966).

Rocks surrounding these cracks have been usually wholly converted to the assemblages of alteration minerals. When the acting hydrothermal waters are acidic, strongly altered rocks of Type I may have been formed, as observed at depths 560, 720 and 815 m in T-2 bore.

On the contrary, in the case of neutral to alkaline solutions rocks of Type IV or V are found around cracks at deep levels, though it is slightly silicified. At shallow levels silicification of the rocks of these types does not progress.

The depth-temperature curve rises suddenly up to higher temperatures at around cracks at depths of 265 m in No. 6 well, 290 m in No. 8 well and 560 m in T-2 bore, indicating the conduits of high-temperature deep waters.

The temperature also increases steeply at transitional places from partially altered rocks to wholly altered ones. In this connection it is worthy of note that the temperature gradient in H-4 well, where partially altered zones are predominant, is not high as in other well, though it is the most prominent in the Otake area.

Fig. 13 shows distribution of alteration zones at the surface in the Otake geothermal area. It is evident from the figure that many lenticular bodies of Type II are distributed in and along or nearly parallel to the faults of north-west direction. Surrounding the zones of Type II, the zones of Type III are well-developed in the Hatchobaru field, whereas in the Otake field the zones of Type IV are predominant. The strongest alteration zone, Type I, is found quite locally as small veins in outcrops of Types II and III.

The schematic section of the distribution of alteration zones in the Otake field is shown in Fig. 14. The figure indicates that the zone of Type II occurs as a lenticular body at the surface and only at shallow levels in wells Nos. 8, 9 and 10. Under the Type II zone, a thick partially altered zone interbedded by thin layers of Type III appears in all the wells. The partially altered zone seems to play the role of "cap rock" for geothermal energy because it is mostly composed of compact pyroxene andesite lavas. At deeper levels, the partially altered zone is followed by the zone of Type V which contains Ca-zeolites, laumontite and wairakite. This zone is considered to be the very reservoir of the geothermal energy which has been utilized for the Otake power plant, as is evident from the following facts:

1) all wells encountered many cracks in this zone,
2) temperature suddenly increases at the top of this zone, and
3) it is mainly composed of tuff breccias with a high porosity.

The spacial distribution of alteration zones in the Hatchobaru field is different remarkably from that in the Otake field as shown in Fig. 15. In the Hatchobaru field, the alteration zones of Types II and III, which have been formed under acidic conditions, are conspicuously developed around T-2 bore in a funnel-like shape. Type II zone reaches from the surface to

other well, though it is
ι in the Otake area.

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ar bodies of Type II are
along or nearly parallel
orth-west direction. Sur-
:s of Type II, the zones
'ell-developed in the Hat-
ıereas in the Otake field
pe IV are predominant.
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lly as small veins in out-
and III.

section of the distribution
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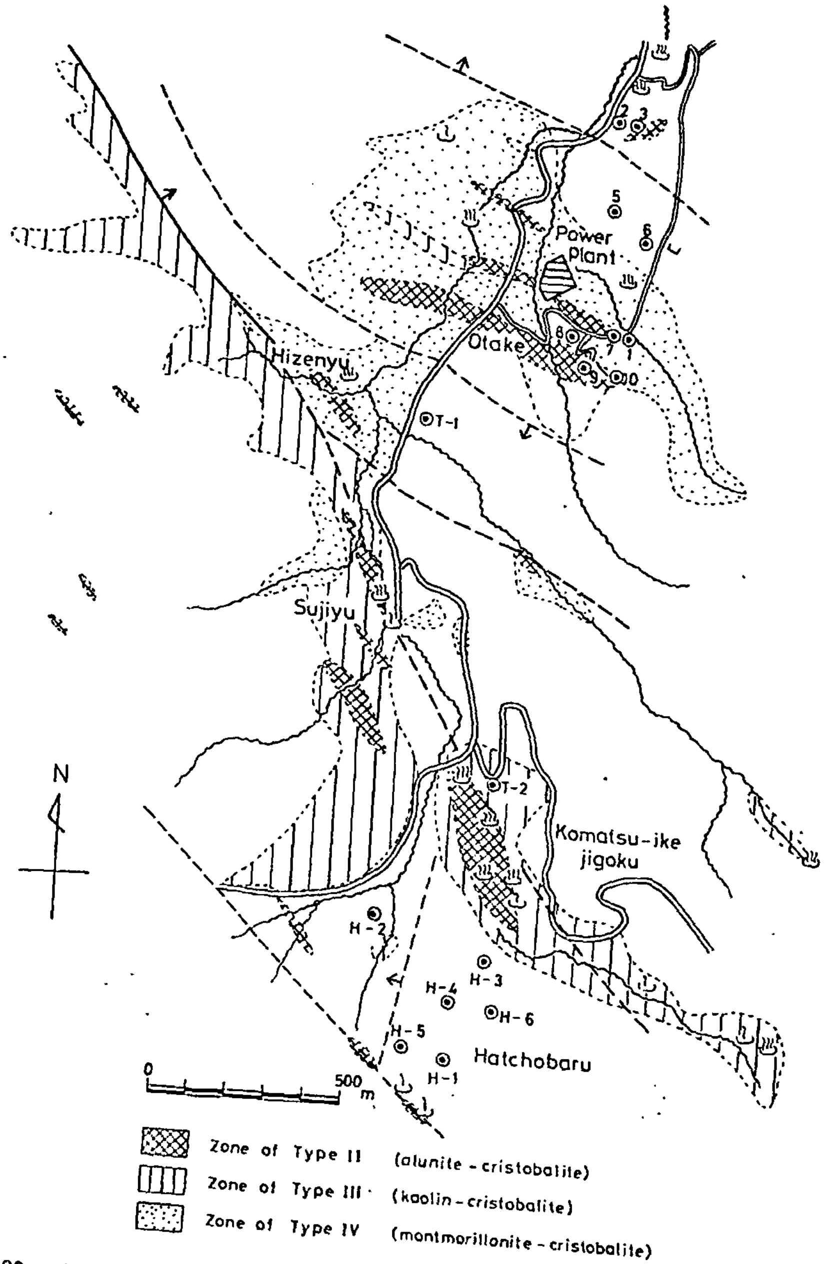
l. The figure indicates
Type II occurs as a len-
the surface and only at
n wells Nos. 8, 9 and 10.
II zone, a thick partially
erbedded by thin layers of
rs in all the wells. The
l zone seems to play the
ıck" for geothermal energy
ostly composed of compact
ite lavas. At deeper levels,
ltered zone is followed by
ype V which contains Ca-
ntite and wairakite. This
red to be the very reservoir
mal energy which has been
ne Otake power plant, as is
he following facts:
s encountered many cracks
one,
ure suddenly increases at
of this zone, and
inly composed of tuff brec-
ı a high porosity.

distribution of alteration
latchobaru field is different
om that in the Otake field
ig. 15. In the Hatchobaru
ation zones of Types II and
e been formed under acidic
re conspicuously developed
ore in a funnel-like shape.
reaches from the surface to

Fig. 13 Distribution of alteration zones at the surface in the Otake geothermal area.



a depth of 380 m in the bore, and Type III zone to a depth of about 1,000 m. Surrounding such acidic zones, the zones of Type IV occur at shallow levels and at partially altered zones at deep levels. Under the partially altered zone, there is the highest temperature Subtype Vd, from where deep waters and gases of the Hatchobaru production wells are coming. The altitude of this zone corresponds geologically to an unconformity between the Kusu group and the younger Hohi volcanic complex. On the other hand, the geothermal energy of T-2 bore which did not reach to the unconformity, was found in cracks at a depth of 560 m (Fig. 12g).

Fig. 14 Schematic section showing distribution of alteration zones in the Otake field.

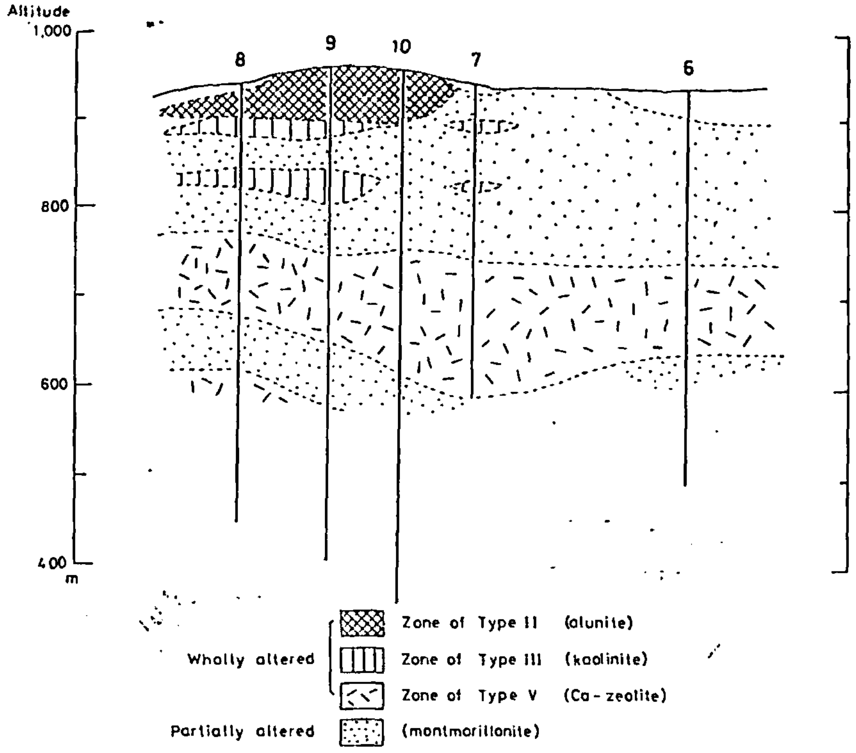
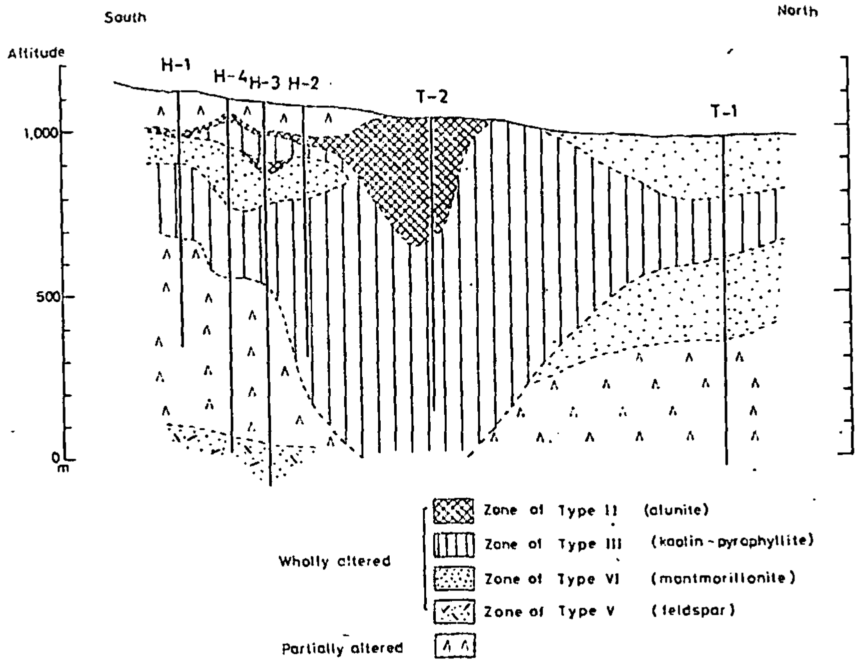
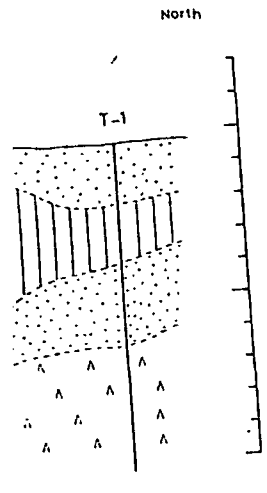


Fig. 15 Schematic section showing distribution of alteration zones in the Hatchobaru field.



in the Otake field.

es in the Hatchobaru field.



V-5. *Zonal Arrangement of Alteration Zones*

As described above, the five types of alteration zones are arranged in accordance with a certain regulation depending mainly upon chemical properties of acting hydrothermal solutions. Zonal arrangements from center to margin which are commonly recognized in the Otake area are as follows:

Arrangements of alteration zones produced by acidic hydrothermal solutions

A. Type II-Type III-Type IV-(partially altered)
B. Type I-Type III-Type IV-(partially altered)
C. Type I-Type III-Type IV-Type V-(partially altered)
D. Type III-Type IV-Type V-(partially altered)

Arrangements of alteration zones produced by neutral to alkaline hydrothermal solutions

A. Type IV-(partially altered)
B. Type IV-Type V-(partially altered)
C. Type V-(partially altered)
D. Weakly silicified Type IV-(partially altered)
E. Weakly silicified Type V-(partially altered)

Under the acidic conditions, the strongly altered zones of Type I or II have been produced at the centeral part where hydrothermal solutions have been flowing. It is transformed into the intermediately altered zones of Type III, probably due to the increasing pH value of the solutions. Such zones of acidic type are surrounded by the zone of Type IV at the inner part and by that of Type V at the outer part.

On the occasion of neutral to weakly alkaline solutions, the zonal arrangements of A and B in the above-described list commonly occur at shallow levels, but the others appear at deep levels.

VI. CHANGES IN CHEMICAL COMPOSITION OF ROCKS DURING ALTERATION

VI 1. *Original Rock*

The altered rocks studied are mostly distributed within a thick pile of pyroxene andesites of the Hohi volcanic complex. The original andesites are compact, dark green in color, and are almost invariable in chemical composition as shown in Table 7a. Apparent specific gravity of the rocks ranges from 2.67 to 2.90. An average content of each oxide in gram per 1,000 cc of the rock is also shown in the 6th column in the table.

Table 7a Chemical composition of pyroxene andesites and their partially altered equivalents.

	1*1	2	3	4	5	6
SiO_2	55.77	57.65	60.4	56.5	55.6	1569
TiO_2	0.68	0.79	0.75	1.49	1.10	26
Al_2O_3	16.39	16.68	17.6	18.5	17.2	471
Fe_2O_3	2.60	2.85	6.39*2	7.64*2	8.33*2	195
FeO	3.54	3.60				
MnO	0.203	0.130	0.16	0.19	0.21	5
MgO	2.83	2.98	1.47	3.81	3.85	82
CaO	5.61	6.28	5.80	7.07	7.75	177
Na_2O	3.32	3.62	3.19	3.09	2.55	86
K_2O	2.39	2.41	1.71	0.45	1.48	46
P_2O_5	0.203	0.231	0.12	0.14	0.22	5
H_2O+	4.08	2.10	2.25*3	2.11*3	2.37*3	75
H_2O-	0.34	0.46				
Total	99.956	99.781	99.84	100.99	100.66	
Ap.G.*4	2.686	2.667	2.695	2.682	2.900	

*1 Including S 0.07 %.
*2 Total of (Fe_2O_3 + FeO) as Fe_2O_3.
*3 Ignition loss.
*4 Apparent specific gravity.

1 and 2 analysed by K. ISHIBASHI (1969).
3 through 5 analysed by an X-ray spectrometer and an atomic absorption spectrometer.

(1) Partially altered pyroxene andesite at a depth of 116 m in No. 7 well.
(2) Pyroxene andesite at the surface in the Otake field.
(3) Partially altered pyroxene andesite at a depth of 292 m in No. 8 well.
(4) Ditto at a depth of 927 m in T-1 bore.
(5) Ditto at a depth of 720 m in T-2 bore.
(6) An average content of each oxide in gram per 1,000 cc of the pyroxene andesite.

Table 7b Chemical composition of some phenocrysts in a pyroxene andesite in the Otake field.

	1	2	3	4	5
SiO_2	49.22	53.93	50.57	53.77	2.76
TiO_2	n.d.	n.d.	1.50	n.d.	4.66
Al_2O_3	31.73	28.18	2.19	0.74	1.34
Fe_2O_3	n.d.	n.d.	n.d.	n.d.	59.97
FeO	n.d.	n.d.	8.96	20.24	26.99
MgO	n.d.	n.d.	14.10	23.46	n.d.
CaO	15.05	11.49	21.83	1.17	2.87
Na_2O	2.74	4.70	n.d.	n.d.	n.d.
K_2O	0.13	0.34	n.d.	n.d.	n.d.
Total	98.87	98.64	98.65	99.38	98.50

(1) Bytownite $(Na_{0.25}Ca_{0.74}K_{0.01})_{1.00}(Al_{1.73}Si_{2.27})_{4.00}O_8$
(2) Labradorite $(Na_{0.42}Ca_{0.56}K_{0.02})_{1.00}(Al_{1.52}Si_{2.47})_{3.99}O_8$
(3) Augite $(Fe_{0.14}Mg_{0.40}Ca_{0.44}Ti_{0.03})_{1.01}(Al_{0.05}Si_{0.95})_{1.00}O_6$
(4) Hypersthene $(Fe_{0.31}Mg_{0.65}Ca_{0.05}Al_{0.02})_{1.03}(Al_{0.01}Si_{0.99})_{1.00}O_6$
(5) Titanomagnetite $(Si_{0.10}Ti_{0.13}Al_{0.06}Fe^{+3}_{1.66}Fe^{+2}_{0.83}Ca_{0.15})_{2.93}O_4$

Table 7b gives the results of chemical analysis of some phenocrysts in an andesite of the Hohi complex. There are two varieties of plagioclase, bytownite ($Ab_{26}An_{74}Or_1$) and labradorite ($Ab_{42}An_{66}Or_2$), which are inferred to be the representatives of Ca-rich and Ca-poor menbers respectively. There are also two kinds of pyroxene: clinopyroxene, augite ($Mg_{41}Fe_{14}Ca_{45}$), and ortho-pyroxene, hypersthene ($Mg_{68}Fe_{32}$). Most opaque minerals are titanomagnetite ranging 4 to 7 percent in TiO_2 content.

VI-2. *Changes in Chemical Composition of Rocks in Zones of Each Type*

(1) Altered Rocks of Type I

Table 7c Chemical composition of altered rocks from the zone of Type I.

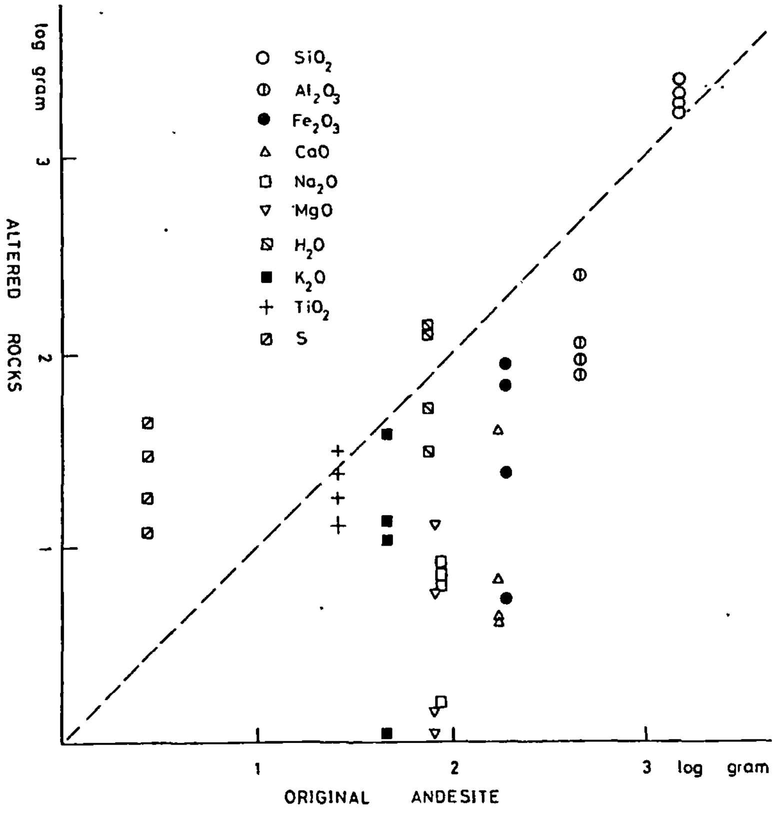
	1	2	3	4	5
SiO_2	85.1	89.9	90.5	75.8	2298
TiO_2	1.19	1.34	0.46	0.77	22
Al_2O_3	4.63	4.76	2.92	10.3	95
Fe_2O_3	0.22	1.03	2.58	3.61	47
MgO	0.01	0.06	0.21	0.56	4
CaO	0.15	0.13	0.21	1.64	4
Na_2O	0.41	0.07	0.23	0.30	4
K_2O	0.55	0.05	0.56	1.68	8
S	0.92	0.50	1.68	1.26	29
Ig. loss	6.38	1.32	1.94	5.21	42
Total	99.56	99.16	101.29	101.13	
Ap. G	1.98	2.34	2.75	2.40	

(1) Porous cristobalite rock at the surface in the Hatchobaru field.
(2) Dickite-pyrite bearing silicified rock at a depth of 560 m in T-2 bore.
(3) Diaspore-pyrite bearing silicified rock at a depth of 808 m in T-2 bore.
(4) Weakly silicified chlorite-albite-quartz-pyrite rock at a depth of 1,054 m in H-5 well.
(5) An average content in gram per 1,000 cc of the typical silica type rocks, Nos. 2 and 3.

Table 7c shows the chemical compositions of four specimens of altered rocks belonging to Type I; No. 1 is a cristobalite rock collected from the surface, Nos. 2 and 3 are compact silicified rocks at deep levels, and No. 4 is a weakly silicified rock formed under weakly alkaline condition. An average content of each oxide in gram per 1,000 cc of the rocks is also shown in the 5th column in the table.

Assuming that there was no volume change during alteration, addition and subtraction of each component during this type of alteration were calculated as shown

Fig. 16a Changes in chemical composition of rocks during alteration of Type I, showing the amount of each oxide in log gram per 1,000 cc of original and altered rocks



in Fig. 16a, in which components above the dotted line may be added to the altered rocks from acting hydrothermal solutions, and components under the line may be leached from the original rock into the solutions. The components near the dotted line are regarded less mobile.

Although the cristobalite rock has a high content of SiO_2, only a little addition of SiO_2 is inferred. Whereas the compact silicified rocks are accompanied with a great addition of SiO_2, and a great subtraction of the other components except for TiO_2. The weakly silicified rock shows a little addition of SiO_2 and considerable subtraction of the other components.

(2) Altered Rocks of Type II

The chemical compositions of five specimens of altered rocks of Type II, in which two specimens contain the aluminum-silicate clay minerals, are shown in Table 7d. The total weight percent of each specimen is considerably less than 100 percent, because the $S+SO_3$ is measured as S. Changes in chemical composition during this type of alteration are also shown in Fig. 16b.

Table 7d Chemical composition of altered rocks from the zone of Type II

	1	2	3	4	5	6
SiO_2	59.6	54.3	49.0	60.1	50.0	1286
TiO_2	0.54	2.22	0.83	0.48	0.81	22
Al_2O_3	12.9	13.0	23.6	9.30	14.6	350
Fe_2O_3	0.20	2.23	3.66	6.20	5.59	91
MgO	0.01	0.01	0.01	0.03	0.01	1
CaO	0.12	0.24	0.20	0.14	0.24	5
Na_2O	0.97	0.67	0.37	0.73	0.49	15
K_2O	2.63	2.70	1.87	2.49	2.38	57
S*	4.77	5.13	3.23	6.45	7.97	132
Ig. Loss	12.0	11.2	13.5	6.12	10.3	230
Total	93.74	91.70	96.49	92.04	92.39	
Ap. G	2.24	1.95	2.51	2.49	2.62	

* Total of ($S + SO_3$) as S

(1) Alunite-cristobalite rock at the surface in the Otake field.

(2) Alunite-cristobalite-pyrite rock at a depth of 80 m in T-2 bore.

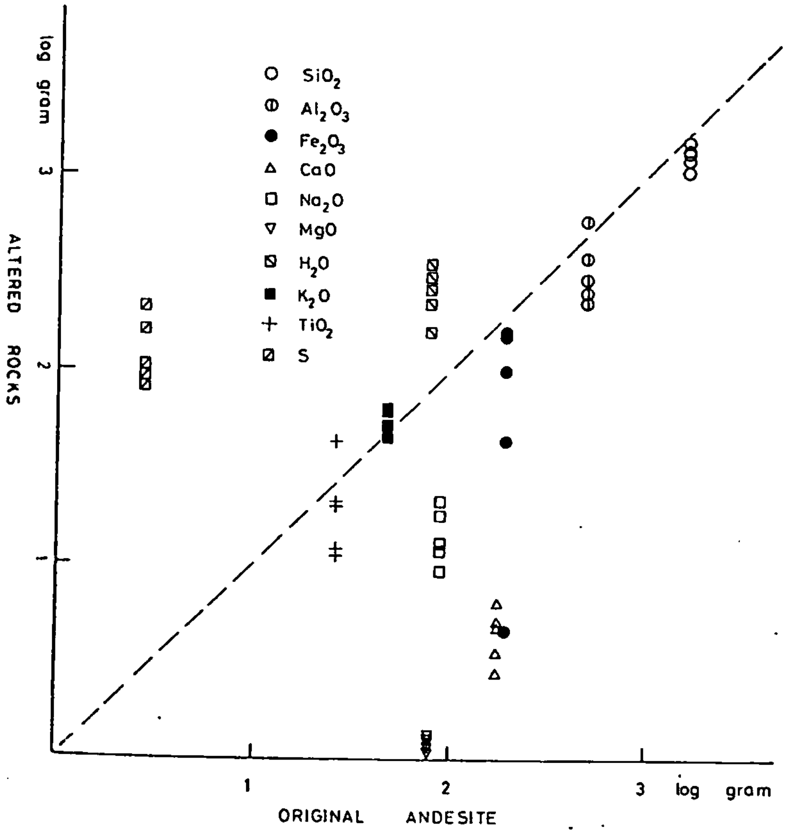
(3) Alunite-kaolinite-quartz-pyrite rock at a depth of 160 m in T-2 bore.

(4) Alunite-quartz-pyrite rock at a depth of 160 m in T-2 bore.

(5) Alunite-pyrophyllite-kaolinite-quartz-pyrite rock at a depth of 350 m in T-2 bore.

(6) An average content in gram per 1,000 cc of the altered rocks.

Fig. 16b Changes in chemical composition of rocks during alteration of Type II.



The two components, SiO_2 and Al_2O_3, are almost immobile in all the specimens. The mobility of Fe_2O_3, most of which must be expressed as Fe, varies greaty among them. The alteration of Type II is generally accompanied with a little addition of K and a great addition of S as well as SO_3, resulting in formation of alunite which is the characteristic mineral of this type. The other components in original rocks are strongly leached into hydrothermal solutions except for TiO_2.

(3) Altered Rocks of Type III

The chemical compositions of five specimens of altered rocks of Type III are shown in Table 7e. Changes in chemical composition during the alteration of Type III are also shown in Fig. 16c.

It is obvious from the figure that the three components, SiO_2, Al_2O_3 and TiO_2, are almost immobile during the alteration of this type. The great addition of H_2O is inferred in the altered rocks. The other components are almost completely subtracted from their original rocks except for Fe, a part of which combines with S to form pyrite.

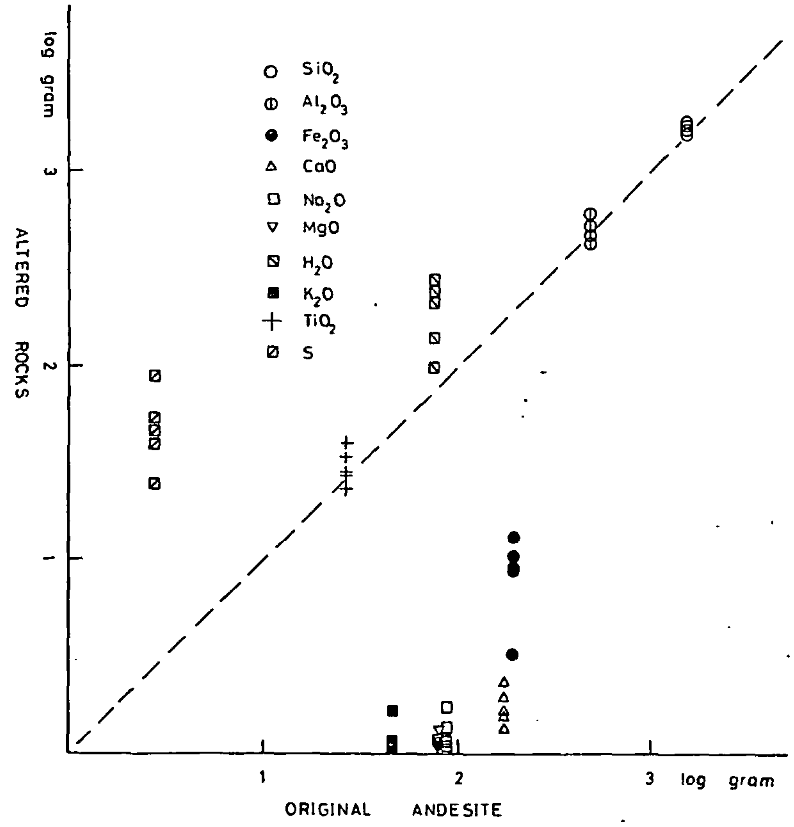
Table 7e Chemical composition of altered rocks from the zone of Type Ⅲ.

	1	2	3	4	5	6
SiO_2	70.1	63.9	66.1	62.5	63.0	1627
TiO_2	0.97	1.45	1.14	1.31	1.06	31
Al_2O_3	19.6	16.3	19.1	22.8	20.0	500
Fe_2O_3	3.93	3.68	4.20	1.21	4.96	89
MgO	0.12	0.01	0.12	0.07	0.02	2
CaO	0.14	0.42	0.29	0.51	0.22	8
Na_2O	0.15	0.05	0.31	0.02	0.08	3
K_2O	0.09	0.03	0.27	0.03	0.04	2
S	1.70	2.05	2.07	0.96	3.21	50
Ig. loss	4.15	8.80	5.56	10.4	8.72	191
Total	100.95	98.69	99.16	100.01	100.31	
Ap. G	2.38	2.35	2.45	2.65	2.73	

(1) Kaolinite-quartz-pyrite rock at a depth of 280 m in T-2 bore
(2) Ditto at a depth of 360 m in T-1 bore.
(3) Pyrophyllite-kaolinite-quartz-pyrite rock at a depth of 410 m in T-2 bore.
(4) Pyrophyllite-dickite-diaspore-quartz-pyrite rock at a depth of 730 m in T-2 bore.
(5) Pyrophyllite-diaspore-quartz- pyrite rock at a depth of 830 m in T-2 bore.
(6) An average content in gram per 1,000 cc of the altered rocks.

(4) Altered Rocks of Type IV

Fig. 16c Changes in chemical composition of rocks during alteration of Type Ⅲ.



ıical composition of altered
s from the zone of Type Ⅲ.

2	3	4	5	6
3.9	66.1	62.5	62.0	1627
1.45	1.14	1.51	1.06	31
18.3	19.1	22.8	20.0	500
3.68	4.20	1.21	4.96	89
0.01	0.12	0.07	0.02	2
0.42	0.29	0.51	0.22	6
0.05	0.31	0.02	0.08	3
0.03	0.27	0.03	0.04	2
2.05	2.07	0.96	3.21	50
8.80	5.56	10.4	8.72	191
98.69	99.16	100.01	100.31	
2.35	2.43	2.65	2.73	

z-pyrite rock at a depth of 280 m in T-2 bore
h of 360 m in T-1 bore.
olinite-quartz-pyrite rock at a depth of 410 m
ckite-diaspore-quartz-pyrite rock at a depth
bore.
iaspore-quartz- pyrite rock at a depth of 830 m
ent in gram per 1,000 cc of the altered rocks.

the altered rocks. The other
are almost completely subtract-
r original rocks except for Fe,
hich combines with S to form

d Rocks of Type IV

ing alteration of Type Ⅲ.

Table 7f Chemical composition of altered rocks from the zone of Type Ⅳ.

	1	2	3	4	5	6
SiO_2	55.1	52.8	64.1	60.0	61.9	1345
TiO_2	1.07	0.96	0.41	0.49	0.53	13
Al_2O_3	16.4	15.3	13.5	17.7	14.3	353
Fe_2O_3	5.91	4.37	2.86	3.71	2.88	88
MgO	1.80	2.23	0.63	0.28	0.33	22
CaO	4.31	5.87	0.40	3.22	4.60	87
Na_2O	2.12	0.16	2.41	0.43	0.50	23
K_2O	0.67	1.21	3.56	3.88	4.27	65
S	2.38	2.50	0.86	3.60	4.21	65
Ig. loss	10.8	13.3	10.9	5.70	5.87	204
Total	100.36	98.70	99.63	99.01	99.59	
Ap. G	1.9	2.2	2.0	2.60	2.70	

(1) Montmorillonite-calcite-quartz-pyrite clay at a depth of 200 m in T-1 bore.
(2) Ditto at a depth of 417 m in T-2 bore.
(3) Sericite/montmorillonite-quartz-pyrite clay at a depth of 140 m in T-1 bore.
(4) Sericite-anhydrite-quartz-pyrite rock at a depth of 830 m in T-2 bore.
(5) Ditto at a depth of 900 m in T-2 bore.
(6) An average content in gram per 1,000 cc of the altered rocks.

The chemical compositions of five specimens of altered rocks of Type IV are shown in Table 7f. Changes in chemical composition during the alteration of this type are also shown in Fig. 16d.

Table 7g Chemical composition of altered rocks from the zone of Type Ⅴ.

	1	2	3	4	5	6	7	8
SiO_2	56.3	51.4	58.3	59.1	60.2	58.0	55.8	1401
TiO_2	0.89	0.99	0.82	0.77	0.76	0.73	0.97	24
Al_2O_3	16.9	18.7	16.8	16.0	14.4	15.3	16.4	401
Fe_2O_3	4.62	6.09	6.31	5.25	6.23	7.93	8.58	177
Fe^*	0.62	0.87	0.75	0.64	0.91	n.d.	n.d.	
MnO	0.20	0.24	0.20	0.15	0.09	n.d.	n.d.	4
MgO	3.19	2.91	2.74	2.72	1.25	2.32	1.89	59
CaO	2.72	6.33	4.41	5.55	3.72	7.03	6.34	129
Na_2O	0.72	2.03	2.59	0.24	0.22	3.93	3.26	47
K_2O	2.92	1.84	0.60	1.53	3.29	3.38	2.30	52
P_2O_5	0.04	0.12	0.00	0.05	0.00	n.d.	n.d.	3
S	0.72	1.00	0.86	0.74	1.04	0.60	0.61	20
Ig. loss	9.46	6.89	6.35	6.46	7.81	2.81	2.73	147
Total	99.30	99.41	100.73	99.20	99.72	100.96	99.08	
Ap. G	2.35	2.20	2.43	2.50	2.47	2.66	2.59	

* Calculated by the assumption that all measured S ions stoichiometrically combine with Fe as pyrite.

(1) Wairakite-laumontite-calcite-montmorillonite-quartz-pyrite rock at a depth of 250 m in No. 6 well.
(2) Wairakite-calcite-chlorite-quartz-pyrite rock at a depth of 335 m in No. 7 well.
(3) Laumontite-calcite-montmorillonite-quartz-pyrite rock at a depth of 200 m in No. 8 well.
(4) Wairakite-laumontite-calcite-sericite/montmorillonite-quartz-pyrite rock at a depth of 230 m in No. 10 well.
(5) Wairakite-laumontite-calcite-montmorillonite-quartz-pyrite rock at a depth of 280 m in No. 10 well.
(6) Albite-chlorite-calcite-quartz-pyrite rock at a depth of 492 m in No. 6 well.
(7) Adularia-chlorite-anhydrite-quartz-pyrite rock at a depth of 994 m in T-1 bore.
(8) An average content in gram per 1,000 cc of the altered rocks.

In addition to SiO_2, Al_2O_3 and TiO_2, the components of Fe_2O_3 and CaO are scarcely mobilized during the alteration of

Fig. 16d Changes in chemial composition of rocks during alteration of Type Ⅳ.

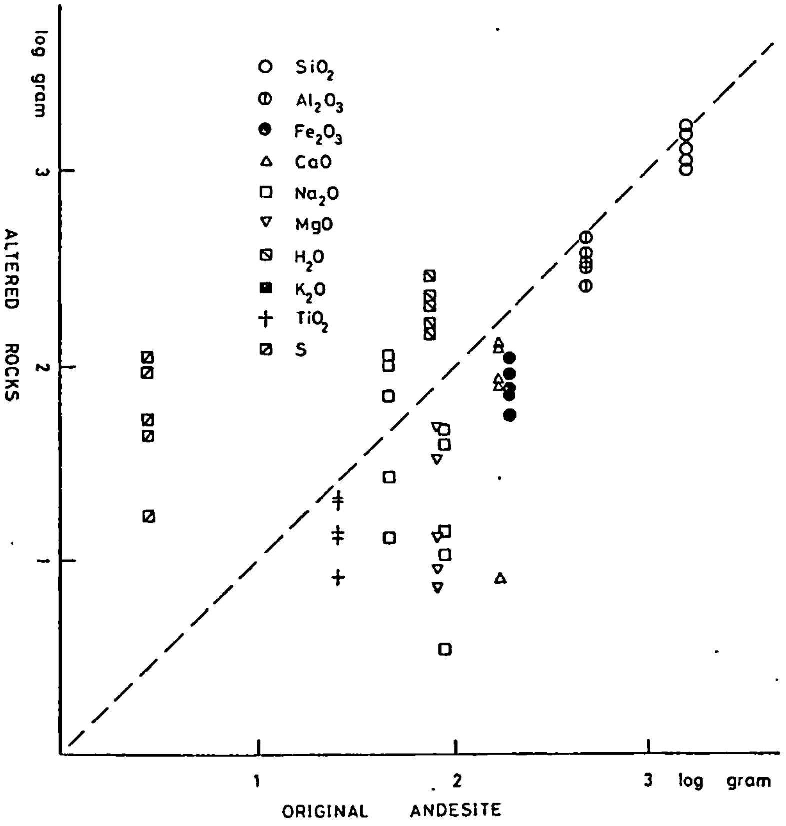
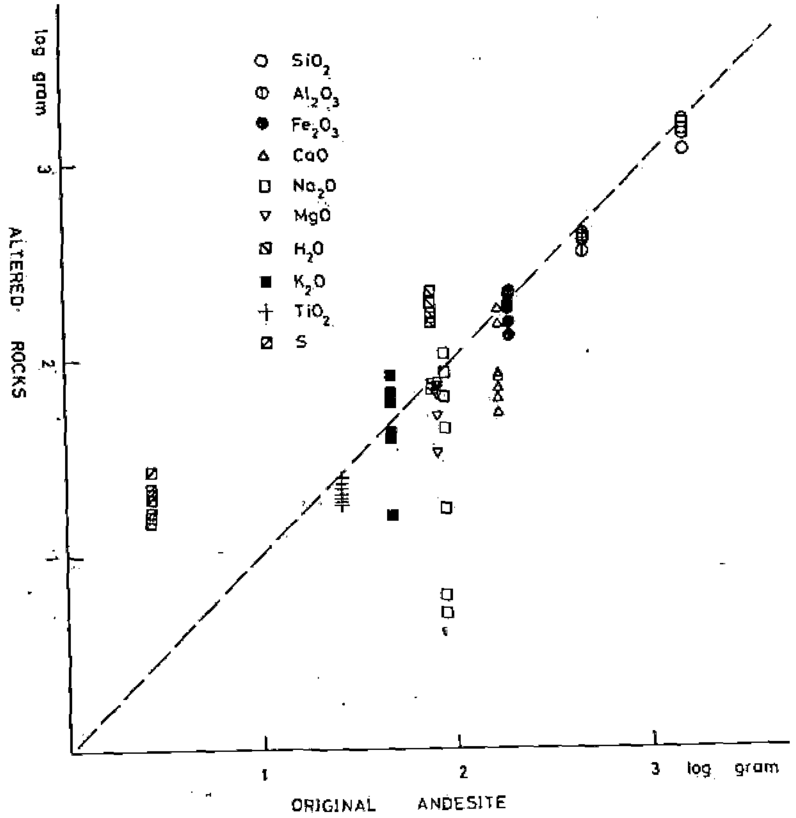


Fig. 16e Changes in chemical composition of rocks during alteration of Type V.



Type IV. The mobilities of components of MgO, Na_2O and K_2O vary greatly among the five specimens.

(5) Altered Rocks of Type V

The chemical compositions of seven specimens of altered rocks of Type V are shown in Table 7g. Changes in chemical composition during the alteration of this type are also shown in Fig. 16e.

There are many immobile components in Type V; namely SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO and TiO_2. This means that Type V is of the most weak alteration among the five types, yet two alkalis, Na_2O and K_2O, are still mobile even in this case.

VII. DISCUSSION

A distinctive feature of the hydrothermal alteration in the Otake area is that various kinds of altered rocks have been formed from original andesites with almost invariable chemical composition.

In this chapter,

1) chemical conditions of each alteration type will be inferred mainly after the concept of thermodynamics of open system by Korzhinskii (1956),

2) temperature and pressure conditions will be estimated taking into consideration the measurements of temperature and vapor pressure, the estimations of temperature by chemical methods, the calculations of total pressure, and the data of hydrothermal synthesis published so far, and

3) comparison of alteration in the Otake area with that in other geothermal areas, will be made.

VII-1. *Chemical Conditions of Each Alteration Type*

Type I with predominant silica minerals will be formed under the highest chemical potential of SiO_2 in hydrothermal solution among the five types. And the potential tion of Type V.

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conditions of each altera-
be inferred mainly after
thermodynamics of open
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ure and pressure conditions
ed taking into consideration
nts of temperature and vapor
estimations of temperature
ethods, the calculations of
and the data of hydrother-
published so far, and
son of alteration in the Otake
t in other geothermal areas,

emical Conditions of Each
teration Type

h predominant silica minerals
ed under the highest chemical
SiO_2 in hydrothermal solution
ive types. And the potential

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must be higher than that of SiO_2 of all the silicates contained in rocks. Under these conditions, all the components are considered to be perfectly mobile (Korzhinskii, personal communication). Therefore, Type I may correspond to the strongest type of alteration.

According to Morey et al. (1962), the solubility of silica (quartz) in water is nearly independent of concentration of dissolved salt species as well as pH value, but increases with rising of the temperature of solvent water. The deep waters in the Otake area contain silica of quantity nearly in equilibrium with rocks at temperatures as shown in Table 3. That is, high temperature deep waters are generally high in chemical potential of SiO_2. The rocks directly in contact with such solutions are considered to be replaced gradually by silica minerals, irrespectively of the pH conditions of solutions. For instance, even in the case of neutral to weakly alkaline solutions, silicification of Type I, though not very strong, is recognized around the conduits of solution in Hatchobaru (H-6; 1,050 m) and in Broadland of New Zealand (Browne, 1970). In the case of acidic solutions, the silicification is accelerated because almost all bases are leached into the solutions. T-2 is a good example.

In the low temperature part at shallow levels, the chemical potential of SiO_2 in solutions is usually not so high, therefore, silicification may be performed mainly by the residual enrichment of silica resulting from leaching of bases by acidic solutions. Consequently, no practical addition of SiO_2 is observed in porous cristobalite rock being formed at low temperature as shown in Table 7c. Iwao (1961) made a similar consideration on the silica ore in the Ugusu mine.

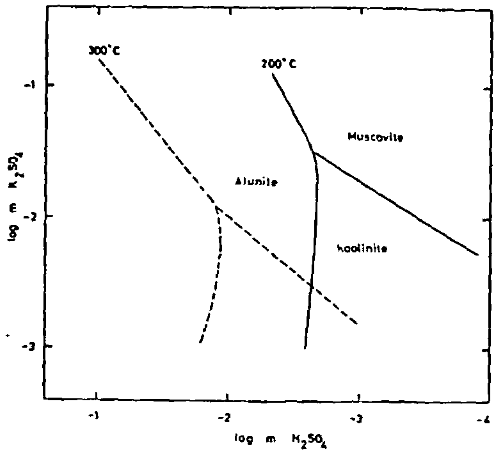
Strong alteration next to Type I may be Type II and III and Subtype IVd, which have characteristic mineral associations as mentioned already. In these alterations, the three components, SiO_2, Al_2O_3 and TiO_2, are almost immobile, of which Al_2O_3 alone is a determining inert component, but SiO_2 is usually an excess component, and TiO_2 is an accessory component. Variations of alteration type in such cases may result from the differences in chemical potentials of SO_4^{2-}, K^+ and H^+ of acting hydrothermal solutions. Thus, Type II is considered to be formed when chemical potentials of all the three are high, Subtype IVd when the potential of K^+ is high, and Type III when the potential of H^+ is high.

It depends upon the chemical potentials of SO_4^{2-} and S^{2-} whether some bases other than Si, Al and Ti are fixed or not in the strongly altered rocks. For instrance, in a case that the chemical potentials of SO_4^{2-} and H^+ are so high as to form Type II, the chemical potential of S^{2-} also may be high, then the altered rocks of Type II have more Fe content fixed as pyrite than those of Type III and Subtype IVd. In a case that the chemical potential of SO_4^{2-} only is high, Ca may be fixed as anhydrite as observed in the altered rocks of Type III in the Otake area. Therefore pyrite and anhydrite are regarded as mobile minerals.

According to the experimental study of the system K_2O-Al_2O_3-SiO_2-H_2O-SO_3 by Hemley et al. (1969), alunite is formed under 15,000 psi and strongly acidic conditions, of which log m H_2SO_4 is over -2.8 (pH smaller than about 4) at 200°C and log m H_2SO_4 is over -2.0 (pH smaller than about 3) at 300°C. The log m K_2SO_4 concentration has hardly influence on the formation of alunite at 200°C, but at 300°C, about -2 of log m K_2SO_4 concentration is most optimum for the formation, as shown in Fig. 17. Therefore, Type II is apt to be formed at low temperature and shallow levels rather than at high temperature and deep levels.

There are other reasons which are favorable for alunite formation at shallow levels. Under the surface conditions, H_2S in the waters is expected to be oxidized by air and also by descending ground water. Sulfuric acid conditions are caused also by the sulfur-oxidizing bacteria as

Fig. 17 Stability relations in the system K_2O-Al_2O_3-SiO_2-H_2O-SO_3 (Hemley et al., 1969). Quartz is present and total pressure is 15,000 psi.



maintained by Schon and Ehrich (1968).

The condition of formation of Type III has pH value being nearer to neutral than Type II. Therefore, contrary to the case of Type II, Type III is apt to be formed at high temperature and deep levels if the H_2SO_4 concentration in acting solutions is the same.

In the case of weakly altered types IV and V, the components such as Fe_2O_3, CaO and MgO are almost immobile in addition to SiO_2, Al_2O_3 and TiO_2. Among these components, TiO_2 is an accessory component, and SiO_2 is an excess component for both types. The three components of Fe_2O_3, CaO and Al_2O_3 are determining inert components for Type IV, and these three and MgO are for Type V. The chemical difference of formation between Types IV and V is that the former has less inert components than the latter. As suggested in Fig. 5, the acting hydrothermal solutions may be weakly acidic to neutral for Type IV, while for Type V neutral to weakly alkaline.

VII-2. *Alteration Temperature and Pressure*

It is very difficult to estimate total pressure and fluid pressure in hydrothermal alterations. In the Otake area, the total pressure was roughly estimated from the largest depths of occurrence of each subtype, on an assumption that there had been no erosion of altered rocks. In the estimation, the specific gravity of rocks including water and void was assumed to be 2.5. For example, Subtype b is not found deeper than 600 m, and therefore, the total pressure is less than 2.5×600/10=150 atm. On the other hand, the fluid pressure was also estimated roughly based on the measurements of vapor pressure at well heads, on the saturated pressure corresponding to the measured or estimated temperature, on the water pressure between the water table and the reservoir, etc. The total pressure and fluid pressure of each subtype are shown in Table 6b. The estimated pressures are very low as compared with 500~tens of thousand atm under which general hydrothermal synthesis have been carried out.

The stability condition of minerals determined by hydrothermal synthesis is generally considerably different from the condition of natural minerals. The reasons are: (1) hydrothermal synthesis by pure water usually determine the upper stability field of minerals, (2) synthesis are usually made under a condition of total pressure equal to vapor pressure, (3) natural hydrothermal solutions contain more kinds of bases and ions than the most complex solutions used in experiments, etc. In the case of the Otake area, the main reason is considered to be the fact that the pressure conditions, especially the fluid pressure, are very low compared with those of hydrothermal synthesis.

In general, the slope of equilibrium curve of dehydration reaction is given by the Clapayron's relation $dp/dt = \Delta S/\Delta V$, and the curve is nearly parallel to the pressure axis in high pressure domain; but in low pressure domain, it becomes nearly parallel to the temperature axis as ΔV becomes larger, and the stable field of a high temperature mineral extends into low temperature domain. For instance, the phase boundary of a reaction,

kaolinite + 2 quartz ⇄ pyrophyllite + vapor

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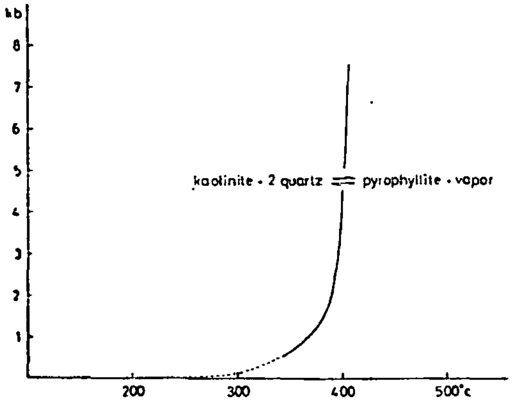
which was determined by Althaus (1969), is almost parallel to the pressure axis above 2,000 bars, but the slope becomes smaller below 2,000 bars as shown in Fig. 18. The curve passes the point of 340°C at 500 bars, the lowest pressure in the synthesis. According to the writer's calculation for lower temperature and lower pressure domain after the constant entropy method (Zen, 1972), the boundary passes on the dotted line indicated in the figure. This result supports that pyrophyllite can be formed under such conditions of low temperature and low pressure as in the Otake area. Moreover, it explains that phase changes of hydrated minerals under low pressure depend not only on temperature but also on pressure considerably.

Fig. 18 Stability relation for the reaction kaolinite +2 quartz⇄pyrophyllite+vapor determined by Althaus (1969). The dotted line indicates an equilibrium curve calculated by the present writer.



Next, consideration will be made on the alteration temperature. The boundary temperature between Subtypes a and b lies on the temperature at which cristobalite is converted to quartz. However, according to Mizutani (1966), amorphous silica is inverted gradually to quartz through cristobalite with a lapse of time. Judging from the Mizutani's data and the measured temperatures in the Otake area, Subtype a is inferred to be formed around 100°C or below.

The temperature range of Subtype b concerns with the stable field of the associations of kaolinite-quartz (IIIb) and of laumontite-wairakite-quartz (IVb). In No. 6 well, where accurate temperature measurements were carried out, a zone of Subtype IVb occurs at depths 190 to 295 m, where the temperature is 120 to 190°C. In No. 7 well, where no higher temperature subtype than IVb appears, the temperature of deep waters estimated by the chemical methods is approximately 200°C. On the other hand, the kaolinite-quartz association (IIIb) occurs first at a depth of 400 m in H-6 well, where the temperature is 100°C. The highest temperature of this association is 190°C, which was measured at a depth of 820 m in H-4 well. From these facts, it is concluded that Subtype b is formed in a temperature range 100 to 200°C.

As to the formation temperature for Subtype c, the associations of albite-quartz (Vc) and of dickite-pyrophyllite-quartz (IIIc) are concerned. The upper limit of the alteration temperature of the albite-quartz association is estimated to be lower than 250°C based on the estimated temperatures of deep waters from the Otake production wells Nos. 6, 8 and 9 (Table 3), where this Subtype occurs at the deepest in the wells. However, the lowest alteration temperature of this association is not known. On the other hand, the lower limit of alteration temperature of the dickite-pyrophyllite-quartz association is estimated to be approximately 150°C from a measurement around 300 m depth of T-1 bore. And, the alteration temperature of this association would not exceed 268°C, the highest temperature measured in the Otake area. Therefore, the range of alteration temperature of Subtype c is estimated to be 150 to 250°C.

Since diaspore is occasionally formed at the highest temperature part of Subtype IIIc, the formation temperature of diaspore is estimated at 250°C or below.

Subtype d may have been formed under the temperature conditions neccessary for the formation of the association of adularia-quartz (Vd) or pyrophyllite-quartz (IIId).

The temperature is comparatively low referred to the data of measurements, e.g. 200°C (H-6; 1,050 m), 212°C (H-4; 1,000 m) and 220°C (H-3; 1,000 m). But the chemically estimated values, 250 to 260°C, are higher than the measured ones. Therefore, Subtype d is inferred to be formed at temperatures of about 230°C or over.

VII-3. *Comparison with Other Geothermal Areas*

As described already, the distinctive feature of the Otake geothermal area is the existence of two kinds of deep water, acidic and weakly alkaline. Such cases are rare in the other geothermal areas, where only one kind of deep water, either acidic or weakly alkaline, is usually found.

Among the geothermal areas producing acidic deep waters, alteration has been best studied at Matsukawa in Tohoku district of Japan (Sumi, 1968). The alteration in this area resembles the acidic type alteration in the Otake area, and is characterized by the development of minerals of Types II and III such as alunite, kaolinite and pyrophyllite. However, the alteration studied by Sumi did not reach the depths of reservoir, and the relationship between the properties of deep waters and the alteration types could not be made clear. Aside from Otake and Matsukawa, many geothermal areas in Taiwan produce acidic deep waters (Chen, 1967), but no detailed study has been made.

The acidic type alteration in Otake and Matsukawa, as pointed out by Katayama (1969), resembles closely the alteration in the pyrophyllite deposits in Japan, but in the active geothermal areas, the silicified zone of Type I has not been developed on a large scale and such high temperature minerals as corundum and andalusite are lacking or rare.

On the other hand, there are many geothermal areas producing weakly alkaline deep waters. The alkaline type alterations in most areas are not different from that in the Otake area essentially. Thus, zeolites are formed in low temperature parts, and feldspars in high temperature parts. There are, however, some differences in mineral association and in chemical composition of minerals among the geothermal areas according to the differences of chemical composition of original rocks and of physicochemical properties of hydrothermal solutions and gases.

In Wairakei, ptilolite, wairakite (+laumontite), albite and adularia occur in this order towards deeper levels, below the sulfuric acid and argillized zones of shallow levels (Steiner, 1953). The only essential difference between Otake and Wairakei is that heulandite is formed in Otake but ptilolite is formed at Wairakei at shallow levels. This difference seems to be due to the following differences in chemical composition of original rocks. The andesite of Otake is rich in CaO (Av. 6.50%), but the ignimbrite of Wairakei is rich in Na_2O (4.31%; Steiner, 1953). In addition, anhydrite, which is common at Otake is not found at Wairakei. The reason may be that the deep waters at Wairakei are poor in SO_4 and the CaO content of the original rocks is low. The alterations of majority of other areas resemble those of Otake and Wairkei.

At Yellowstone, however, Na-zeolites such as clinoptilolite, mordenite and analcime are produced, but Ca-zeolite has not been detected (Honda and Muffler, 1970). This may be due to the fact that the Na/K mol ratio of the deep water is as high as 36.1 and the original sedimentary rocks are poor in CaO.

In the Salton Sea geothermal area, where no zeolite is produced but feldspar is found in deep levels, the hydrothermal solutions are weakly acidic to neutral. According to Ellis (1969), the pH value, at which Na- and K-feldspars are at equilibrium with the solution, is dependent on the temperature and the molarity of Na+K, and the pH value at 250°C is 7.2 at 0.008 *m* (Hveragergdi), 6.5 at 0.044 *m* (Wairakei) and 4.6 at 2.5 *m* (Salton Sea). Therefore, when the molarity of Na+K is large, feldspars can be formed even under

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VIII. SUMMARY

Hydrothermal alteration in the Otake geothermal area has been studied mainly from mineralogical and geochemical viewpoints. There occur two kinds of hydrothermal solution, acidic and weakly alkaline, bringing about various kinds of alteration from the original rocks, which have almost invariable chemical composition.

The alterations are classified into five types according to essential alteration minerals and pH values of acting hydrothermal solution. They are Types I, II, III, IV and V: Type I is characterized by the predominant formation of silica minerals; Type II by the formation of alunite and its kindred sulfates; Type III by the formation of aluminum-silicates with layer structures such as kaolinite, dickite and pyrophyllite; Type IV by the formation of aluminosilicates with layer structures such as montmorillonite, chlorite, sericite, etc., but is lacking in zeolite or feldspar; and Type V by the formation of aluminosilicates with framework structures such as Ca-zeolites, Na-feldspar and K-feldspar, accompanied by the clay minrals of Type IV. Each type is further classified into four subtypes according to alteration temperature and pressure, which resulted in progressive changes of essential mineral associations. These are summarized in Tables 6a and 6b.

Type I may be produced under both acidic and alkaline conditions, if the chemical potential of SiO_2 in acting hydrothermal solution is very high. However, it is apt to be formed under strongly acidic to acidic conditions, especially at shallow and low temperature levels. All components are mobile in this type of alteration. Therefore, Type I is regarded as the strongest alteration.

Types II and III and Subtype IVd may be strong to intermediate alterations, in which the three components of SiO_2, Al_2O_3 and TiO_2 are almost immobile. Of the three, TiO_2 is an accessory component, SiO_2 is usually an excess component, and Al_2O_3 alone is a determining inert component. Variations of alteration type may result from the differences in chemical potentials of SO_4^{2-}, K^+, H^+, etc. in the hydrothermal solutions.

In the case of weak alteration of Types IV and V, the components of Fe_2O_3, CaO and MgO are almost immobile in addition to SiO_2, Al_2O_3 and TiO_2. However, even in these weakly altered types, two alkalis, Na_2O and K_2O, are still mobile.

Temperature and pressures of each alteration subtype are inferred using both measured and estimated data as listed in Table 6b. The estimated temperature and pressures of the alteration subtype, especially the fluid pressure, are very low compared with those of usual hydrothermal synthesis.

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要　旨

熱水の物理化学的性質と変質作用との関係を究明することを目的として，九州大岳地熱地域において火山地質，各試錐の地質および変質柱状図，変質岩の鉱物組成，変質岩や変質鉱物の化学組成，地表および地下の変質分帯，熱水中のおもな化学成分などについて研究を行なった。

大岳地域の基盤岩は，新第三紀（中新世）の玖珠層群で，本域の地下1,000m以深で確められる。これを被覆する豊肥火山岩類（第四紀，下部更新世）との不整合面が，南部の“八丁原地区”で有力な地熱貯溜層となっている。

豊肥火山岩類は，全層厚900m，主として輝石安山岩質の熔岩と火山砕屑岩類との互層よりなる。その中部層は，凝灰角礫岩に富む互層で，北部の“大岳地区”でおもな貯溜層を構成している。

これらを貫入被覆する九重火山岩類（中～上部更新世）は，角閃石安山岩類を主とし，本域のまわりに数多くの熔岩ドームを形成し，現在の地熱活動はその“後火山作用”に由来する。

本域にはNW-SEに走る主断層系，およびこれに斜交する小断層が発達し，これらは噴気孔，温泉，変質岩などの地熱徴候の分布と密接な関係を有する。

本域の変質作用の特徴は，化学組成の類似する輝石安山岩を原岩とし，これに作用した熱水の物理化学的性質の違いにより種々の変質岩が生じていることである。まず最初に，作用した熱水溶液の化学的性質（主としてpH値）を反映している特徴的変質鉱物によって，これらの変質岩を，下表のようにⅠ, Ⅱ, Ⅲ, Ⅳ, Ⅴ型の5つのタイプに大別した。次に，変質作用の温度，圧力の上昇による主要な鉱物組合せの変化によって各タイプをそれぞれa, b, c, dの4つのサブタイプに細分した。

各サブタイプの生成温度は，主として孔井内の実測値を利用し，または熱水中のSiO_2含有量やNa/K比などから推定した。全圧は各サブタイプが出現する深度から算出し，流体圧は，各孔口の実測値，あるいは蒸気と熱水の量比などから推定した。

変質作用に伴う主成分の移動性を検討した結果，Ⅰ型の変質作用ではすべての成分が移動成分であり，以

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PRESENT STATUS AND FUTURE PROSPECTS OF THE GEOTHERMAL ENERGY DEVELOPMENT IN JAPAN

SITUATION ACTUELLE ET PERSPECTIVES D'AVENIR DU DEVELOPPEMENT DE L'ENERGIE GEOTHERMIQUE AU JAPON

By

Tsutomu Inoue
Counciller, Director General's Secretariat
Agency of Natural Resources and Energy

Forword

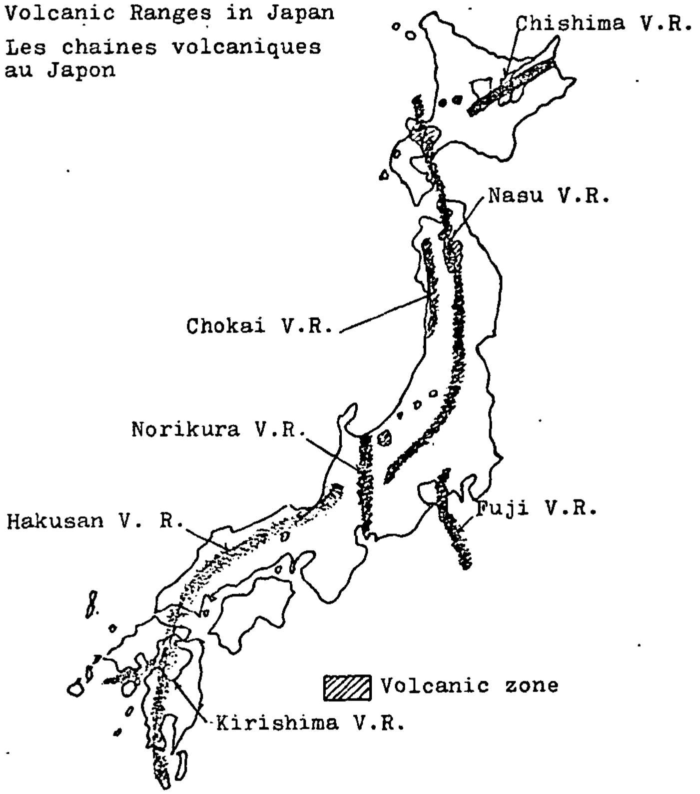
Energy requirements in Japan are constantly growing with the development of industry and the advance of living standards of the people. Around 85% of her energy requirements is met by oil which almost entirely comes from abroad. Under the present tendency towards oil shortage in the international market and the complicated international situations the stable supply of energy in Japan is being threatened by its high dependence on overseas resources. Japan needs to utilize more effectively her domestic energy resources. She is one of the most important volcanic countries in the world and is assumed to be abundant in geothermal energy resources, so that it is highly desirable to use this form of energy for electric power generation and also for space heating of houses and garden plants for the benifit of the regional people.

1. Geothermal Resources in Japan

The land of Japan forms a part of the volcanic belt surrounding the Pacific Ocean and ranges of volcanoes run through the area in succession. Among these volcanoes, Mts. Mihara, Asama, Aso and Sakurajima are active and Mt. Fuji was once active, though it is now dormant. Hot springs occurring in the vicinity of these volcanoes have been used for bathing from the ancient times. Prospective sites for geothermal energy development usually lie around the hot spring zones of volcanoes. These areas include the Kurile volcanic range running to the Tohoku District along the Ou mountain range, Chokai running parallel with the Nasu, Fuji in Kanto District, Noritake in Chubu District, Hakusan running along the Japan Sea and Kirishima in Kyushu. The total probable reserves available for electric power generation in these regions is estimated at 140 million kW, of which 20 million will be developable by present techniques and under the present economic conditions. The latter figure is roughly compared with the total hydro power potential in Japan. Exploitable reserves will increase with the technical advance in the future.

Fig.1 Volcanic Ranges in Japan

Fig.1 Les chaines volcaniques au Japon



2. Stages of Geothermal Devlopment

The geothermal power development is usually carried out through the five stages mentioned below:

(1) The first stage is a general or basic survey. At this stage geological maps showing the distribution of geothermal indications in certain regions covering 200 - 500 km^2, respectively are compiled by the aid of aerial infrared-photographs. Rock analysis and chemical analysis of hot springs are also conducted. Through these investigations prospective areas for geothermal development are found.

(2) The second stage is a detailed survey and borings. The detailed survey including electric and seismic investigations, shallow temperature measurement are conducted in prospective sites each covering 2-5 km^2. Test borings are also carried out to investigate the geological formation in the areas by means of examinations and analysis of sand and rock, and the temperature logging. Through these investigations promising sites for geothermal exploitation are selected.

(3) The third stage is drilling of an exploration well. Exploration wells are drilled in the promising sites mentioned above to examine the nature of steam and possibility of obtaining the required geothermal energy for the project.

(4) The fourth stage is drilling of a producing well. Producing wells are drilled in those sites where the availability of the required characters has been ascertained by the above investigations.

(5) The fifth and last stage is the installation of electric generation and utilization equipments. The geothermal energy produced from the wells is fed to the power station.

3. Brief History of Geothermal Energy Development

As early as in 1904 geothermal energy was first used for electric power generation in Japan. However, a genuine development only started after the World War II.1)

<u>1947</u> Miyagi Prefectural government planned to exploit geothermal energy in the area of Naruko and studied its utlization by the aid of the steam wells drilled by the Tone Boring Co. On the other hand, Ministry of Commerce and Industry at that time commenced a research and development of geothermal power generation, establishing an engineering committee for the geothermal energy development.

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1) The early development after the War is given in: T. Yoshioka, The Trend of Investigation on Electric Generation by Subterranean Steam in Japan (A paper submitted to the Fifth World Power Conference, Vienna, 1956, 22K/1)

<u>1948</u> The Tone Boring Co. made experiments on geothermal power generation at Izu-Atakawa. The Industrial Technology Council of the Ministry of Commerce and Industry set up the Engineering Council for Geothermal Energy Development and the Geological Survey of Japan conducted borings at Beppu in Kyushu and generated electricity, using the steam produced.

<u>1951</u> Industrial Technology Council (the present Agency of Industrial Science and Technology) of The Ministry of International Trade and Industry (former Ministry of Commerce and Industry) made a test electric generation of 30kW with the steam produced at Beppu.

<u>1953</u> The Geological Survey of Japan commenced a geological survey at Mt. Showa-Shinzan in Hokkaido and Mt. Kirishima in Kyushu.

Kyushu Electric Power Co. Inc. carried out two test borings at Otake. (The company received a subsidy of 27 million yen from the Agency of Industrial Science and Tecnology.

<u>1955-58</u> The Geological Survey Institute of Japan carried out three test borings at a depth of 200 - 250 m at Onikobe.

<u>1960</u> The Geological Survey of Japan conducted two test borings at Matsukawa area in Iwate Prefecture. Receiving a subsidy of 13 million yen from Agency of Industrial Science and Technology, The Japan Metals and Chemicals Co. (then Azuma Chemical Co.) conducted two test borings in the same area.

<u>1961</u> Succeeded in emitting steam by a boring made in the Matsukawa area, the Japan Metals and Chemicals Co. applied to the New Technology Development Coorporation for commercialization of the project.

The Electric Power Development Co. resumed the suspended work at Onikobe, conducting three borings there. The Yawata Steel Co. Ltd. made a test boring of 200 m deep at Takenoyu (Kyushu) but abondoned it later.

<u>1963</u> Mitsubishi Metal Mining Co. Ltd. started the exploitation of geothermal energy at Goshokake and Onuma areas in Akita Prefecture.

<u>1964</u> The Electric Bureau of Tochigi Prefectural Government carried out three test borings of which one succeeded in emitting steam. However, the work was

suspended afterwards.

1965 The Underground Resources Survey Institute of Hokkaido conducted two test borings at Shikabe which ended in failure and moved the exploration to Sôunkyo.

1966 The Japan Metals and Chemicals Co. was entrusted with a study of "producing techniques of geothermal steam for electric generation", receiving a subsidy amounting to 305 million yen from the New Technology Development Coorporation and succeeded in building a geothermal power station with a 20 MW capacity.

1967 The Kyushu Electric Power Co. Inc. completed a Geothermal Power Station of a 11MW capacity at Otake.

4. Present Status of Geothermal Energy Exploitation

(1) Geothermal Power Stations under Operation

At present, the following two geothermal power stations are being operated in Japan.

Name of Companh	Name of Station	Loca-tion	Capacity (kW)	Date of	
				Starting Construction	Starting operation
Japan Metals and Chemicals Co.	Matsukawa	Iwate Pref.	22,000	Sept. 1964	Oct. 1966
Kushu Electric Power Co.	Otake	Ôita Pref.	11,000	Jan. 1966	Oct. 1967

Note: Matsukawa Station started operation with a capacity of 20,000 kW in October 1966 and incresed the capacity to 22,000 kW in April 1973.

(a) Matsukawa Geothermal Power Station of Japan Metals and Chemicals Co. Ltd.

Matsukawa Station is situated in the area of National Park Towada-Hachimantai and is adjacent to the Matsukawa hot spring zone where hot springs at the temperature of 30 - 50°C occur. Seven steam wells from No.1 to No.7 at depths ranging from 945 - 1,500. The produced steam contains H_2S and H_2CO_3. A mixture of steam and hot water produced from the wells is separated into steam and hot water by a separator provided at each well-head. The separated steam is sent through a transmission main into a steam-receiver at the power station and lead through a separator again to a turbine. The steam conditions at the entrance of the turbine represent a pressure of 3.5 kg/cm^2 and a temperature of 147°C. After passing through a turbine it is condensed by a barometric condenser. Cooling water for the condensers is supplied from by the River Matsukawa through a pool in the sand.(Fig.2)

(b) Otake Geothermal Power Station of Kyushu Electric Power Co. Inc.

Situated about 6 km north of Mt. Kujū, Ôtake Station lies in a steam-field at 900 - 1,100 m above the sea level in the Kujū mountain range running from south to north. The station has five production wells from No.6 to No.10, the last one being a spare well. These wells are 360 - 600 m deep, respectively, and produce steam with a high content of CO_2. The steam produced with a pressure of about 2.1 kg/cm^2 is led to a turbine through a steam reciver. The pressure of steam falls to 1.5 kg/cm^2 at the entrance of the turbine. It is controlled by a jet valve. When the pressure rises due to the reduction of loads, a jet valve opens and excessive steam is discharged into the air through a silencer. Exhaust steam from a turbine is led to a barometric type jet condenser and condensed with cooling water ejected into the condenser. Condenser vacuum is -687mmHg. Non-condensable gas contained in the steam is taken out by a vacuum pump and discharged into the air. As the condensed water with a temperature of 41°C can not be used, it is sent by a hot water pump to a cooling tower of a forced air cooling type. It is cooled to 26°C and pressure raised by cooling water pump and then ejected into a condenser. (Fig.3)

Fig.2 Main Flow Diagram of Matsukawa Geothermal Power Station
Le diagramme du courant principal de l'énergie géothermique à Matsukawa.

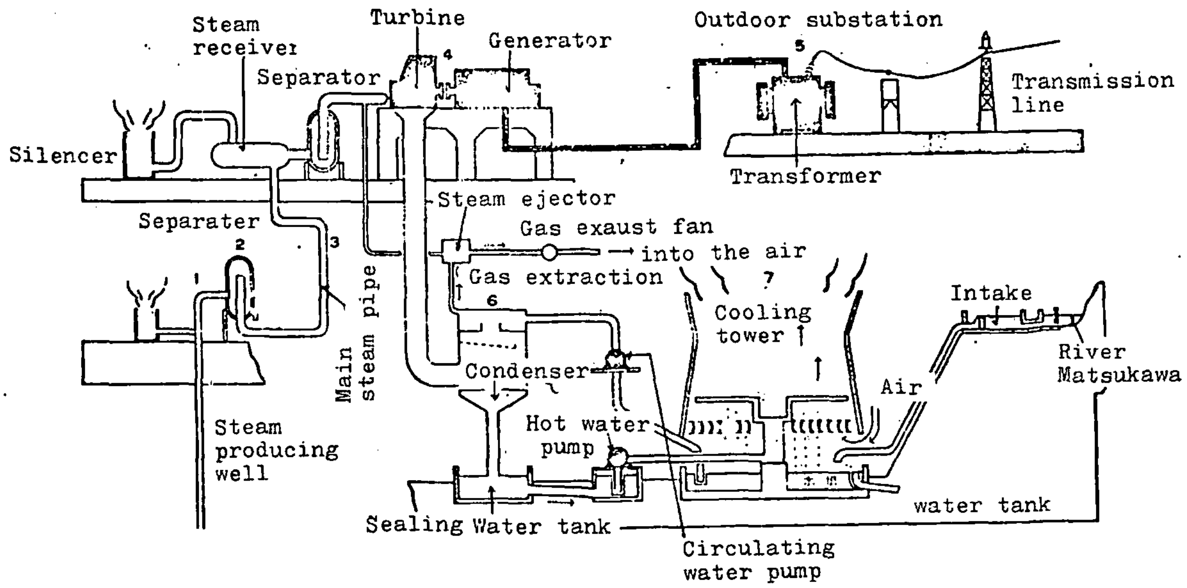
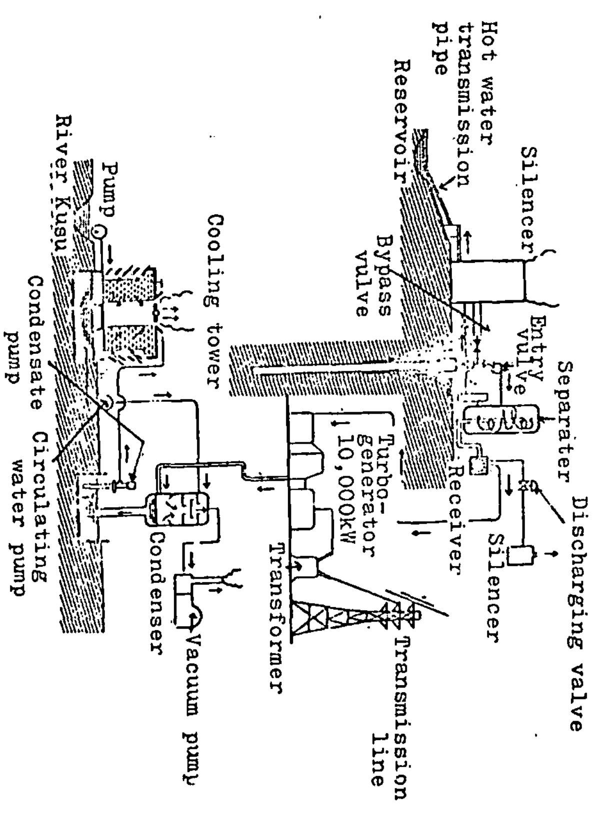


Fig.3 Main Flow Diagram of Otake Geothermal Power Station
Fig.3 Le diagramme du courant principal de l'énergie géothermique à la station de Otake



(2) Geothermal Power Station under Construction

Geothermal power stations under construction or planning are shown in the following table.

Name of Company	Name of Station	Location	Capacity (kW)	Date of starting Const-ruction	Scheduled Date for Operation
Mitsubishi Metal Mining Co.	Ônuma	Akita Pref.	10,000	May, 1970	April, 1974
Japan Metals and Chemicals Co.* Tōhoku Electric Power Co.	Katsukonda	Iwate Pref.	50,000	Oct. 1974	Nov. 1976
Electric Power Development Co.	Onikobe	Miyagi Pref.	25,000	Jan. 1973	April, 1975
Kyushu Electric Power Co.	Hatchobaru	Ôita Pref.	50,000	Jan. 1974	April, 1976

* Japan Metals and Chemicals Co. installs steam facilities and supplies Tohoku Electric Power Co. with produced steam. Tohoku Electric Power Co. constructs generating facilities and produces electricity, using purchased steam from J.M.C.

(a) Ônuma Station of Mitsubishi Metal Mining Co.

Ônuma Station is situated in the area of Towada-Hachimantai National Park adjacent to the border between Akita and Iwate Prefectures. Many hot springs and fumaroles are found in the area. The Company plans to drill four production wells. Three have been completed and the remaing one is being drilled. The three completed wells are emitting steam at the average rate of 51t/h and hot water at the rate of 288t/h. A trial run of the generating facilities are going on and the maximum capacity reached 6,000 kW.

The main facilities are:

Site Area

Station Yard	5,600 m^2
Steam Well	aprox. 3,000 m^2

Station Building

Floor area	348 m^2
Capacity	3,600 m^2

Well-Head Equipments

Steam Well	Number: 4	Diameter: 20.3 cm.
Silencer	Number: 4	Inside diameter: 2,500 m/m Height: 6,000 m/m
Steam separator	Number: 4	Type: Steel cyclone

Steam Turbine

Number	1
Type	Single-cylinder, impulse type condensing turbine
Rated capacity	10,000 kW
Speed	3,600 r.p.m.
Steam consumption (at the rated capacity)	110 t/h
Steam turbine stage	4 stages

Generator

Number	1
Type	Horizontal axis, cylindical rotating-field
Capacity	12,500 kVA
Rated output	1,000 kW
Speed	3,600 r.p.m.
Voltage	6,600 V
Power-factor	0.9
Cooling system	Air cooling

Main Transformer

Number	1
Type	Oil immersed, self-cooling

Capacity	15,000 kVA
Number of phase	Three-phase
Voltage	Primary side : 6,600 V Secondary side: 66,000 V

Condenser

Number	1
Type	Barometric jet type

Cooling Tower

Number	1
Type	Mechanical double drafting
Cell number	3 cells

Transmission Line

From the construction site to the sending end of the Company's Akita Transmission Line a 60 kV transmission line of the length of 30 km is to be constructed.

Steam Transmission Main

Number	Inside diameter: 400 m/m Inside diameter: 550 m/m	Length: 375 m Length: 145 m
Insulation Material	Magnesia carbonate product and rockfiber	
Thickness of insulation material	Approx. 60 m/m	
Outer Covering	Galvanized steel plate or aluminium plate	

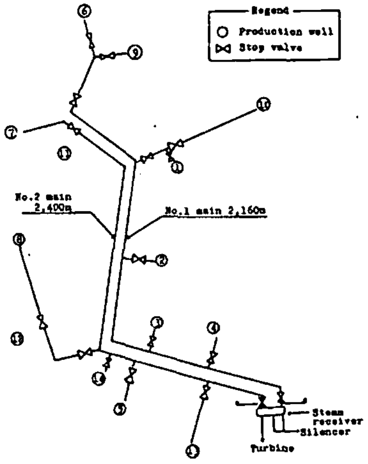
(b) Katsukonda Geothermal Power Station of Japan Metals and Chemicals Co. and Tohoku Electric Power Co.

Katsukonda Geothermal Power Station is being built jointly by the Japan Metals and Chemicals and the Tohoku Electric Power Co. Inc. The site of the Station lies within a national forest zone (Shizukuishi-cho, Iwate Pref.) and in this region hot springs and fumaroles are scattered over a distance of 5 km. Emitting steam is neutral or weak alkaline and hot water is alkaline, having a high Na.SiO_2 content. Gas content of steam is very low, its ratio ranging 0.5 - 0.05 vol%. Four exploration wells have been drilled since September 1972. At present all wells have a high water leakage. Pumping a test of water has been made and an unexpectedly large quantity of steam and hot water have been obtained. Approximately 500 t/h of steam will be required for the electric generation at the capacity of 50,000 kW. Therefore, it is planned to drill 14 wells, assuming a steam output of 40 - 50 t/h per well.

No.1 and No.2 steam transmission mains will be built along the Katsukonda River. Their specification is given below:

1)	Total length	4,560 m
2)	Diameter	35.55 - 76.19 cm (14" - 30")
3)	Design pressure	Max. 10 kg/cm^2
	Design temperature	Max. 220°C
4)	Pressure loss	Below 1.5 kg/cm^2
5)	Speed of flow	Below 40 m/s
6)	Heat insulation	Thickness of calcium silicate casing: 75 mm with outer covering of aluminium sheet
7)	Outer load resistance	Wind velocity: 60 mm/s Earthquake (horizontal) 0.3 Weight 10 t/m^2

Fig.4 Plan of Steam Transmission Mains of Katsukonda Station
Le plan de la transmission principale de vapeur à la station de Katsukonda.



The main generating facilities

Steam Turbine

Number	1
Type	Impulse type condensing turbine
Rated Capacity (generation end)	50,000 kW

Condenser

Number	1
Type	Jet condenser

Cooling Tower

Number	1
Type	Horizontal axis, rotating field
Capacity	59,000 kVA
Voltage	Approx. 20 kV
Cooling system	Direct hydrogen cooling

Main Transformer

Number	1
Capacity	59,000 kVA
Voltage	Primary side: Approx. 20 kV Secondary side: 151-154-157-161 kV
Cooling system	Oil immersed self cooling

Transportation Road and Site

Exploration well	Road	25,242 m^2
	House	6,000 "
Steam producing well	Road	34,218 "
	House	5,330 "
Main steam transmission main		15,960 "
Power plant		24,250 "

Ancillary Equipments

Building	Structure and Site		Number
Field office	wooden one-stoeied	97.20 m^2	1
Warehouse	"	77.76 m^2x 2	2
Laboratory	"	38.88 m^2	1
Repair-shop	"	79.00 m^2	1
Lodging	wooden two-storied	556.068 m^2	1
Garage	wooden one-storied	77.76 m^2	1

(c) Onikobe Geothermal Power Station of Electric Power Development Co.

Onikobe Power Station is located at a secluded place at about 20 Km distance from Naruko-cho, Miyagi Prefecture, within the area of Kurikoma Quasi-National Park near to the border between Yamagata and Akita Prefs. In the region, surface indications (fumaroles and mud volcano), peculiarities to geothermal fields are found. It is planned to drill 12 producing wells and the results hitherto obtained from drilling show that produced steam has a pressure of 4 kg/cm^2 and its output is 13-29 t/h. The output of hot water is very small. The main generating facilities are given below:

Lands

Total Area	124,000 m^2
Power Station Grounds	28,700 m^2
Steam Equipment Grounds	16,100 m^2
Intake equipments	1,600 m^2
Entering Road to Station	1,000 m^2
Provisional Equipments	3,000 m^2

Power Station Building

Scale	Building area: 492 m Total area: 1,045 m
Structure	Ferro-concrete two-floor building
Number	1 building

Steam Well

Diametre	178 ø
Depth	Approx. 350 m
Number	12

Wellhead Equipment

Separator

Type: Steel plate, vertical cyclone
Number: 12

Silencer

Type: Steel plate, vertical absorbed type
Number: 12

Steam Transmission Main

Number	4
Total length	Approx. 1,500 m
Maximum Diameter	Approx. 780 ø

Steam Turbine

Type	Single-cylinder, impulse type condensing turbine
Capacity	25,000 kW
Number	1 unit

Condenser

Type	Barometric jet condenser
Circulating water flow	8,000 m^3/h
Number	1 unit

Coolying Tower

Type	Forced draft absorbing, counter-flow type
Circulating water flow	Approx. 8,500 m^3/h
Number	1 unit

Generator

Capacity	28,000 kW
Number	1 unit

Principal Transformer

Capacity	Approx. 28,000 kVA
Voltage	11 kV/66 kV
Number	1 unit

(d) Hatchobaru Geothermal Power Station of Kyushu Electric Power Co. Inc.

The Hatchobaru area is a natural steam field in the Kuju volcanic range and in its neighbourhood a geothermal zone where surface activity of the earth such as hot springs and fumaroles is active is found. Topographically, the area forms a plain in the basin of a mountain range at 1,300 m above the sea and a tributary of the Kuma river runs through the area.

After examining the characteristics of the structures by drilling exploration wells, the Company plans to sink ten producing wells. The work was started from July 1968 and up to now six wells have been completed. The wells produce at the rates of 20-48 t/h and hot water at the rates of 50-140 t/h. The pressure varies from 5 to 42 kg/cm^2 and the depth of a well ranges from 740 to 1,600 m.

The features of the Hatchobaru Station are given below:

(1) While at Ôtake Station the produced steam separated from hot water by a separator is used, at Hatchobaru Station not only the produced steam but also the secondary steam obtained by flashing the hot water are used to fully utilize the heat. It is expected that by this means the generating capacity can be increased by about 20%.

(2) Hitherto, a steam separator has been provided at each well-head and the separated steam alone has been sent to a power station. However, at Hatchobaru a mixture of steam and hot water produced from wells will be transmitted without separation to a central separator provided near to the Station and the separation will be made by it collectively. In this new system the total length of transmission mains can be considerably shortened and at the same time the separating equipments at a well-head will become unnecessary, thus making the operation and maintenance easier.

(3) At Hatchobaru Station, the hot water produced will be returned underground by three wells.

The flow sheet of the electric generation at the station is given below. (Fig. 5)

5. Problems of Geothermal Power Development

Geothermal energy resources are a natural endowment. The question is how to find prospective sites for exploitation. Some guidances can be given because geothermal sites usually occur in hot spring zones. However, it is still to be proved by a through investigation requiring a great deal of expenditure whether the development of asite for geothermal power generation is actually feasible. These hot spring zones have peculiar landscapes such as volcanic valleys and have often been designated as national parks or quasi-national parks. The geothermal development within the area of a national park needs beforehand permission of the Director of Environment Agency. The Director gives a decision to the applicant after hearing opinions of the National Park Council. It often takes considerable time before the permission is given. When a development site is situated within the area of a quasi-national park, permission from a Prefectural Governor is required.

Hot springs in Japan have been used for bathing and towns composed of hot spring inns are usually found in these districts. When the exploitation of geothermal energy is planned in the vicinity of a hot spring resort, it would be natural that the bathkeepers of the town fear that the hot springs they use may run dry by the exploitation. The Hot Spring Law provides that people who wish to drill a well in the area have to obtain permission from the Prefectural

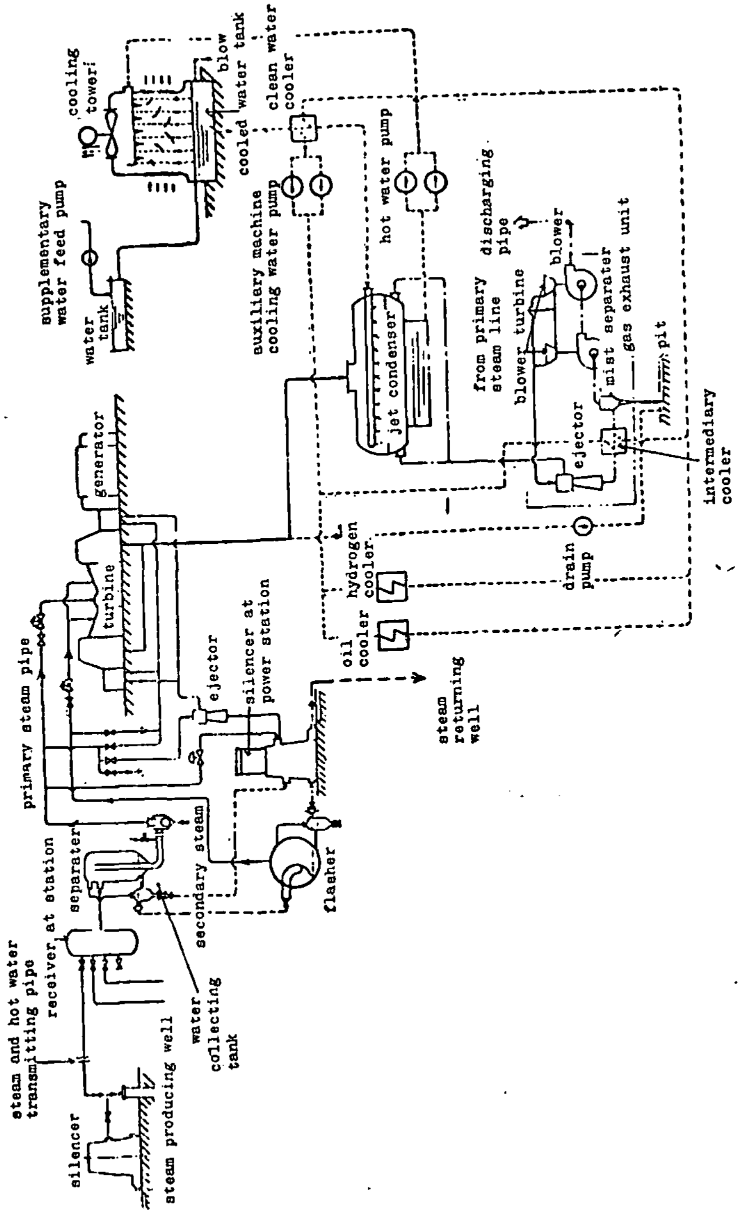


Fig.5 Main flow Diagram of Hatchobaru Geothermal Power Station

Fig.5 Le Diagramme du courant principal de l'énergie géothermale à la station de Hatchobaru

Governor concerned and that before giving permission, the Governor needs to put the matter to the Hot-Spring Council whose members are mainly composed of the bathkeepers in the area. Under the circumstances, the Governor's permission would not be easily obtained.

Many volcanic zones are found within the areas of national forests. One who wishes to develop geothermal energy in these areas must obtain the government permission for the lease of the land required in accordance with the provisions of the National Forest Law.

Besides the fact that a great deal of investment is required, the necessity to obtain various permits under laws would diminish private enterprisers' will to develop geothermal energy.

However, in view of the very high dependance of Japan's energy supply on foreign resources, the exploitation of the domestic geothermal energy resources should be promoted as a national policy to secure the stable energy supply in this country.

6. Government Aids to Geothermal Development in the past

Government aids given to the geothermal energy development in the past are mentioned below:

(1) In 1954 a subsidy for the experiments and investigations amounting to 27 million yen was granted to Kyushu Electric Power Co. Inc.

(2) In 1960 a subsidy for the experiments and investigations of 13 million yen was granted to Japan Metals and Chemicals Co.

(3) In 1966 the New Technology Development Corporation entrusted Japan Metals and Chemicals with a study regarding the techniques for the production of geothermal steam used for electric power generation, granting a subsidy of 350 million yen, on the recommendation of the Industrial Science and Technology Agency.

(4) In 1972 the New Technology Development Corporation entrusted Japan Metals and Chemicals with a study regarding the techniques for steam pruducing wells for geothermal, granting a subsidy of 760 million yen.

7. Government Policy for Geothermal Energy Development in 1973

In 1973 the Ministry of International Trade and Industry planned to take the following measures for the development of geothermal energy.

(1) Investigations of geothermal power generation

The Natural Resources and Energy Agency will carry out on a two-year plan for the following technical investigations, appropriating an amount of 2,061,000 yen for this purpose in the 1973 budget.

(a) Steam emitted from a producing well often contains a large quantity of hot water. The steam separated from hot water by a separator is led to a turbine. The separated hot water can be utilized for the district heating and culture of vegetables. The technical study for the utilization of hot water will be conducted with the purpose of building a geothermal power station serving the benifits of the regional people.

(b) The new technique for detecting geothermal reserves and steam well drilling will be examined to improve the exploration efficiency and various technical problems regarding a large scale geothermal power generation will be studied.

(c) Prospective areas for geothermal exploration are usually found in volcanic zones often designated as national or quasi national parks under the National Park Law for their senic beauty. The geothermal exploitation in these areas needs the consideration for the harmony with the natural environment. Technical problems encountered in the course of various stage of the development including a basic investigation, drilling of exploration and production wells and construction of the power station should be fully studied to conserve the natural environment conditions.

A committee for inquiring into technical problems on the geothermal development consisting of certain scholars, experts and officers from the authorities concerned was set up in the Natural Resources and Energy Agency for the purpose of studying the technical problems mentioned above. The method of research and development by the Committee is as follows:

The committee considers the general policy for the research and development and entrusts The Japan Geothermal Energy Association with the technical investigations which the Committee proposes. An amount of 1,600,000 yen has been provided in the 1973 budget(a calendar year from 1st April 1963 and to 31th March 1974).

The Japan Geothermal Energy Association submitts its interim report to the Committee when the investigation has reached a certain stage. Examining the report, the Committee will inform the Association with its view pointing out the matters for consideration, amendments, change of the investigation plan, etc.

When the definite report is submitted from the Association, the Committee will complete its own research after studying the report by the Association as basic materials.

(2) Study of the Hot Water flow system in Geothermal Fields

The Geological Survey of Japan of the Agency of Industrial Science and Technology plans to conduct a survey, on a five-year basis beginning 1973, over the Onikobe-Naruko, South and Akinomiya fields for the purpose of obtaining the basic information regarding the subterranean hot water in a geothermal field which are useful for effective exploitation of geothermal energy. An amount of six million yen has been provided for the 1973 survey, covering the following items:

(a) Research on mass and heat balance of geothermal fluid at a geothermal field

This research will make clear the mass and heat balance by measuring natural out-put of hot water and steam and in-put of meteoric water into the underground.

(b) Isotope geology

To research the origin of geothermal fluid and to estimate the age of the fluid which is considered as meteoric origin, the study of isotope of oxygen and hydrogen etc. will be carried out.

(c) Research on geothermal fluid reservoirs

The research on the fractured pattern of strata and reservoir engineering will be conducted by the geological and geophysical method.

(3) National Survey of Geothermal Energy

The Geological Survey of Japan plans to conduct a nation-wide investigation of the geothermal energy over 30 districts on a three-year plan with the purpose of fixing the position of geothermal energy development in the government policy. For the 1973 investigation eighty million yen has been appropriated in the 1973 Budjet. The standards for selection and procedures are as follows.

(a) The volcanic zones have been classified into ten groups in accordance with their characterstics.

(b) The areas where the consent of the regional people to the exploitation has been obtained and where the working conditions are favourable were chosen for the 1973 investigation.

(c) Priority was given to the areas where the exploitation seems to be most promising from the existing data, although the explotation has not yet been carried out.

The areas selected for the 1973 investigation are given below: **(Fig. 6)**

(a) North part of Mt. Komagatake (Hokkaido)
(b) North part of Kurikoma (Akita Pref.)
(c) North part of Azuma (Yamagata Pref.)
(d) South part of Izu (Shizuoka Pref.)
(e) South Satsuma (Kagoshima Pref.)

(4) The Treasury Investment and Loan

Based on the findings of the above mentioned technical investigations and the national survey, the government policy will be definitely established and various measures such as the designation of certain geothermal development areas, granting of a subsidy and low-interest loan, preferential treatment in taxation will be taken. However, under the existing legislation there remain many problems to be solved for carrying out these measures.

Meanwhile, as for financial aids, it is decided to make the Treasury Investment and Loan to the enterprises from the fiscal year 1973. A loan amounting to 650 million yen at a special interest of 7.2% was decided to be made to the two geothermal power development projects at Katsukonda, Iwate Pref. and Hatchobaru, Oita Pref. of which construction work **was** scheduled to start shortly.

8. Government Plan for 1974

The research and development of the geothermal energy requires systematic work over a wide area based on the scientific study. For this purpose large amounts of investments must be made long before the start of the production. Therefore, the government aids in the fields of techniques as well as finance and taxation.

In succession to the 1973 plan, the Ministry of International Trade and Industry will take the following measures in the fiscal year 1974.

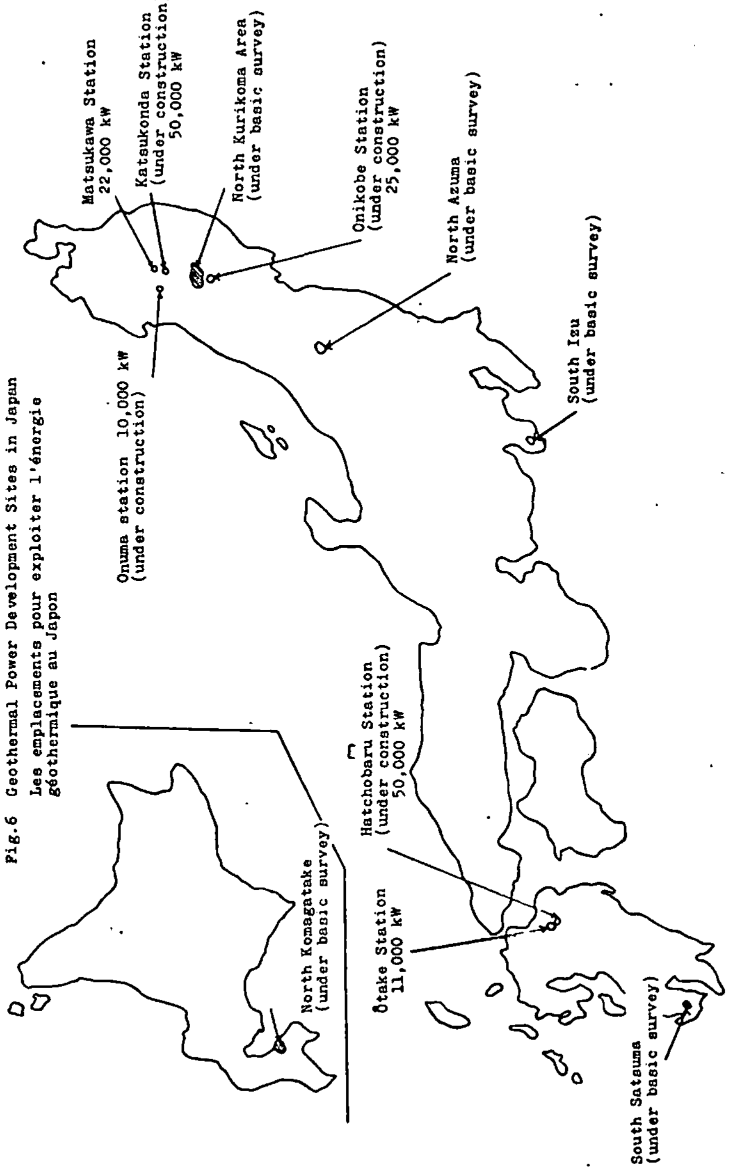


Fig.6 Geothermal Power Development Sites in Japan
Les emplacements pour exploiter l'énergie géothermique au Japon

(1) The amount of the Treasury Investment and Loan will be increased from 1,600 million yen in 1973 to 2,600 million in 1974 and besides the Katsukonda and Hatchobaru projects, the Ônuma Geothermal power development project will be added to the program.

(2) An expenditure of 250 million yen will be appropriated in the 1974 budget and the investigation will be extended from the 5 areas to 15 areas.

(3) Based on the findings of the 1973 survey, the detail investigations including structure drilling will be conducted with an expenditure of about 280 million yen provided in the 1973 budget, for the purpose of promoting the exploitation by enterprises on a commercial base.

In parallel with the exploitation using the present techniques, the research and development of a larger capacity geothermal power generation in the future based on the new techniques utilizing an enormous volume of heat energy contained in the hot dry rock of the earth crust will be promoted. To extract the heat energy on a stable and economical basis, the development of a large scale electric generation by geothermal energy of volcanoes and ultra-deep geothermal steam power of the crust will be carried out. At first the installation of a model experiment equipment and a design of a geothermal power plant of a binary-cycle will be made.

For this purpose the following expenditure is estimated.

(a) Expenditure for ultra-deep geothermal steam power generating system

		1,000 yen
R and D for Technology of physical and chemical measurement in geothermal wells	Technology of physical and chemical measurement in geothermal wells To make clear the geologic and physical character of strata and the existing state of the underground geothermal fluid	54,910 ($183,000)
Development of materials for drilling	Materials which will be available in the geothermal fluid of high temperature and pressure which is rich in H_2S etc. contents	9,920 ($33,000)

(b) Expenditure for generating system by thermal energy of volcanoes

Feasibility study	Technology of production of electric power by using volcanic energy Study of a harmony between environmental effects and the above technology	9,760 ($42,900)
Development of technology for volcanic energy and heat distribution survey	1. Measuring technique of volcanic energy 2. Technique to find out the underground high temperature part 3. Development of a survey method of the underground thermal structure	109,000 ($363,000)
Development of drilling technique of high temperature formation	Drilling-technique of the high temperature formation which will be necessary to develop the technology of electric production by using volcanic energy	44,450 ($148,000)

Summary

Energy requirement in Japan is constantly growing with the development of industry and the advance of living standards of the people and they are mostly met by the overseas oil supply. The high dependance on the imported oil has caused a feeling of uneasiness about the stable supply of energy in the future. It is necessary, therefore, to utilize more effectively the domestic energy resources.

Japan is one of the most important volcanic country in the world and is assumed to be abundant in geothermal energy resources, so that it is highly desirable to utilize this form of energy for the electric generation and also for space heating of dwellings and green-houses, for the benifit of the regional people.

The procedure of geothermal energy development in Japan comprises five stages: general survey, detailed survey, exploration-well drilling, production-well drilling and installation of electric power generating and other equipments.

It was in 1904 that geothermal energy was first used for electric power generation in Japan. However, its real development began only after the World War II.

In 1947 the government started a fundamental survey of geothermal energy and following this survey several private enterprises carried out more detailed surveys in the prospective sites and exploitations.

At present, the Matsukawa geothermal power station with installed capacity of 20,000 kW of the Japan Metals and Chemicals Co. and the Otake geothermal power station with installed capacity of 10,000 kW of the Kyushu Electric Power Co. are under operation. Besides, the following four geothermal power stations are under construction and/or planning.

Ônuma Station (10,000 kW)	Mitsubishi Metal Mining Co. Ltd.
Katsukonda Station (50,000 kW)	Tohoku Electric Power Co. Inc. (purchasing produced steam from Japan Metals and Chemicals Co.)
Onikobe Station (25,000 kW)	Electric Power Development Co.
Hatchobaru Station (50,000 kW)	Kyushu Electric Power Co., Inc.

The development of geothermal energy involves great risks and a large amount of investments. Moreover, prospective sites are often found within the area of natural and quasi-natural parks or in the vicinity of hot spring resorts. The exploitation in these areas needs the permissions of the Authorities concerned under the provisions of the Natural Park Law and the Hot Spring Law. These circumstances diminish private enterprises' interest in the exploitation.

Hitherto, the government has assisted the geothermal energy development, granting a subsidy to the enterprises. On the other hand, the basic survey over 30 prospective fields started from 1973 onward and the detailed survey will be carried out over certain areas. Besides, the research and development of new electric generation systems utilizing thermal energy of volcanoes and ultra-deep geothermal steam energy of the crust are to be conducted. Financial aid by the Treasury on investment and loan will also be made to the geothermal energy development.

A study group for the geothermal energy development of 51 members from the Liberal Democratic Party has prepared the outline of the Geothermal Resources Development Promoting Bill (tentatively designated), with the purpose of submission of the Bill to the Diet.

Résumé

Au Japon, la consommation de l'énergie est constamment augmentée en conséquence du développement de l'industrie et du niveau de la vie quotidienne. La pauvreté des ressources de l'énergie au Japon nécéssite leur approvisionnement par les pays étrangers. La dépendence en l'énergie des pays étrangers lui fait inquiéter un approvisionnement stable de l'énergie.

C'est de ce fait qu'il faudrait étudier l'utilisation efficace des ressources d'énergie à l'intérieur du pays. Le Japon est un des pays volcaniques renommés dans le monde, et on prévoit qu'il devait y avoir beaucoup d'énergie géothermique pour la production d'éléctricité, et pour le chauffage des maisons et des serres de la région restreinte dans son pays.

Au Japon, la manière d'exploiter l'énergie géothermique est constituée en cinq étapes, i.e. (1) sondage général du terrain, (2) sondage détaillé du terrain, (3) creusement d'essai des puits, (4) creusement régulier des puits pour la production et (5) mise au point de la station éléctrique et des autres équipements.

En 1904, l'énergie géothermique a été utilisée pour la première fois. Cependant, c'est seulement après la deuxième grande guerre mondiale qu'on se mettait à étudier, avec ardeur ce problème au Japon.

En 1947, le gouvernement commençait les sondages des terrains et ces affaires ont été succédées par des entreprises privées dans le but des sondages détaillés et de la transformation de cette énergie à l'énergie éléctrique. En ce moment, les deux stations pour la transformation de l'énergie géothermique à l'énergie éléctrique sont mises en marche: la station de Matsukawa de "The Japan Metals and Chemicals Co." avec la capacité de 20,000 kW et la station d'Otaké de "The Kyushu Electric Power Co." avec la capacité de 10,000 kW. Les quatre stations suivantes sont en construction ou en projet: la station d'Omura de "Mitsubishi Metal Mining Co., Ltd." (10,000 kW), la station de Katsukonda de "Tohoku Electric Power Co., Inc." (50,000 kW) (en achetant la vapeur produite par "The Japan Metals and Chemicals Co."), la station d'Onikobé de "Electric Power Development Co." (25,000 kW), et la station de Hachobaru de "Kyushu Electric Power Co., Inc." (50,000 kW).

L'exploitation de l'énergie géothermique nécéssite des frais énormes avec beaucoup de risque. De plus, la plupart de temps, les localités convenables pour les stations se trouvent dans les régions de parc national, de parc quasi-national. Donc, l'exploitation dans cette région exige

la permission de l'autorité concernant la loi du parc national et la loi de la source thermale. Dans cette circonstance, des entreprises ne s'intéressent pas beaucoup à l'exploitation de l'énergie géothermique.

Jusqu'ici, le gouvernement japonais subventionnait des entreprises privées en leur donnant les subsides pour des recherches concernant l'énergie géothermique. D'autre part, des sondages généraux de terrains dans 30 régions du pays sont commencés sous la direction gouvernementale. Les sondages détaillés de certains terrains, des recherches pour le développement du système nouveau transformant l'énergie géothermique de volcan ou de sousterrain très profond se succéderont aussi sous la direction gouvernementale. Des aides financières par le Ministère des Finances pour l'exploitation des ressources géothermiques se sont aussi accomplies. Un groupe étudiant le problème de l'énergie géothermique organisé par 51 membres du parti libéral démocratique a préparé le projet de loi pour accéler le développement de l'exploitation des ressources géothermiques, et il le présentera à la Diète prochainement.

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PRESENT STATUS AND FUTURE PROSPECTS OF THE GEOTHERMAL ENERGY DEVELOPMENT IN JAPAN

SITUATION ACTUELLE ET PERSPECTIVES D'AVENIR DU DEVELOPPEMENT DE L'ENERGIE GEOTHERMIQUE AU JAPON

By

Tsutomu Inoue
Counciller, Director General's Secretariat
Agency of Natural Resources and Energy

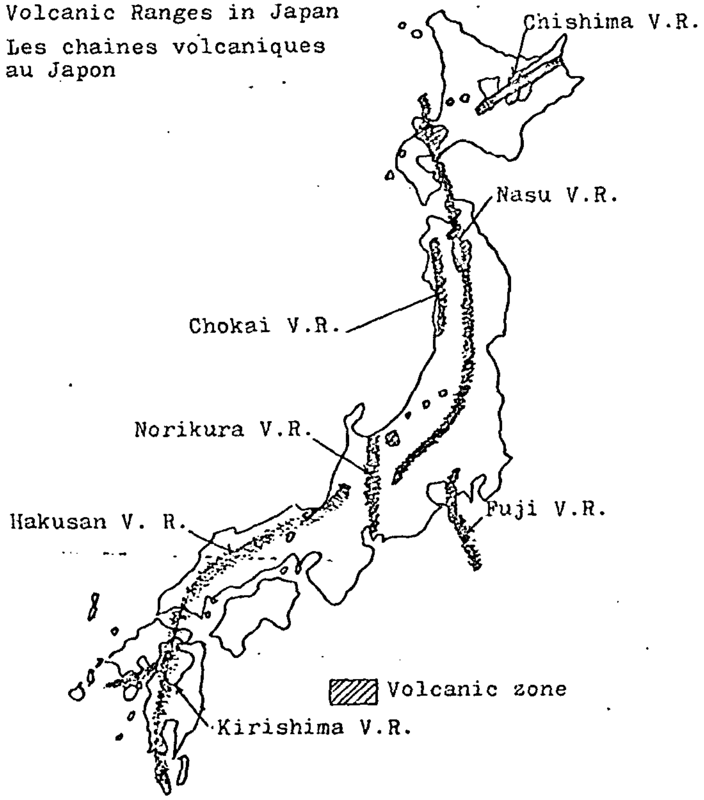
Forword

Energy requirements in Japan are constantly growing with the development of industry and the advance of living standards of the people. Around 85% of her energy requirements is met by oil which almost entirely comes from abroad. Under the present tendency towards oil shortage in the international market and the complicated international situations the stable supply of energy in Japan is being threatened by its high dependence on overseas resources. Japan needs to utilize more effectively her domestic energy resources. She is one of the most important volcanic countries in the world and is assumed to be abundant in geothermal energy resources, so that it is highly desirable to use this form of energy for electric power generation and also for space heating of houses and garden plants for the benifit of the regional people.

1. Geothermal Resources in Japan

The land of Japan forms a part of the volcanic belt surrounding the Pacific Ocean and ranges of volcanoes run through the area in succession. Among these volcanoes, Mts. Mihara, Asama, Aso and Sakurajima are active and Mt. Fuji was once active, though it is now dormant. Hot springs occurring in the vicinity of these volcanoes have been used for bathing from the ancient times. Prospective sites for geothermal energy development usually lie around the hot spring zones of volcanoes. These areas include the Kurile volcanic range running to the Tohoku District along the Ou mountain range, Chokai running parallel with the Nasu, Fuji in Kanto District, Noritake in Chubu District, Hakusan running along the Japan Sea and Kirishima in Kyushu. The total probable reserves available for electric power generation in these regions is estimated at 140 million kW, of which 20 million will be developable by present techniques and under the present economic conditions. The latter figure is roughly compared with the total hydro power potential in Japan. Exploitable reserves will increase with the technical advance in the future.

Fig.1 Volcanic Ranges in Japan
Fig.1 Les chaines volcaniques au Japon



2. Stages of Geothermal Devlopment

The geothermal power development is usually carried out through the five stages mentioned below:

(1) The first stage is a general or basic survey. At this stage geological maps showing the distribution of geothermal indications in certain regions covering 200 - 500 km^2, respectively are compiled by the aid of aerial infrared-photographs. Rock analysis and chemical analysis of hot springs are also conducted. Through these investigations prospective areas for geothermal development are found.

(2) The second stage is a detailed survey and borings. The detailed survey including electric and seismic investigations, shallow temperature measurement are conducted in prospective sites each covering 2-5 km^2. Test borings are also carried out to investigate the geological formation in the areas by means of examinations and analysis of sand and rock, and the temperature logging. Through these investigations promising sites for geothermal exploitation are selected.

(3) The third stage is drilling of an exploration well. Exploration wells are drilled in the promising sites mentioned above to examine the nature of steam and possibility of obtaining the required geothermal energy for the project.

(4) The fourth stage is drilling of a producing well. Producing wells are drilled in those sites where the availability of the required characters has been ascertained by the above investigations.

(5) The fifth and last stage is the installation of electric generation and utilization equipments. The geothermal energy produced from the wells is fed to the power station.

3. Brief History of Geothermal Energy Development

As early as in 1904 geothermal energy was first used for electric power generation in Japan. However, a genuine development only started after the World War II.1)

1947 Miyagi Prefectural government planned to exploit geothermal energy in the area of Naruko and studied its utlization by the aid of the steam wells drilled by the Tone Boring Co. On the other hand, Ministry of Commerce and Industry at that time commenced a research and development of geothermal power generation, establishing an engineering committee for the geothermal energy development.

1948 The Tone Boring Co. made experiments on geothermal power generation at Izu-Atakawa. The Industrial Technology Council of the Ministry of Commerce and Industry set up the Engineering Council for Geothermal Energy Development and the Geological Survey of Japan conducted borings at Beppu in Kyushu and generated electricity, using the steam produced.

1951 Industrial Technology Council (the present Agency of Industrial Science and Technology) of The Ministry of International Trade and Industry (former Ministry of Commerce and Industry) made a test electric generation of 30kW with the steam produced at Beppu.

1953 The Geological Survey of Japan commenced a geological survey at Mt. Showa-Shinzan in Hokkaido and Mt. Kirishima in Kyushu.

Kyushu Electric Power Co. Inc. carried out two test borings at Otake. (The company received a subsidy of 27 million yen from the Agency of Industrial Science and Tecnnology.

1955-58 The Geological Survey Institute of Japan carried out three test borings at a depth of 200 - 250 m at Onikobe.

1960 The Geological Survey of Japan conducted two test borings at Matsukawa area in Iwate Prefecture. Receiving a subsidy of 13 million yen from Agency of Industrial Science and Technology, The Japan Metals and Chemicals Co. (then Azuma Chemical Co.) conducted two test borings in the same area.

1961 Succeeded in emitting steam by a boring made in the Matsukawa area, the Japan Metals and Chemicals Co. applied to the New Technology Development Coorporation for commercialization of the project.

The Electric Power Development Co. resumed the suspended work at Onikobe, conducting three borings there. The Yawata Steel Co. Ltd. made a test boring of 200 m deep at Takenoyu (Kyushu) but abondoned it later.

1963 Mitsubishi Metal Mining Co. Ltd. started the exploitation of geothermal energy at Goshokake and Onuma areas in Akita Prefecture.

1964 The Electric Bureau of Tochigi Prefectural Government carried out three test borings of which one succeeded in emitting steam. However, the work was

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1) The early development after the War is given in: T. Yoshioka, The Trend of Investigation on Electric Generation by Subterranean Steam in Japan (A paper submitted to the Fifth World Power Conference, Vienna, 1956, 22K/1)

suspended afterwards.

1965 The Underground Resources Survey Institute of Hokkaido conducted two test borings at Shikabe which ended in failure and moved the exploration to Sôunkyo.

1966 The Japan Metals and Chemicals Co. was entrusted with a study of "producing techniques of geothermal steam for electric generation", receiving a subsidy amounting to 305 million yen from the New Technology Development Coorporation and succeeded in building a geothermal power station with a 20 MW capacity.

1967 The Kyushu Electric Power Co. Inc. completed a Geothermal Power Station of a 11MW capacity at Otake.

4. Present Status of Geothermal Energy Exploitation

(1) Geothermal Power Stations under Operation

At present, the following two geothermal power stations are being operated in Japan.

Name of Companh	Name of Station	Location	Capacity (kW)	Date of	
				Starting Construction	Starting operation
Japan Metals and Chemicals Co.	Matsukawa	Iwate Pref.	22,000	Sept. 1964	Oct. 1966
Kushu Electric Power Co.	Otake	Ôita Pref.	11,000	Jan. 1966	Oct. 1967

Note: Matsukawa Station started operation with a capacity of 20,000 kW in October 1966 and incresed the capacity to 22,000 kW in April 1973.

(a) Matsukawa Geothermal Power Station of Japan Metals and Chemicals Co. Ltd.

Matsukawa Station is situated in the area of National Park Towada-Hachimantai and is adjacent to the Matsukawa hot spring zone where hot springs at the temperature of 30 - 50°C occur. Seven steam wells from No.1 to No.7 at depths ranging from 945 - 1,500. The produced steam contains H_2S and H_2CO_3. A mixture of steam and hot water produced from the wells is separated into steam and hot water by a separator provided at each well-head. The separated steam is sent through a transmission main into a steam-receiver at the power station and lead through a separator again to a turbine. The steam conditions at the entrance of the turbine represent a pressure of 3.5 kg/cm^2 and a temperature of 147°C. After passing through a turbine it is condensed by a barometric condenser. Cooling water for the condensers is supplied from by the River Matsukawa through a pool in the sand.(Fig.2)

(b) Otake Geothermal Power Station of Kyushu Electric Power Co. Inc.

Situated about 6 km north of Mt. Kujū, Ôtake Station lies in a steam-field at 900 - 1,100 m above the sea level in the Kujū mountain range running from south to north. The station has five production wells from No.6 to No.10, the last one being a spare well. These wells are 360 - 600 m deep, respectively, and produce steam with a high content of CO_2. The steam produced with a pressure of about 2.1 kg/cm^2 is led to a turbine through a steam reciver. The pressure of steam falls to 1.5 kg/cm^2 at the entrance of the turbine. It is controlled by a jet valve. When the pressure rises due to the reduction of loads, a jet valve opens and excessive steam is discharged into the air through a silencer. Exhaust steam from a turbine is led to a barometric type jet condenser and condensed with cooling water ejected into the condenser. Condenser vacuum is -687mmHg. Non-condensable gas contained in the steam is taken out by a vacuum pump and discharged into the air. As the condensed water with a temperature of 41°C can not be used, it is sent by a hot water pump to a cooling tower of a forced air cooling type. It is cooled to 26°C and pressure raised by cooling water pump and then ejected into a condenser. (Fig.3)

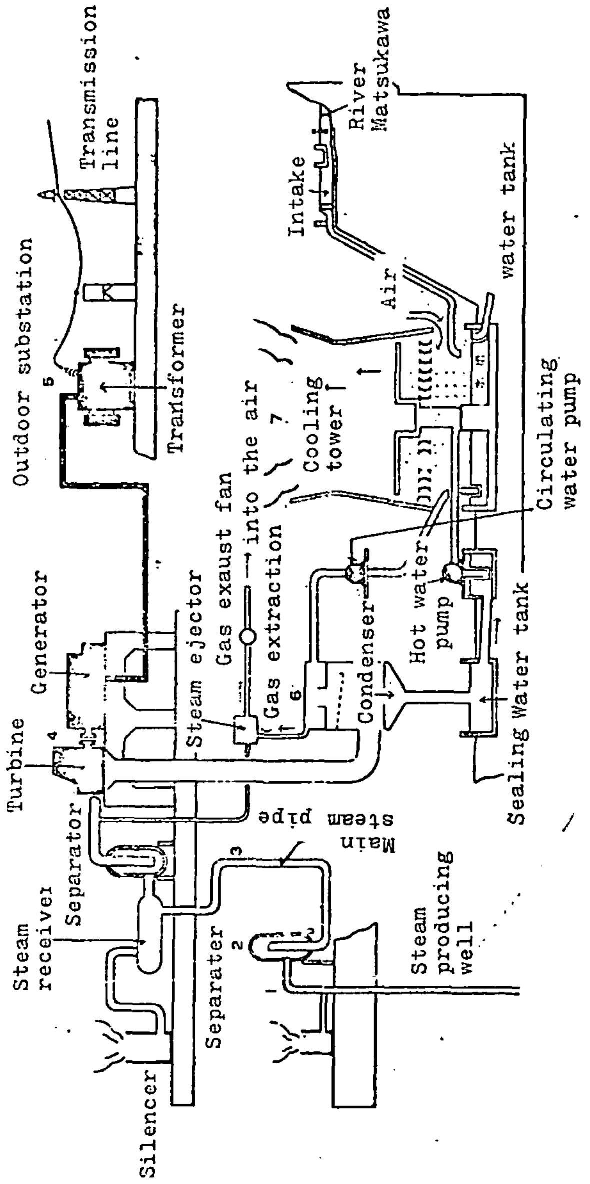
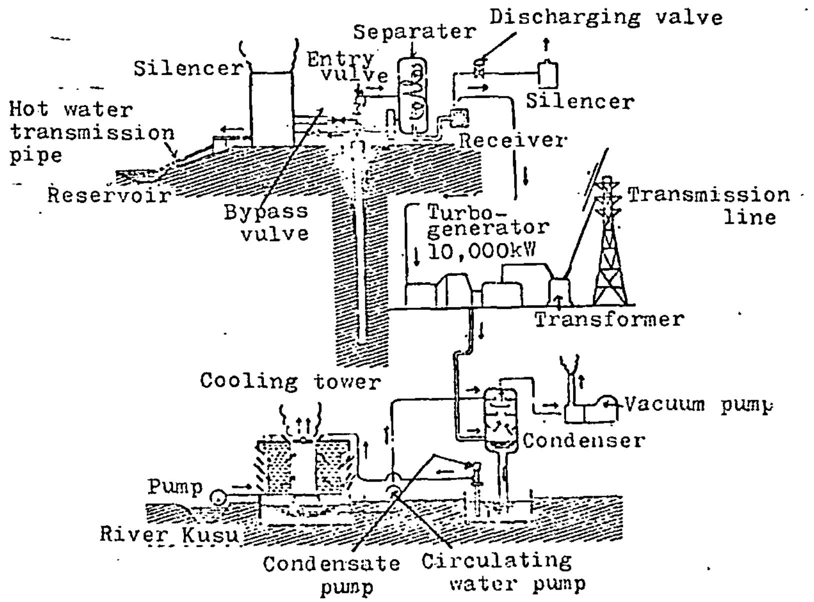


Fig.2 Main Flow Diagram of Matsukawa Geothermal Power Station
Le diagramme du courant principal de l'énergie géothermique à Matsukawa.

Fig.3 Main Flow Diagram of Otake Geothermal Power Station

Fig.3 Le diagramme du courant principal de l'énergie géothermique à la station de Otaké



(2) Geothermal Power Station under Construction

Geothermal power stations under construction or planning are shown in the following table.

Name of Company	Name of Station	Location	Capacity (kW)	Date of starting Construction	Scheduled Date for Operation
Mitsubishi Metal Mining Co.	Ônuma	Akita Pref.	10,000	May, 1970	April, 1974
Japan Metals and Chemicals Co.* Tōhoku Electric Power Co.	Katsukonda	Iwate Pref.	50,000	Oct. 1974	Nov. 1976
Electric Power Development Co.	Onikobe	Miyagi Pref.	25,000	Jan. 1973	April, 1975
Kyushu Electric Power Co.	Hatchobaru	Ôita Pref.	50,000	Jan. 1974	April, 1976

* Japan Metals and Chemicals Co. installs steam facilities and supplies Tohoku Electric Power Co. with produced steam. Tohoku Electric Power Co. constructs generating facilities and produces electricity, using purchased steam from J.M.C.

(a) Ônuma Station of Mitsubishi Metal Mining Co.

Ônuma Station is situated in the area of Towada-Hachimantai National Park adjacent to the border between Akita and Iwate Prefectures. Many hot springs and fumaroles are found in the area. The Company plans to drill four production wells. Three have been completed and the remaing one is being drilled. The three completed wells are emitting steam at the average rate of 51t/h and hot water at the rate of 288t/h. A trial run of the generating facilities are going on and the maximum capacity reached 6,000 kW.

The main facilities are:

Site Area

Station Yard	5,600 m^2
Steam Well	aprox. 3,000 m^2

Station Building

Floor area	348 m^2
Capacity	3,600 m^2

Well-Head Equipments

Steam Well	Number: 4	Diameter: 20.3 cm.
Silencer	Number: 4	Inside diameter: 2,500 m/m Height: 6,000 m/m
Steam separator	Number: 4	Type: Steel cyclone

Steam Turbine

Number	1
Type	Single-cylinder, impulse type condensing turbine
Rated capacity	10,000 kW
Speed	3,600 r.p.m.
Steam consumption (at the rated capacity)	110 t/h
Steam turbine stage	4 stages

Generator

Number	1
Type	Horizontal axis, cylindical rotating-field
Capacity	12,500 kVA
Rated output	1,000 kW
Speed	3,600 r.p.m.
Voltage	6,600 V
Power-factor	0.9
Cooling system	Air cooling

Main Transformer

Number	1
Type	Oil immersed, self-cooling

Capacity	15,000 kVA
Number of phase	Three-phase
Voltage	Primary side : 6,600 V Secondary side: 66,000 V

Condenser

Number	1
Type	Barometric jet type

Cooling Tower

Number	1
Type	Mechanical double drafting
Cell number	3 cells

Transmission Line

From the construction site to the sending end of the Company's Akita Transmission Line a 60 kV transmission line of the length of 30 km is to be constructed.

Steam Transmission Main

Number.	Inside diameter: 400 m/m Length: 375 m Inside diameter: 550 m/m Length: 145 m
Insulation Material	Magnesia carbonate product and rockfiber
Thickness of insulation material	Approx. 60 m/m
Outer Covering	Galvanized steel plate or aluminium plate

(b) Katsukonda Geothermal Power Station of Japan Metals and Chemicals Co. and Tohoku Electric Power Co.

Katsukonda Geothermal Power Station is being built jointly by the Japan Metals and Chemicals and the Tohoku Electric Power Co. Inc. The site of the Station lies within a national forest zone (Shizukuishi-cho, Iwate Pref.) and in this region hot springs and fumaroles are scattered over a distance of 5 km. Emitting steam is neutral or weak alkaline and hot water is alkaline, having a high $Na.SiO_2$ content. Gas content of steam is very low, its ratio ranging 0.5 - 0.05 vol%. Four exploration wells have been drilled since September 1972. At present all wells have a high water leakage. Pumping

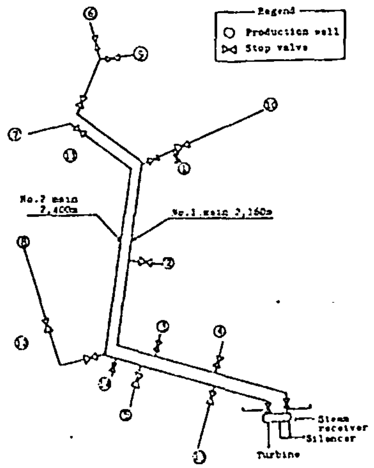
a test of water has been made and an unexpectedly large quantity of steam and hot water have been obtained. Approximately 500 t/h of steam will be required for the electric generation at the capacity of 50,000 kW. Therefore, it is planned to drill 14 wells, assuming a steam output of 40 - 50 t/h per well.

No.1 and No.2 steam transmission mains will be built along the Katsukonda River. Their specification is given below:

1) Total length	4,560 m
2) Diameter	35.55 - 76.19 cm (14" - 30")
3) Design pressure	Max. 10 kg/cm^2
Design temperature	Max. 220°C
4) Pressure loss	Below 1.5 kg/cm^2
5) Speed of flow	Below 40 m/s
6) Heat insulation	Thickness of calcium silicate casing: 75 mm with outer covering of aluminium sheet
7) Outer load resistance	Wind velocity: 60 mm/s Earthquake (horizontal) 0.3 Weight 10 t/m^2

Fig.4 Plan of Steam Transmission Mains of Katsukonda Station

Le plan de la transmission principale de vapeur à la station de Katsukonda.



The main generating facilities

Steam Turbine

Number	1
Type	Impulse type condensing turbine
Rated Capacity (generation end)	50,000 kW

Condenser

Number	1
Type	Jet condenser

Cooling Tower

Number	1
Type	Horizontal axis, rotating field
Capacity	59,000 kVA
Voltage	Approx. 20 kV
Cooling system	Direct hydrogen cooling

Main Transformer

Number	1
Capacity	59,000 kVA
Voltage	Primary side: Approx. 20 kV Secondary side: 151-154-157-161 kV
Cooling system	Oil immersed self cooling

Transportation Road and Site

Exploration well	Road	25,242 m2
	House	6,000 "
Steam producing well	Road	34,218 "
	House	5,330 "
Main steam transmission main		15,960 "
Power plant		24,250 "

Ancillary Equipments

Building	Structure and Site		Number
Field office	wooden one-stoeied	97.20 m2	1
Warehouse	"	77.76 m2x 2	2
Laboratory	"	38.88 m2	1
Repair-shop	"	79.00 m2	1
Lodging	wooden two-storied	556.068 m2	1
Garage	wooden one-storied	77.76 m2	1

(c) Onikobe Geothermal Power Station of Electric Power Development Co.

Onikobe Power Station is located at a secluded place at about 20 Km distance from Naruko-cho, Miyagi Prefecture, within the area of Kurikoma Quasi-National Park near to the border between Yamagata and Akita Prefs. In the region, surface indications (fumaroles and mud volcano), peculiarities to geothermal fields are found.

It is planned to drill 12 producing wells and the results hitherto obtained from drilling show that produced steam has a pressure of 4 kg/cm^2 and its output is 13-29 t/h. The output of hot water is very small. The main generating facilities are given below:

Lands

Total Area	124,000 m^2
Power Station Grounds	28,700 m^2
Steam Equipment Grounds	16,100 m^2
Intake equipments	1,600 m^2
Entering Road to Station	1,000 m^2
Provisional Equipments	3,000 m^2

Power Station Building

Scale	Building area: 492 m Total area: 1,045 m
Structure	Ferro-concrete two-floor building
Number	1 building

Steam Well

Diametre	178 ø
Depth	Approx. 350 m
Number	12

Wellhead Equipment

Separator

Type: Steel plate, vertical cyclone
Number: 12

Silencer

Type: Steel plate, vertical absorbed type
Number: 12

Steam Transmission Main

Number	4
Total length	Approx. 1,500 m
Maximum Diameter	Approx. 780 ø

Steam Turbine

Type	Single-cylinder, impulse type condensing turbine
Capacity	25,000 kW
Number	1 unit

Condenser

Type	Barometric jet condenser
Circulating water flow	8,000 m3/h
Number	1 unit

Coolying Tower

Type	Forced draft absorbing, counter-flow type
Circulating water flow	Approx. 8,500 m3/h
Number	1 unit

Generator

Capacity	28,000 kW
Number	1 unit

Principal Transformer

Capacity	Approx. 28,000 kVA
Voltage	11 kV/66 kV
Number	1 unit

(d) Hatchobaru Geothermal Power Station of Kyushu Electric Power Co. Inc.

The Hatchobaru area is a natural steam field in the Kuju volcanic range and in its neighbourhood a geothermal zone where surface activity of the earth such as hot springs and fumaroles is active is found. Topographically, the area forms a plain in the basin of a mountain range at 1,300 m above the sea and a tributary of the Kuma river runs through the area.

After examining the characteristics of the structures by drilling exploration wells, the Company plans to sink ten producing wells. The work was started from July 1968 and up to now six wells have been completed. The wells produce at the rates of 20-48 t/h and hot water at the rates of 50-140 t/h. The pressure varies from 5 to 42 kg/cm2 and the depth of a well ranges from 740 to 1,600 m.

The features of the Hatchobaru Station are given below:

(1) While at Ôtake Station the produced steam separated from hot water by a separator is used, at Hatchobaru Station not only the produced steam but also the secondary steam obtained by flashing the hot water are used to fully utilize the heat. It is expected that by this means the generating capacity can be increased by about 20%.

(2) Hitherto, a steam separator has been provided at each well-head and the separated steam alone has been sent to a power station. However, at Hatchobaru a mixture of steam and hot water produced from wells will be transmitted without separation to a central separator provided near to the Station and the separation will be made by it collectively. In this new system the total length of transmission mains can be considerably shortened and at the same time the separating equipments at a well-head will become unnecessary, thus making the operation and maintenance easier.

(3) At Hatchobaru Station, the hot water produced will be returned underground by three wells.

The flow sheet of the electric generation at the station is given below. (Fig. 5)

5. Problems of Geothermal Power Development

Geothermal energy resources are a natural endowment. The question is how to find prospective sites for exploitation. Some guidances can be given because geothermal sites usually occur in hot spring zones. However, it is still to be proved by a through investigation requiring a great deal of expenditure whether the development of asite for geothermal power generation is actually feasible. These hot spring zones have peculiar landscapes such as volcanic valleys and have often been designated as national parks or quasi-national parks. The geothermal development within the area of a national park needs beforehand permission of the Director of Environment Agency. The Director gives a decision to the applicant after hearing opinions of the National Park Council. It often takes considerable time before the permission is given. When a development site is situated within the area of a quasi-national park, permission from a Prefectural Governor is required.

Hot springs in Japan have been used for bathing and towns composed of hot spring inns are usually found in these districts. When the exploitation of geothermal energy is planned in the vicinity of a hot spring resort, it would be natural that the bathkeepers of the town fear that the hot springs they use may run dry by the exploitation. The Hot Spring Law provides that people who wish to drill a well in the area have to obtain permission from the Prefectural

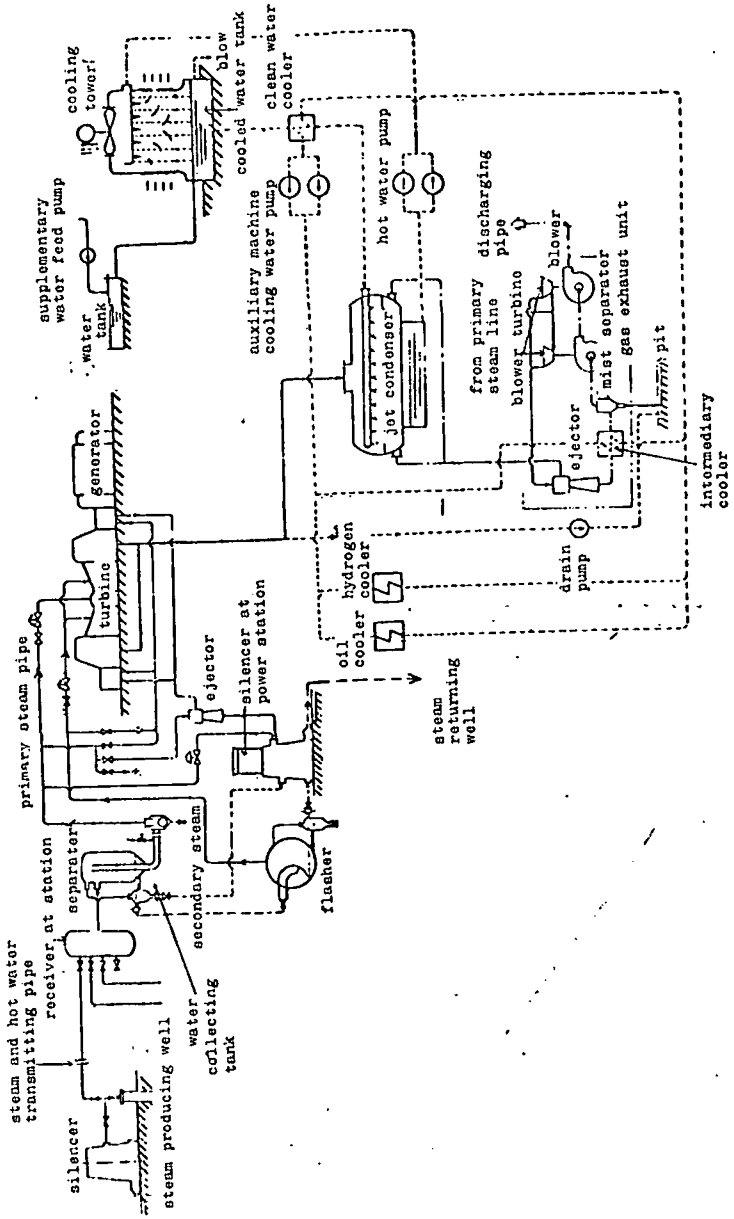


Fig.5 Main flow Diagram of Hatchobaru Geothermal Power Station

Fig.5 Le Diagramme du courant principal de l'énergie géothermale à la station de Hatchobaru

Governor concerned and that before giving permission, the Governor needs to put the matter to the Hot-Spring Council whose members are mainly composed of the bathkeepers in the area. Under the circumstances, the Governor's permission would not be easily obtained.

Many volcanic zones are found within the areas of national forests. One who wishes to develop geothermal energy in these areas must obtain the government permission for the lease of the land required in accordance with the provisions of the National Forest Law.

Besides the fact that a great deal of investment is required, the necessity to obtain various permits under laws would diminish private enterprisers' will to develop geothermal energy.

However, in view of the very high dependance of Japan's energy supply on foreign resources, the exploitation of the domestic geothermal energy resources should be promoted as a national policy to secure the stable energy supply in this country.

6. Government Aids to Geothermal Development in the past

Government aids given to the geothermal energy development in the past are mentioned below:

(1) In 1954 a subsidy for the experiments and investigations amounting to 27 million yen was granted to Kyushu Electric Power Co. Inc.

(2) In 1960 a subsidy for the experiments and investigations of 13 million yen was granted to Japan Metals and Chemicals Co.

(3) In 1966 the New Technology Development Corporation entrusted Japan Metals and Chemicals with a study regarding the techniques for the production of geothermal steam used for electric power generation, granting a subsidy of 350 million yen, on the recommendation of the Industrial Science and Technology Agency.

(4) In 1972 the New Technology Development Corporation entrusted Japan Metals and Chemicals with a study regarding the techniques for steam pruducing wells for geothermal, granting a subsidy of 760 million yen.

7. Government Policy for Geothermal Energy Development in 1973

In 1973 the Ministry of International Trade and Industry planned to take the following measures for the development of geothermal energy.

(1) Investigations of geothermal power generation

The Natural Resources and Energy Agency will carry out on a two-year plan for the following technical investigations, appropriating an amount of 2,061,000 yen for this purpose in the 1973 budget.

(a) Steam emitted from a producing well often contains a large quantity of hot water. The steam separated from hot water by a separator is led to a turbine. The separated hot water can be utilized for the district heating and culture of vegetables. The technical study for the utilization of hot water will be conducted with the purpose of building a geothermal power station serving the benefits of the regional people.

(b) The new technique for detecting geothermal reserves and steam well drilling will be examined to improve the exploration efficiency and various technical problems regarding a large scale geothermal power generation will be studied.

(c) Prospective areas for geothermal exploration are usually found in volcanic zones often designated as national or quasi national parks under the National Park Law for their senic beauty. The geothermal exploitation in these areas needs the consideration for the harmony with the natural environment. Technical problems encountered in the course of various stage of the development including a basic investigation, drilling of exploration and production wells and construction of the power station should be fully studied to conserve the natural environment conditions.

A committee for inquiring into technical problems on the geothermal development consisting of certain scholars, experts and officers from the authorities concerned was set up in the Natural Resources and Energy Agency for the purpose of studying the technical problems mentioned above. The method of research and development by the Committee is as follows:

The committee considers the general policy for the research and development and entrusts The Japan Geothermal Energy Association with the technical investigations which the Committee proposes. An amount of 1,600,000 yen has been provided in the 1973 budget(a calendar year from 1st April 1963 and to 31th March 1974).

The Japan Geothermal Energy Association submitts its interim report to the Committee when the investigation has reached a certain stage. Examining the report, the Committee will inform the Association with its view pointing out the matters for consideration, amendments, change of the investigation plan, etc.

When the definite report is submitted from the Association, the Committee will complete its own research after studying the report by the Association as basic materials.

(2) Study of the Hot Water flow system in Geothermal Fields

The Geological Survey of Japan of the Agency of Industrial Science and Technology plans to conduct a survey, on a five-year basis beginning 1973, over the Onikobe-Naruko, South and Akinomiya fields for the purpose of obtaining the basic information regarding the subterranean hot water in a geothermal field which are useful for effective exploitation of geothermal energy. An amount of six million yen has been provided for the 1973 survey, covering the following items:

(a) Research on mass and heat balance of geothermal fluid at a geothermal field

This research will make clear the mass and heat balance by measuring natural out-put of hot water and steam and in-put of meteoric water into the underground.

(b) Isotope geology

To research the origin of geothermal fluid and to estimate the age of the fluid which is considered as meteoric origin, the study of isotope of oxygen and hydrogen etc. will be carried out.

(c) Research on geothermal fluid reservoirs

The research on the fractured pattern of strata and reservoir engineering will be conducted by the geological and geophysical method.

(3) National Survey of Geothermal Energy

The Geological Survey of Japan plans to conduct a nation-wide investigation of the geothermal energy over 30 districts on a three-year plan with the purpose of fixing the position of geothermal energy development in the government policy. For the 1973 investigation eighty million yen has been appropriated in the 1973 Budjet. The standards for selection and procedures are as follows.

(a) The volcanic zones have been classified into ten groups in accordance with their characterstics.

(b) The areas where the consent of the regional people to the exploitation has been obtained and where the working conditions are favourable were chosen for the 1973 investigation.

(c) Priority was given to the areas where the exploitation seems to be most promising from the existing data, although the explotation has not yet been carried out.

The areas selected for the 1973 investigation are given below: **(Fig. 6)**

(a) North part of Mt. Komagatake (Hokkaido)
(b) North part of Kurikoma (Akita Pref.)
(c) North part of Azuma (Yamagata Pref.)
(d) South part of Izu (Shizuoka Pref.)
(e) South Satsuma (Kagoshima Pref.)

(4) The Treasury Investment and Loan

Based on the findings of the above mentioned technical investigations and the national survey, the government policy will be definitely established and various measures such as the designation of certain geothermal development areas, granting of a subsidy and low-interest loan, preferential treatment in taxation will be taken. However, under the existing legislation there remain many problems to be solved for carrying out these measures.

Meanwhile, as for financial aids, it is decided to make the Treasury Investment and Loan to the enterprises from the fiscal year 1973. A loan amounting to 650 million yen at a special interest of 7.2% was decided to be made to the two geothermal power development projects at Katsukonda, Iwate Pref. and Hatchobaru, Oita Pref. of which construction work was scheduled to start shortly.

8. Government Plan for 1974

The research and development of the geothermal energy requires systematic work over a wide area based on the scientific study. For this purpose large amounts of investments must be made long before the start of the production. Therefore, the government aids in the fields of techniques as well as finance and taxation.

In succession to the 1973 plan, the Ministry of International Trade and Industry will take the following measures in the fiscal year 1974.

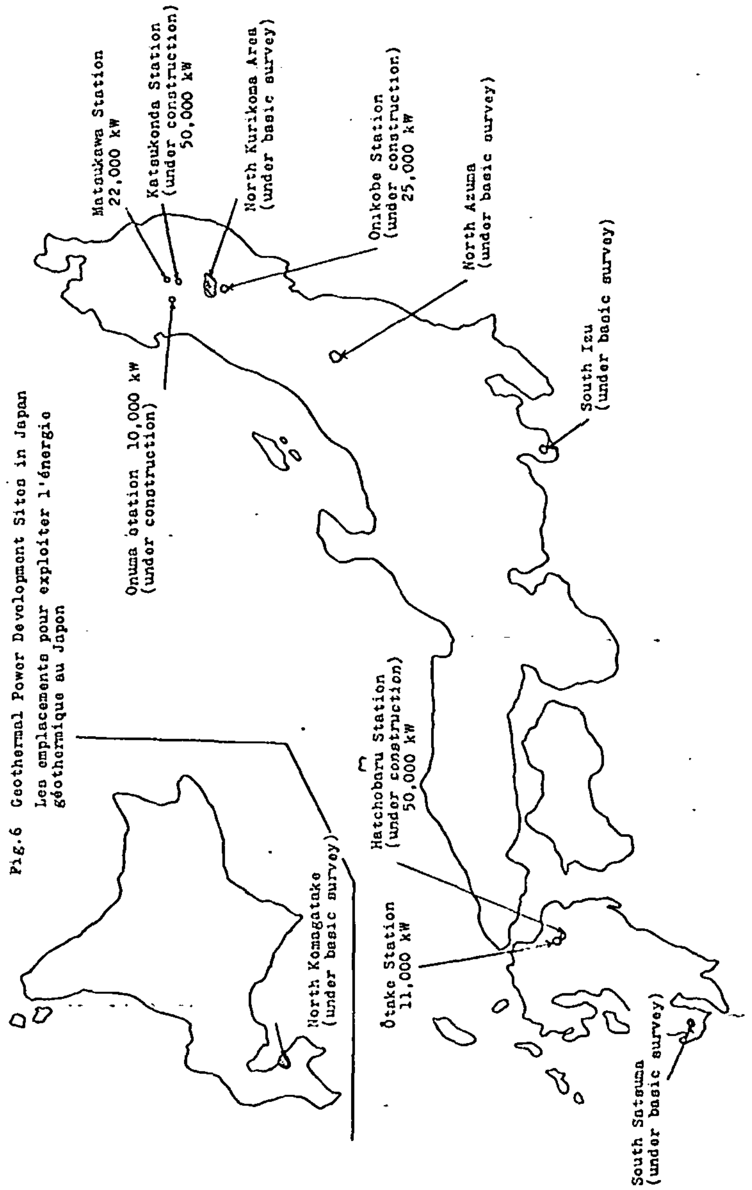


Fig.6 Geothermal Power Development Sites in Japan
Les emplacements pour exploiter l'énergie géothermique au Japon

(1) The amount of the Treasury Investment and Loan will be increased from 1,600 million yen in 1973 to 2,600 million in 1974 and besides the Katsukonda and Hatchobaru projects, the Ōnuma Geothermal power development project will be added to the program.

(2) An expenditure of 250 million yen will be appropriated in the 1974 budget and the investigation will be extended from the 5 areas to 15 areas.

(3) Based on the findings of the 1973 survey, the detail investigations including structure drilling will be conducted with an expenditure of about 280 million yen provided in the 1973 budget, for the purpose of promoting the exploitation by enterprises on a commercial base.

In parallel with the exploitation using the present techniques, the research and development of a larger capacity geothermal power generation in the future based on the new techniques utilizing an enormous volume of heat energy contained in the hot dry rock of the earth crust will be promoted. To extract the heat energy on a stable and economical basis, the development of a large scale electric generation by geothermal energy of volcanoes and ultra-deep geothermal steam power of the crust will be carried out. At first the installation of a model experiment equipment and a design of a geothermal power plant of a binary-cycle will be made.

For this purpose the following expenditure is estimated.

(a) Expenditure for ultra-deep geothermal steam power generating system

		1,000 yen
R and D for Technology of physical and chemical measurement in geothermal wells	Technology of physical and chemical measurement in geothermal wells To make clear the geologic and physical character of strata and the existing state of the underground geothermal fluid	54,910 ($183,000)
Development of materials for drilling	Materials which will be available in the geothermal fluid of high temperature and pressure which is rich in H_2S etc. contents	9,920 ($33,000)

(b) Expenditure for generating system by thermal energy of volcanoes

Feasibility study	Technology of production of electric power by using volcanic energy Study of a harmony between environmental effects and the above technology	9,760 ($42,900)
Development of technology for volcanic energy and heat distribution survey	1. Measuring technique of volcanic energy 2. Technique to find out the underground high temperature part 3. Development of a survey method of the underground thermal structure	109,000 ($363,000)
Development of drilling technique of high temperature formation	Drilling-technique of the high temperature formation which will be necessary to develop the technology of electric production by using volcanic energy	44,450 ($148,000)

Summary

Energy requirement in Japan is constantly growing with the development of industry and the advance of living standards of the people and they are mostly met by the overseas oil supply. The high dependance on the imported oil has caused a feeling of uneasiness about the stable supply of energy in the future. It is necessary, therefore, to utilize more effectively the domestic energy resources.

Japan is one of the most important volcanic country in the world and is assumed to be abundant in geothermal energy resources, so that it is highly desirable to utilize this form of energy for the electric generation and also for space heating of dwellings and green-houses, for the benifit of the regional people.

The procedure of geothermal energy development in Japan comprises five stages: general survey, detailed survey, exploration-well drilling, production-well drilling and installation of electric power generating and other equipments.

It was in 1904 that geothermal energy was first used for electric power generation in Japan. However, its real development began only after the World War II.

In 1947 the government started a fundamental survey of geothermal energy and following this survey several private enterprises carried out more detailed surveys in the prospective sites and exploitations.

At present, the Matsukawa geothermal power station with installed capacity of 20,000 kW of the Japan Metals and Chemicals Co. and the Otake geothermal power station with installed capacity of 10,000 kW of the Kyushu Electric Power Co. are under operation. Besides, the following four geothermal power stations are under construction and/or planning.

Ônuma Station (10,000 kW)	Mitsubishi Metal Mining Co. Ltd.
Katsukonda Station (50,000 kW)	Tohoku Electric Power Co. Inc. (purchasing produced steam from Japan Metals and Chemicals Co.)
Onikobe Station (25,000 kW)	Electric Power Development Co.
Hatchobaru Station (50,000 kW)	Kyushu Electric Power Co., Inc.

The development of geothermal energy involves great risks and a large amount of investments. Moreover, prospective sites are often found within the area of natural and quasi-natural parks or in the vicinity of hot spring resorts. The exploitation in these areas needs the permissions of the Authorities concerned under the provisions of the Natural Park Law and the Hot Spring Law. These circumstances diminish private enterprises' interest in the exploitation.

Hitherto, the government has assisted the geothermal energy development, granting a subsidy to the enterprises. On the other hand, the basic survey over 30 prospective fields started from 1973 onward and the detailed survey will be carried out over certain areas. Besides, the research and development of new electric generation systems utilizing thermal energy of volcanoes and ultra-deep geothermal steam energy of the crust are to be conducted. Financial aid by the Treasury on investment and loan will also be made to the geothermal energy development.

A study group for the geothermal energy development of 51 members from the Liberal Democratic Party has prepared the outline of the Geothermal Resources Development Promoting Bill (tentatively designated), with the purpose of submission of the Bill to the Diet.

Résumé

Au Japon, la consommation de l'énergie est constamment augmentée en conséquence du développement de l'industrie et du niveau de la vie quotidienne. La pauvreté des ressources de l'énergie au Japon nécéssite leur approvisionnement par les pays étrangers. La dépendence en l'énergie des pays étrangers lui fait inquiéter un approvisionnement stable de l'énergie.

C'est de ce fait qu'il faudrait étudier l'utilisation efficace des ressources d'énergie à l'intérieur du pays. Le Japon est un des pays volcaniques renommés dans le monde, et on prévoit qu'il devait y avoir beaucoup d'énergie géothermique pour la production d'éléctricité, et pour le chauffage des maisons et des serres de la région restreinte dans son pays.

Au Japon, la manière d'exploiter l'énergie géothermique est constituée en cinq étapes, i.e. (1) sondage général du terrain, (2) sondage détaillé du terrain, (3) creusement d'essai des puits, (4) creusement régulier des puits pour la production et (5) mise au point de la station éléctrique et des autres équipements.

En 1904, l'énergie géothermique a été utilisée pour la première fois. Cependant, c'est seulement après la deuxième grande guerre mondiale qu'on se mettait à étudier, avec ardeur ce problème au Japon.

En 1947, le gouvernement commençait les sondages des terrains et ces affaires ont été succédées par des entreprises privées dans le but des sondages détaillés et de la transformation de cette énergie à l'énergie éléctrique. En ce moment, les deux stations pour la transformation de l'énergie géothermique à l'énergie éléctrique sont mises en marche: la station de Matsukawa de "The Japan Metals and Chemicals Co." avec la capacité de 20,000 kW et la station d'Otaké de "The Kyushu Electric Power Co." avec la capacité de 10,000 kW. Les quatre stations suivantes sont en construction ou en projet: la station d'Omura de "Mitsubishi Metal Mining Co., Ltd." (10,000 kW), la station de Katsukonda de "Tohoku Electric Power Co., Inc." (50,000 kW) (en achetant la vapeur produite par "The Japan Metals and Chemicals Co."), la station d'Onikobé de "Electric Power Development Co." (25,000 kW), et la station de Hachobaru de "Kyushu Electric Power Co., Inc." (50,000 kW).

L'exploitation de l'énergie géothermique nécéssite des frais énormes avec beaucoup de risque. De plus, la plupart de temps, les localités convenables pour les stations se trouvent dans les régions de parc national, de parc quasi-national. Donc, l'exploitation dans cette région exige

la permission de l'autorité concernant la loi du parc national et la loi de la source thermale. Dans cette circonstance, des entreprises ne s'intéressent pas beaucoup à l'exploitation de l'énergie géothermique.

Jusqu'ici, le gouvernement japonais subventionnait des entreprises privées en leur donnant les subsides pour des recherches concernant l'énergie géothermique. D'autre part, des sondages généraux de terrains dans 30 régions du pays sont commencés sous la direction gouvernementale. Les sondages détaillés de certains terrains, des recherches pour le développement du système nouveau transformant l'énergie géothermique de volcan ou de sousterrain très profond se succéderont aussi sous la direction gouvernementale. Des aides financières par le Ministère des Finances pour l'exploitation des ressources géothermiques se sont aussi accomplies. Un groupe étudiant le problème de l'énergie géothermique organisé par 51 membres du parti libéral démocratique a préparé le projet de loi pour accéler le développement de l'exploitation des ressources géothermiques, et il le présentera à la Dìète prochainement.

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Hydrogen and Oxygen Isotopic Compositions of Fluid Inclusions in the Kuroko Deposits, Japan

Hiroshi Ohmoto and Robert O. Rye

Abstract

Initial data on the hydrogen and oxygen isotopic compositions of water in fluid inclusions in pyrite and chalcopyrite from some of the Kuroko deposits in the Hokuroku district of Japan fall within a narrow range: $\delta D = -26$ to -18 per mil and $\delta^{18}O = -1.6$ to -0.3 per mil, relative to SMOW.

These data together with geologic and other geochemical data indicate that the Kuroko ore fluids were predominantly of sea-water origin. A small proportion (less than 25 percent) of magmatic and/or meteoric water may have been mixed in the ore fluids.

A model for the formation of the ores by convective circulation of sea water through high-temperature volcanic rocks is presented.

Introduction

The Kuroko deposits are massive Fe-Cu-Pb-Zn sulfide deposits which occur in the Green Tuff region in the Japanese Islands, a region characterized by a thick accumulation of green-colored volcanic rocks of Miocene age. Although more than 100 Kuroko ore bodies have been discovered throughout the Green Tuff region, the majority occur in a small area (about 25 × 25 km) in the Hokuroko district in northwestern Honshū Island. These deposits have been the subject of intensive study by Japanese geologists since the beginning of this century and many excellent reviews are available (e.g., Aoki et al., 1970; Matsukuma and Horikoshi, 1970).

The Kuroko deposits are characterized by their close association with submarine acidic volcanism and by a characteristic mineralogical zonation. The ores occur as disseminations and veinlets along fractures in rhyolite domes and lava flows and as stratiform massive bodies in rhyolitic tuff, tuff breccia, and mudstones that overlie the rhyolites. The ages of all these rocks are approximately 13 million years (Ikebe et al., 1972). Disseminated ores in the footwall rhyolites consist primarily of quartz, pyrite, and chalcopyrite (siliceous ores). The stratiform massive ores, on the other hand, often show vertical zonation: pyrite ores at the bottom of the sequence, yellow ores (chalcopyrite + pyrite), black ores (sphalerite + galena + barite + chalcopyrite), barite ores, and ferruginous quartz beds (quartz + hematite) at the top of the sequence. These stratiform metallic ores are often underlain by extensive gypsum-anhydrite beds (gypsum-anhydrite ores).

Recent geological and geochemical studies on the Kuroko deposits (e.g., Sato, 1968; Horikoshi, 1969; Horikoshi and Sato, 1970; Kajiwara, 1970, 1971; Ohmoto et al., 1970; Rye and Ohmoto, 1974;) have suggested that (1) the hydrothermal fluids moved up along the fissures in the rhyolite, (2) some of the upper portions of the stratiform massive ores were deposited on the sea floor and/or in the unconsolidated volcanic sediments under marine conditions (the depth of overlying sea water was several hundred meters), and (3) the depositional temperatures were around 300°C for the stockwork ores and between about 300°C and about 200°C for the stratiform massive sulfide ores.

The purpose of this paper is to present initial data on the hydrogen and oxygen isotopic compositions of water in fluid inclusions in sulfide minerals of the Kuroko deposits and to present some preliminary interpretations of their implication.

Techniques and Results

Four types of samples were analyzed for δD and $\delta^{18}O$ values: (1) water in fluid inclusions in pyrite and chalcopyrite crystals from the siliceous pyrite ores (i.e., the lower part of the stratiform pyrite ores) and from the yellow ores, (2) water in altered rhyolitic tuff of the ore-bearing formation (mostly OH-water in sericite), (3) water in fluid inclusions (with possibly some structural water) from secondary gypsum crystals, and (4) water from Lake Towada. The latter two types of samples were expected to provide the δD values of recent meteoric water in the area. The mineral and the rock samples were collected from two deposits, the Matsumine deposit of the Dowa Mining Co. and the Shakanai No. 1 deposit of the Shakanai mine, located approximately 1 km apart in Akita Prefecture, Honshū Island. Lake Towada is located about 30 km northeast of these deposits.

The techniques used in the isotopic analysis of fluid inclusions are essentially those described in

Rye (1966) and Rye and O'Neil (1968). Water from inclusions in pyrite, chalcopyrite, and secondary gypsum was extracted by crushing crystals and crystal aggregates in evacuated stainless-steel tubes. The released water was converted to hydrogen gas through reaction with hot uranium for D/H ratio measurements or converted to CO_2 in a BrF_5 system for $^{18}O/^{16}O$ ratio measurements. The deuterium content of water from the altered rhyolite tuff was measured on H_2O extracted from the rock by heating under vacuum to 1,400°C with an induction furnace.

The δD and $\delta^{18}O$ values of these samples, expressed as their per mil deviation from SMOW, together with a brief description of the samples, are presented in Table 1. The δD values of water in inclusions in secondary gypsum, however, are distinctly more negative than those of the fluid inclusions from the primary minerals and are similar to the present-day meteoric water in the region (Matsubaya and Sakai, 1973). Our only sample of meteoric water, from Lake Towada in the Hokuroku district, has a higher δD value than typical local ground water, which probably reflects evaporation in the lake. The whole-rock (mostly water in sericite) δD value of a highly altered rhyolite tuff sample is −49 per mil.

Water extracted from the sulfide samples was probably a mixture of primary, pseudo-secondary, and secondary fluid inclusions. It is not possible to determine directly the proportions of different types of fluid inclusions present in sulfides because they are opaque. However, comparison of the isotopic compositions of the water extracted from fluid inclusions with the isotopic compositions of the gangue minerals present in the ores and with the composition of the associated volcanic rocks provides some indication of whether the fluids in the inclusions are representative of the ore fluids.

The $\delta^{18}O$ values of barite in the Kuroko ores are mostly between +5 and +7 per mil (Sakai et al., 1970). These values, together with the depositional temperatures of about 250°C (temperature deduced from fluid inclusion and sulfur isotopic data; see Rye and Ohmoto, 1974) and the isotopic fractionation factors for oxygen between HSO_4^- and H_2O (Mizutani and Rafter, 1969), indicate that the $\delta^{18}O$ values of the hydrothermal fluids were between −2 and 0 per mil, or essentially identical to the values determined from analyses of the water in fluid inclusions in pyrite (i.e., -1.0 ± 0.5 per mil). Similar calculations based on the $\delta^{18}O$ values of quartz in the veinlets of the Kuroko deposits also suggested

TABLE 1. Hydrogen and Oxygen Isotopic Compositions of Water in Fluid Inclusions, Altered Rhyolite Tuff, and Meteoric Water from the Hokuroku District, Honshu Island

No.	Sample description	Location	δD (per mil)[1]	$\delta^{18}O$ (per mil)[1]
Water in Fluid Inclusions				
(1)	Pyrite: Euhedral pyritohedron crystals (~2 cm)	Siliceous pyrite ore, L195, Matsumine deposit	−25.8	
(2)	Pyrite: Aggregates of euhedral crystals (0.2 to 1 cm)	Siliceous pyrite ore, L195, Matsumine deposit	−25.6	
(3)	Pyrite: Aggregates of euhedral crystals (0.2 to 1 cm)	Siliceous pyrite ore, L180-S-5, Matsumine deposit	−21.3	
(4)	Pyrite: Aggregates of euhedral crystals (0.2 to 1 cm)	Siliceous pyrite ore, L180-S-5 Matsumine deposit	−25.5	
(5)	Chalcopyrite: Massive coarse-grained chalcopyrite ore	Yellow ore, L-180, Matsumine deposit	−26.0	
(6)	Pyrite: Massive coarse-grained chalcopyrite ore	Siliceous pyrite ore, Shakanai No. 1 deposit	−18.3	
(7)	Pyrite: Massive coarse-grained chalcopyrite ore	Siliceous pyrite ore, Shakanai No. 1 deposit		−0.6
(8)	Pyrite: Massive coarse-grained chalcopyrite ore	Siliceous pyrite ore, Shakanai No. 1 deposit		−0.3
(9)	Pyrite: Same as (6) except for different cyrstal aggregate	Siliceous pyrite ore, Shakanai No. 1 deposit		−1.6
(10)	Pyrite: Same as (6) except for different crystal aggregate	Siliceous pyrite ore, Shakanai No. 1 deposit		−0.5
(11)	Gypsum: Secondary euhedral crystal (5 cm)	Shakanai mine	−65.5[2]	
(12)	Gypsum: Same as (11) except for different crystal	Shakanai mine	−71.6[2]	
Water in Altered Rhyolite Tuff				
(13)	Altered white rhyolitic tuff (predominantly OH-water in sericite)	T3 tuff zone, L-190, Matsumine deposit	−49.0	
Meteoric Water				
(14)	Lake water	Yasumiya, Towada Lake	−54.2	

[1] Uncertainty: ±0.5 per mil for δD and ±0.1 per mil for $\delta^{18}O$ values. Values expressed as per mil deviation from SMOW.
[2] May include some structural water.

$\delta^{18}O$ values of about 0 per mil for the Kuroko ore-forming fluids (Sakai, pers. commun., 1973). A calculation, based on the δD value of −49 per mil for the water in altered rhyolite (mostly in sericite) and the hydrogen isotope fractionation factors between sericite and water at 300°C (see Taylor, 1974 for a summary of the isotopic fractination factors), indicates a δD value of around −20 per mil for the fluids involved in the wall-rock alteration; this value falls in the range of the δD values for water in the fluid inclusions in the Kuroko ore minerals. These data, therefore, suggest that the water in the inclusions in pyrite and chalcopyrite probably represents the composition of the hydrthermal fluid responsible for the formation of the Kuroko ores and alteration of the rhyolite tuff.

Discussion

Deposition of the Kuroko ores was closely associated with submarine volcanism, and the ore deposition occurred a few kilometers from the contemporaneous coast line (e.g., Horikoshi and Sato, 1970). In such a geologic enviroment, sea water, meteoric water, and magmatic water must be considered as possible sources of ore-forming fluids. In Figure 1 the δD and $\delta^{18}O$ values of the Kuroko ore fluids are compared with those of "primary magmatic water" (Sheppard et al., 1969), of sea water, and of present-day meteoric water (throughout the discussion, the isotopic composition of the Miocene meteoric water in the Hokuroku district is assumed to be similar to that of the present-day meteoric water). The isotopic composition of the Kuroko ore fluids are fairly close to that of sea water, suggesting that the ore fluids were predominately sea water with a possible meteoric and/or magmatic water component. However, in order to evaluate the isotope data quantitatively, it is necessary to consider the possible changes that may have occurred in the isotopic composition of water in the Kuroko hydrothermal systems.

The $\delta^{18}O$ and δD values of water from a single source can be increased or decreased during the evolution of hydrothermal fluids, such as by loss of vapor phase, by redox reactions, by membrane filtration, and by isotopic exchange reactions with various types of rocks. Under the geologic conditions of the Kuroko formation, probably the most important mechanism which may have affected the isotopic compositions of water (other than possible mixing of fluids) was the oxygen and hydrogen isotopic exchange reactions with country rocks.

The magnitude of the change in the $\delta^{18}O$ and δD values of water by isotopic exchange reactions with

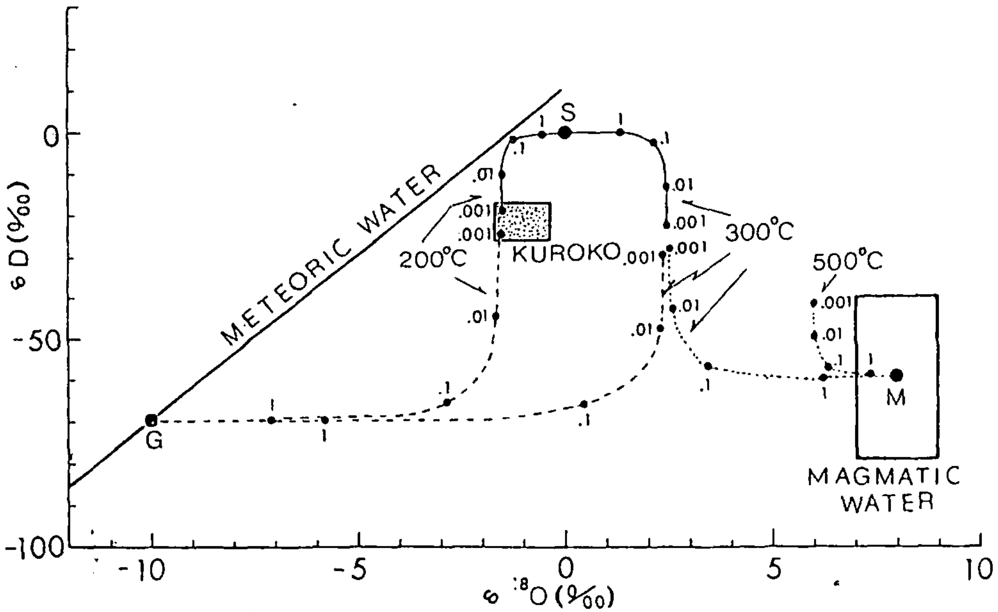

FIG. 1. Hydrogen and oxygen isotopic compositions of the Kuroko ore fluids compared with those of "primary magmatic water" (Sheppard et al., 1969), sea water (S), and local meteoric water (G). Other lines indicate the changes in the $\delta^{18}O$ and δD values of magmatic water (initial point M and dotted lines), of meteoric water (initial point G and dashed lines), and of sea water (initial point S and solid lines) through equilibrium isotopic exchange with volcanic rocks at various temperatures and with various (water/rock) weight ratios. The numbers 1 through .001 indicate the water/rock weight ratio (R value). The volcanic rocks were assumed to have had initial isotopic compositions of $\delta^{18}O = +8$ and $\delta D = -70$, and a water content ($+H_2O$) of 1 weight percent. (See text).

country rocks depends on: (1) the initial isotopic compositions of the water (δ^i_w) and of the rock (δ^i_r) involved in the isotopic exchange reactions; (2) the ratio of exchangeable oxygen (or hydrogen) atoms in the water to those in the rock (w/r); (3) temperature, which determines the equilibrium isotopic fractionation factor between the rock and water (Δ_{r-w}); and (4) the degree of isotopic equilibration. When the water and the rock become isotopically equilibrated at a given temperature, the final isotopic composition of water (δ^f_w) can be expressed as follows:

$$\delta^f_w = \frac{\delta^i_r - \Delta + (w/r)\cdot\delta^i_w}{1 + (w/r)} \qquad (1)$$

(see Sheppard et al., 1969, 1971; Taylor, 1971, 1974 for similar equations of oxygen isotopic exchange reactions between water and rock).

In the Kuroko deposits, the rocks which could have undergone isotopic exchange with hydrothermal fluids are predominantly volcanic flows and breccias of rhyolite and dacite compositions. These rocks contain an average of 50 weight percent oxygen and about 0.11 weight percent hydrogen (i.e., 1 weight percent (+) H_2O) according to the chemical analyses by Aoki et al. (1970). If we assume that these rocks had *initial* isotopic compositions similar to typical igneous rocks: $\delta^{18}O^i_r = +7$ and $\delta D^i_r = -70$, the $\delta^{18}O$ and δD values of water after the completion of isotopic exchange with these rocks can be expressed as follows:

$$\delta^{18}O^f_w = \frac{+7 - \Delta\delta^{18}O_{r-w} + 2\cdot R\cdot\delta^{18}O^i_w}{1 + 2\cdot R} \qquad (2)$$

and

$$\delta D^f_w = \frac{-70 - \Delta\delta D_{r-w} + 100\cdot R\cdot\delta D^i_w}{1 + 100\cdot R} \qquad (3)$$

in which R is water/rock *weight ratio*. $\Delta\delta^{18}O_{r-w}$ and $\Delta\delta D_{r-w}$ values may be assumed to be similar to those of feldspar (An $\simeq$ 30)—H_2O and biotite ($\simeq$chlorite)—H_2O, respectively, (Taylor, 1974) and are as follows for various temperatures:

	500°C	300°C	200°C
$\Delta\delta^{18}O_{r-w}$	+1.0	+4.5	+8.5
$\Delta\delta D_{r-w}$	−30	−45	−50

Using the above equations and Δ_{r-w} values, the change in the $\delta^{18}O$ and δD values of water with respect to temperature and R values (water/rock weight ratio) was computed for a magmatic water ($\delta^{18}O^i_w = +8$ and $\delta D^i_w = -60$), for a meteoric water ($\delta^{18}O^i_w = -10$ and $\delta D^i_w = -70$), and for a sea water ($\delta^{18}O^i_w = 0$ and $\delta D^i_w = 0$). The results are also shown in Figure 1.

Circulation of water through rock causes the *effective* water/rock ratio for a *unit mass of water* to decrease and the *effective* water/rock ratio for a *unit mass of rock* to increase, even if the *true* water/rock ratio remains constant. To illustrate this concept, let us consider a simple model in which sea water convectively circulates through a pile of volcanic rocks (Figure 2). Rock 1 lies immediately underneath the sea floor and becomes saturated with sea water. If this rock has a porosity of 10 (volume) percent, the water/rock ratio becomes about .04. The pore fluid in rock 1 moves into rock 2, and rock 1 is filled by overlying sea water. If all the rock has the same porosity of 10 percent, and if all the rocks are initially free of pore fluid, the first water unit which fills rock 1 changes its *effective* R value from .04 to .02 and to .04/N as the water unit passes successively through rock 2 . . . and rock N, while the *true* R value at a given time remains constant at .04. (The *effective* water/rock ratio for a *unit mass of rock* (such as for rock 1) increases from .04 to .08 and to .04 × N as the overlying sea water successively passes through the rock.) The *effective* water/rock ratio depends upon the history of water (e.g., convective circulation) and is an important variable to consider in evaluating data on the isotopic composition of hydrothermal fluids.

The above example in Figure 2 and the results of computation in Figures 1 and 3c suggest that sea water alone can evolve into the observed isotopic compositions of the Kuroko ore fluids by equilibrium isotopic exchange reactions with volcanic rocks at temperatures between 200° and 300°C. These temperatures are in agreement with those indicated by fluid inclusion filling temperatures and also by sulfur isotopic temperatures (see Rye and Ohmoto, 1974, for discussion of the Kuroko temperature data).

In natural hydrothermal systems, isotopic exchange reactions between water and rocks may not proceed in equilibrium fashion. The degree of isotopic equilibrium depends on many parameters, such as the water/rock ratio, flow rate, type of rocks, and temperature. However, the changes in the isotopic compositions of water in partial isotopic equilibrium systems can be evaluated also from equations (2) and (3). In partial equilibrium systems, the isotopic fractionation factors between rock and water (Δ_{r-w} values) would become smaller than the equilibrium isotopic fractionation factors at the same temperature. In other words, partial isotopic equilibrium reactions at a certain temperature can be regarded as similar to the case in equilibrium isotopic exchange reactions at higher temperatures. For example, if the degree of isotopic exchange reactions between water and rock at 200°C was such that the $\Delta\delta^{18}O = +4.5$ and $\Delta\delta D = -45$, instead of the equilibrium values of +8.5 and −50, respectively, the changes in the isotopic compositions of water will become similar to that in the equilibrium isotopic exchange reactions at 300°C. Therefore, even if the isotopic exchange reactions between sea water and the high-temperature volcanic rocks did not preceed in equilibrium fashion, it is quite possible that sea water obtained the $\delta^{18}O$ and δD values identical to those of the Kuroko ore fluids.

Magmatic water and meteoric water may also obtain the observed isotopic compositions of the Kuroko ore fluids if the *effective* water/rock ratio becomes sufficiently small ($R \lesssim .001$) and if the temperature of isotopic equilibration was around 200°C (see Figure 1). However, the geologic data in the area rule out the possibility that magmatic water alone produced the large ore bodies. For example, Horikoshi (1969) demonstrated through a very detailed study of the volcanic history in the Kuroko region that the formation of the metallic deposits was never associated with the prime (explosive) stages of a volcanic cycle but always took place during the waning stage. His observation indicates that the separation of fluids from magma and thus the extraction of metals from magma took place mostly before the Kuroko depositional stage. If magmatic water was responsible for the Kuroko ore deposition, the formation of the ores would have occurred most likely during the explosive stage and not during the waning stage of igneous activity. Because the deposition of the Kuroko ores took place under submarine conditions, it is also unlikely that meteoric water alone became the ore-forming fluid.

In the preceeding discussions, we have suggested that if water from only one source was responsible for the Kuroko formation it was most likely sea

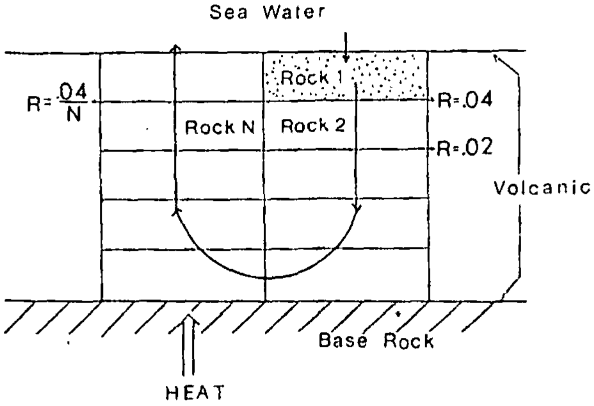

FIG. 2. A schematic model illustrating the change in the *effective* water/rock weight ratios (R values) of a given mass of water during the convective circulation of sea water through volcanic rocks. The porosity of the rocks is assumed to be 10 percent. (See text).

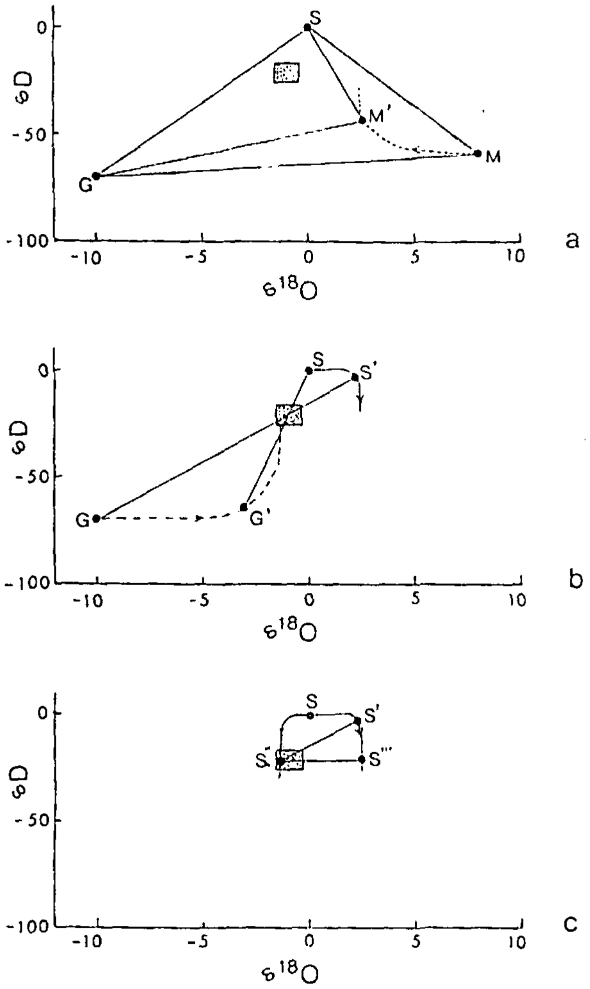

FIG. 3. Possible mechanisms to produce the observed δD and $\delta^{18}O$ values of the Kuroko ore fluids.

(a) Mixtures of magmatic, meteoric, and sea waters. If the mixtures consisted of "unevolved" components, M, G, and S, the proportions of each component would be about 10 percent magmatic water, 20 percent meteoric water, and 70 percent sea water. However, if the mixtures consisted of "evolved" magmatic water (point M' which corresponds to conditions at $R = .1$ and 300°C, dotted line, in Figure 1) and "unevolved" meteoric and magmatic waters, the percentage of the magmatic water would be about 25.

(b) Mixtures of meteoric and sea waters. Mixtures of "evolved" meteoric water (G' which corresponds to the conditions at $R = .1$ and 200°C, dashed line, in Figure 1) and "unevolved" sea water (S), or mixtures of "unevolved" meteoric water (G) and "evolved" sea water (S' which corresponds to the conditions at $R = .1$ and 300°C, solid line, in Figure 1) can produce the observed isotopic composition of the Kuroko ore fluids. So do many other mixtures of "evolved" meteoric water and "evolved" sea water. In any case, it is very unlikely that the meteoric water was more predominant than sea water.

(c) Mixtures of "evolved" sea waters. Sea water and/or mixtures of sea waters which had different thermal (T: 200 ~300°C) and convective histories (i.e., different R values) can produce the observed isotopic composition of the Kuroko fluids (e.g., mixtures of S″ and S′ or S″ and S‴). (See text).

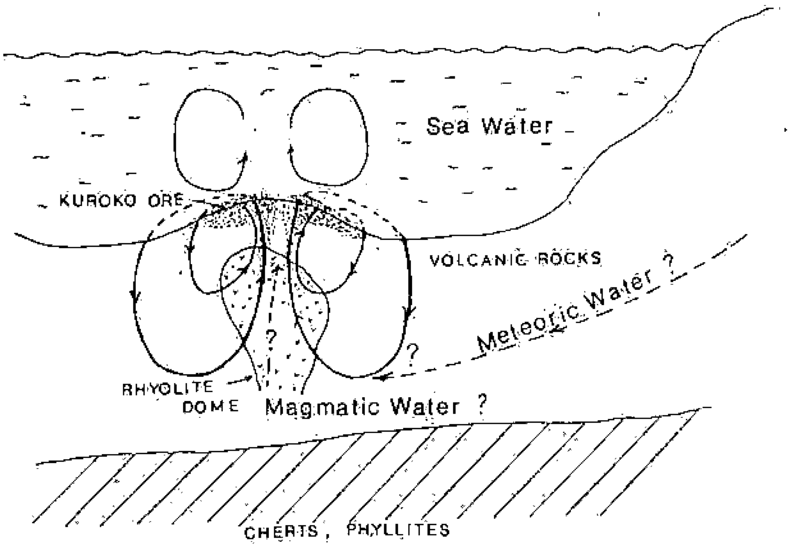

FIG. 4. A model for the formation of the Kuroko ores. Heat associated with shallow submarine volcanic activity initiates convective circulation of sea water in the volcanic rocks. Because the solubility of gypsum decreases with increasing temperature, gypsum and anhydrite may precipitate directly from the overlying sea water (i.e., formation of gypsum/anhydrite beds). Sea water which circulates through hot volcanic rocks may become an ore-forming fluid by decreasing its oxidation state and by dissolving metals from volcanic rocks. Small amounts of magmatic and/or meteoric water may mix with the circulating sea water. When a drop in temperature and change in the chemical environments occur near the sea floor, precipitation of metallic sulfides may take place.

water. We cannot, however, rule out the possibility that small amounts of magmatic and/or meteoric water was present in the Kuroko ore fluids. The Kuroko ore fluids could have been mixtures of magmatic, sea, and meteoric waters, or mixtures of meteoric and sea waters (see Figures 3a and 3b). Among the three possible mechanisms to produce the observed isotopic compositions of the Kuroko ore fluids (Figures 3a–c), at this stage it is not possible to select one from the others. In any case, however, it is unlikely that the magmatic and/or meteoric component constituted more than 25 percent of the Kuroko ore fluids.

A possible model for the formation of the Kuroko ores is presented in Figure 4. By analogy to the concept of convective circulation of meteoric water caused by shallow intrusions in continental regions and its possible role in the formation of ore deposits (e.g., Ohmoto and Rye, 1970; Sheppard et al., 1969, 1971; Taylor, 1973, 1974), sea water (with or without the component of meteoric water) may become a potential ore-forming fluid in regions where igneous activity takes place under submarine conditions. During the initial phases of igneous activity, gypsum and/or anhydrite may precipitate directly from the overlying sea water (i.e., formation of the gypsum/anhydrite beds which underly the metallic ore bodies) because the solubility of gypsum/anhydrite decreases with increasing temperature. Sea water, which convectively circulates through hot volcanic rocks, may decrease its pH value (e.g., by alkali exchange with feldspar and mica), dissolve metals from the rocks, decrease its oxidation state (e.g., by reactions with Fe^{2+} in the rocks) which may cause partial reduction of SO_4^{2-} into H_2S (and HS^-), and thus may become potential ore-forming fluids. These "evolved" sea waters may precipitate ores near the ocean floor where a drop in temperature and change in chemical environments take place.

The above proposed model is also supported by sufur isotopic and mineralogic studies of the Kuroko ores (e.g., Ohmoto et al., 1970; Rye and Ohmoto, 1974). These studies indicate that both the sulfur isotopic composition and the total sulfur content of the Kuroko ore fluids were identical to those of sea water (i.e., $\delta^{34}S_{\Sigma S} = \sim +20$ per mil and $\Sigma S = \sim 10^{-2}$ moles/kg·H_2O), and that the $\Sigma SO_4^{2-}/H_2S$ ratio in the fluids was between ~1 and ~50.

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H. O.
Department of Geosciences
The Pennsylvania State University
University Park, Pennsylvania 16802
R. O. R.
U. S. Geological Survey
Federal Center
Denver, Colorado 80225

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Sulphides of Mercury, Antimony, and Arsenic, Forming From the Active Thermal Spring of Kamchatka and Kuril Islands

by N. A. Ozerova, S. I. Naboko and V. I. Vinogradov

Institute for the Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry of the USSR Academy of Sciences, Stromonetny, 35, Moscow, USSR

Investigations of contemporary hydrothermal formation of ore minerals are of great interest for the general problems of ore genesis. We present here new data on the present-time precipitation of the sulphides of mercury, antimony, and arsenic in the Kurilo-Kamchatka volcanic area, and on the conditions of formation of the metalliferous solutions that produce these sulphides.

Main Mineralogical Features

We describe various examples of the mineralization of this type exhibited at Mendeleev volcano (Island of Kunashir, Kuril Islands), in the volcanic-tectonic structure Uzon, and at Apapel'skie and Dvukhyurtochye springs on Kamchatka.

At the Mendeleev volcano a rather rare type of mercury ore formation was established, represented by near-surface pyritic ores with mercury mineralization (Ozerova *et al.*, 1969). The areal distribution of mercury in the pyritic lode indicates that this lode may be considered as a small-scale mercury ore mineralization with poor ore. The isoline of mercury content of $1\cdot10^{-3}$ per cent on the map (Fig. 1), as may be seen comprises a significant part of the area of the pyritic lode.

Mercury mineralization is represented at this place by cinnabar and metacinnabar, cinnabar being markedly predominant; in addition, a significant amount of mercury is connected with iron sulphides, *i.e.* pyrite and marcasite, where its content amounts to $n\cdot10^{-2}$ per cent. Mercury sulphides are characterized by non-uniform distribution in the pyritic lode. In massive ore they rarely occur, and they are found principally in impregnation ores. Besides pyrite and marcasite, these ores contain sphalerite, covellite, less abundant chalcocite and antimonite, and also a few separations of native copper and native gold. Opal and native sulphur are the most widespread hydrothermal gangue minerals; opal fills stringers and forms peculiar ball-like concretions. It is difficult to elucidate the order of separation of ore minerals because indications of their age relations are almost absent; we may only note that metacinnabar is generally later than cinnabar.

Occasionally cinnabar forms significant clots within the pyritic lode, separating as dense impregnation and drusy intergrowths. The largest crystals of cinnabar are up to 0.2 mm across, but most are hundredths and thousandths of a mm (Fig. 2a). In spite of certain differences, all the investigated crystals are characterized mainly by a flat rhombohedral habit.

It is necessary to emphasize that the major mass of the iron and mercury sulphides was deposited from the solutions metasomatically. At the same time mercury sulphides form also directly from vapour-gaseous jets. The precipitation of cinnabar goes on at the present time along with sulphur and insignificant amounts of iron disulphides.

Complex mercury-antimony-arsenic mineralization was revealed within Uzon volcanic-tectonic structure (Naboko and Glavatskikh, 1970). Its most intensive manifestation is found at the places of discharge of hot thermal waters. This mineralization enriches aqueous precipitates of amorphous silica, the cement of proluvium, and hydrothermally altered rocks. Realgar, orpiment, and antimonite are predominantly developed; of the other sulphides there are pyrite, marcasite, cinnabar, metacinnabarite, sphalerite, covellite, chalcocite. Gangue minerals are represented by opal, sulphur, gypsum, barite, clay minerals and bitumens and at depth by calcite.

Ore mineralization is traced out to the depth of 7.5 m. Orpiment and sulphur are intercalated below the siliceous crust, and with depth the ore becomes enriched in realgar, antimonite and cinnabar. Still lower, pyrite and marcasite prevail among the ore minerals, the amount of marcasite decreasing with depth.

Similar sulphide mineralization was found at the bottom of Chloridnoe Lake.

Realgar is frequently found as prismatic crystals (Fig. 3a) up to 2–5 mm across; the shape of the crystals is represented by a combination of pinacoid and rhombic prism. Orpiment is usually observed as powder separations and cryptocrystalline sinters and seldom as microscopic balls (Fig. 3b). Antimonite is found as acicular radial aggregates, as well as in the form of a powder-like mass. Cinnabar is most often observed in the form of sinters and the finest crusts, where the smallest spheres may be recognized under high magnifications; prismatic crystals are found much less frequently. Metacinnabarite was observed as black earthy masses.

The sulphides of mercury, antimony, and arsenic are in close spatial association. Most close relations are observed for realgar and cinnabar: the delicate needles of realgar overgrow on the sinter aggregates of cinnabar, and in turn cinnabar in the form of the smallest spheres was deposited on the prismatic crystals of realgar.

At the Apapel'skie springs mercury mineralization is observed in gryphones both on the bottom and on the walls and also at the places of drainage. Mercury sulphides were found in clayey-opaline rock and on the pebbles of quartzite in the form of small film-like separations, crustified forms, and far less frequently as crusts composed of fine-grained cinnabar.

In a number of cases rhythmic alternation of metacinnabar and cinnabar was observed, precipitation of metacinnabar preceding that of cinnabar (Ozerova, Lebedev, 1970). At least two of such rhythms were established. Part of the cinnabar apparently replaces metacinnabar, but most of it was deposited independently directly from the solution. Quantitatively cinnabar notably prevails over metacinnabar. In rare cases the rhythm of metacinnabar and cinnabar is terminated by the deposition of realgar; rare spot-like inclusions of orpiment are noticed in the films of realgar. Occasionally pyrite is recorded. Calcite and amorphous silica are accompanying gangue minerals.

The degree of crystallinity of the minerals varies. Among ore sulphides metacinnabar is crystallized to a lesser extent than cinnabar, not more than 50 per cent. Study under the electron microscope showed that metacinnabar films are built up by spherical particles whose surfaces are partly crystallized (Fig. 4); crystalline particles are equant, their dimensions are hundredths of a micron. Cinnabar in film separations possesses fainly crystalline structure; some individuals are larger than those of metacinnabar, their dimensions ranging from 1 to 10 microns. Coarsely crystalline segregations of cinnabar consist of crystals 0.1–0.2 mm across; the commonest form is the rhombohedron sometimes complicated by small faces of the pinacoid, prism, and rhombohedron (Fig. 2b).

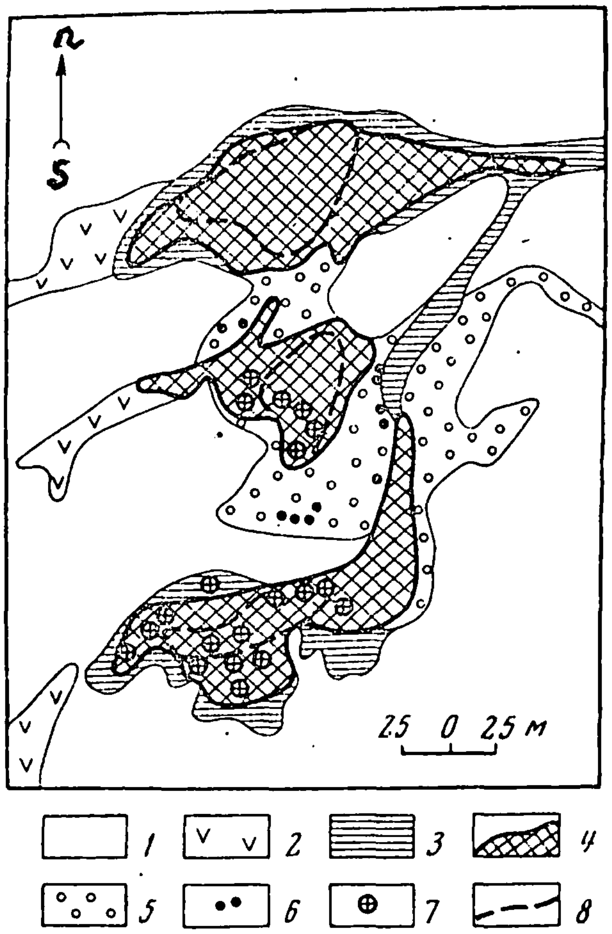


Fig. 1: Lithological scheme of mercury mineralization at the Mendeleev volcano (Northeastern fumarolic field). 1 – talus and proluvium deposits and industrial wastes of the sulphur mine; 2 – lavas and tuff-breccias of andesitic composition; 3 – opalized rocks with insignificant sulphidization; 4 – pyrite ores; 5 – opalites with superimposed sulphur ores; 6 – extinct solfataras; 7 – active solfataras; 8 – contour of constant mercury concentration ($1 \cdot 10^{-3}$ per cent).(10 ppm)

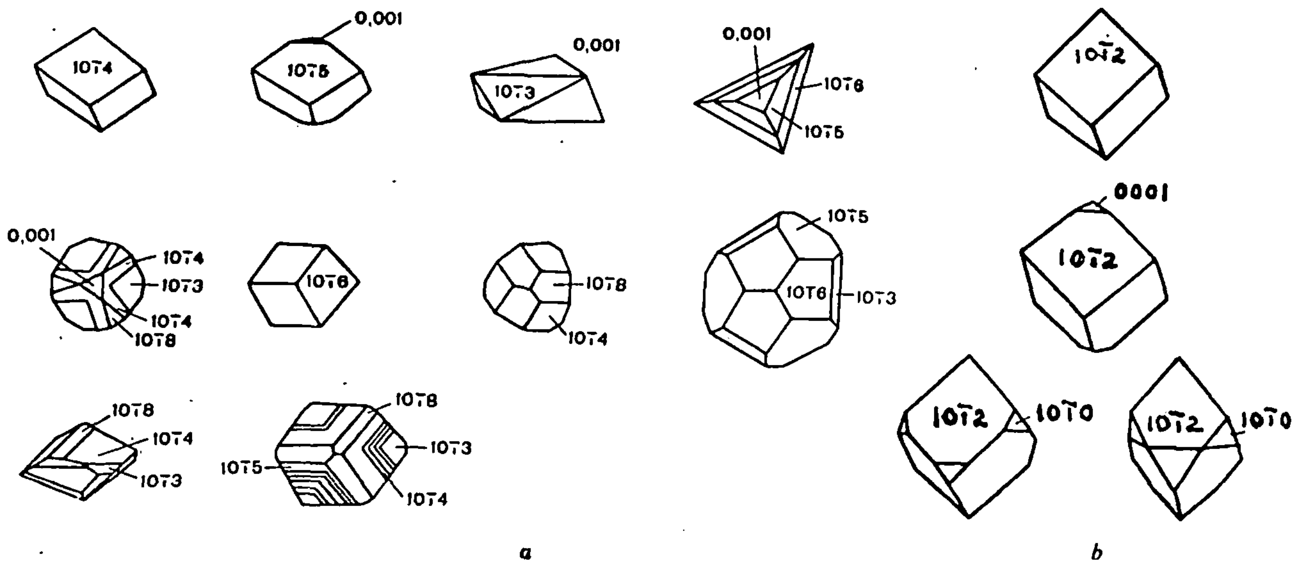


Fig. 2: Crystals of cinnabar: a – the Mendeleev volcano; b – Apapel'skie springs.

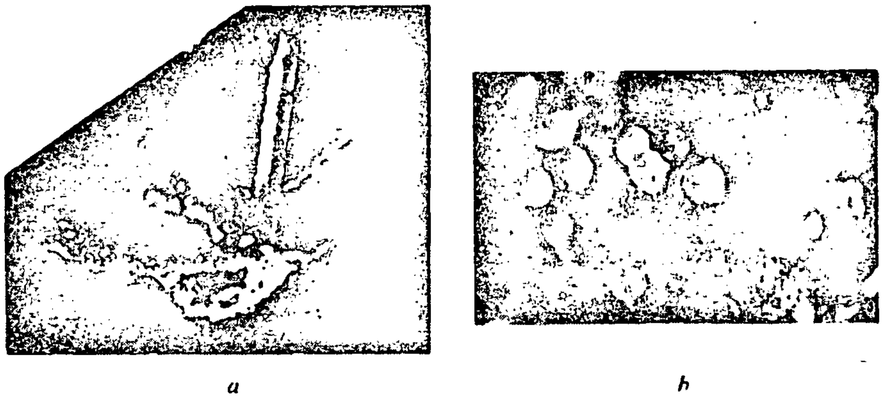


Fig. 3: Arsenic sulphides from caldera Uzon: a – intergrowth of realgar crystals; b – small spheres of orpiment; magnification × 90.

Extraordinarily curious formations—oolites of pyrite with strikingly high mercury content (2 per cent) were found at the bottom of the cauldron at the places of issue of gryphons at Dvukhyurtochnye springs. Such a percentage of mercury was not recorded even for pyrites of mercury deposits; besides, high arsenic content (2.7 per cent) was also found for these oolites.

Oolites possess spherical and flat round shapes, their sizes ranging from fractions of a milimeter to 2–3 mm (Fig. 5). They are characterized by a concentric-zoned structure; alternating zones are composed of pyrite and silica minerals, in some cases of pyrite zones only, crystallized to various degrees. On the background of this concentric-zoned structure there are also spots in oolite which consists of segregations of lighter coloured apparently recrystallized pyrite, they are reminiscent of septarian cracks in concretions and were obviously formed during the ageing and crystallization of iron sulphide gels. In the central parts of oolites, fragments of gangue minerals or magnetite are usually present.

In order to find out the form of mercury present in pyrite its distribution in the sections of oolites was studied by means of electron microprobe analyzer MS/46 Cameca. The constancy of mercury content in the main mass of oolites and its decrease to radialelongated segregations of later pyrite has been established in this way. It is interesting to note that the decrease in mercury content is correlated with the percentage of iron. It is possible that during the redeposition of the iron of the sulphide gel along the septarian cracks and its crystallization the depletion of mercury took place. Calculations of the dimensions of elementary units demonstrated essentially larger values for pyrite from Dvukhyurtochnye springs compared with the reference pyrite with low mercury content. These data suggest that mercury in this case enters the crystalline lattice of pyrite and, having an ionic radius larger than that of iron, expands the lattice, increasing its parameters (Ozerova, Borodaev *et al.*, 1969). The increase in parameter can not be due to the presence of arsenic, even if it is present in isomorphous form, because its ionic radius is less than that of iron. As was established by laser microspectral analysis, arsenic is also characterized by uniform distribution in oolites.

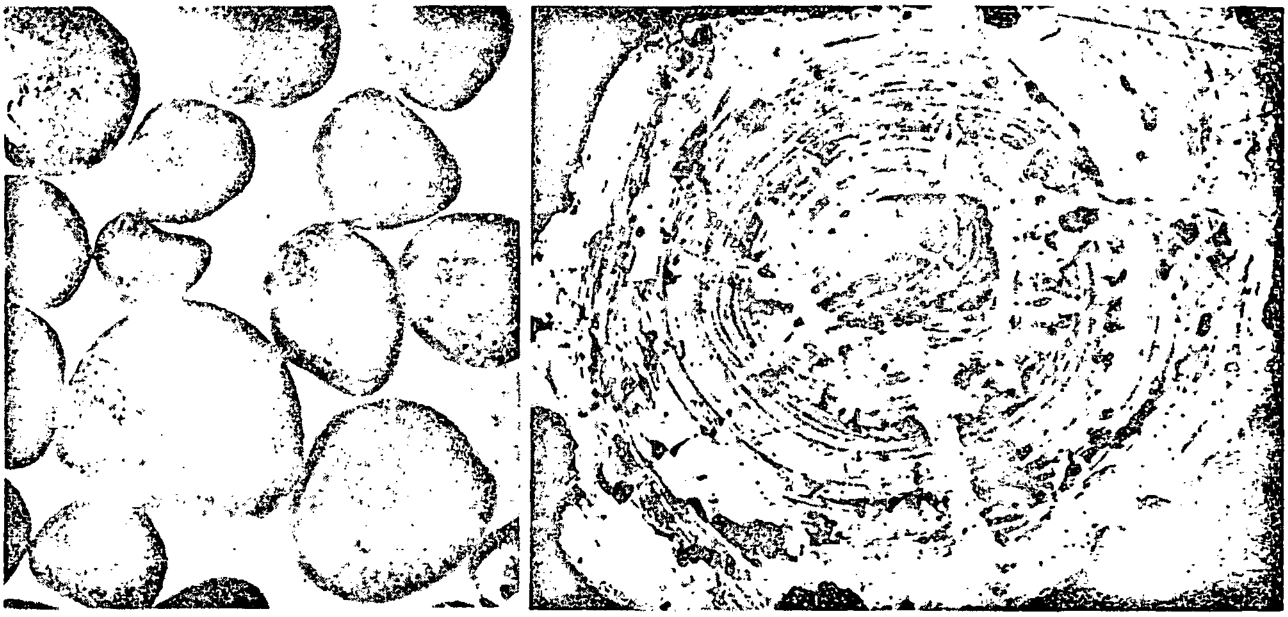
Information Bearing on the Origin of Hydrothermal Solutions Forming Mercury–Antimony–Arsenic Mineralization

The manifestation of present metalliferous hydrotherms is related in time to active andesite-basaltic volcanism. The vents of abyssal hydrotherms are localized within volcano-tectonic depressions which are characterized by widespread development of the products of young acid volcanism (ash-pumice tuffs of dacite, ignimbrites, and extrusions of dacite and liparite) and more recent basaltic areal volcanism (Naboko, 1970). The solutions of deep origin are represented by weakly alkaline chloride-sodic waters with small quantities of SO_4^{2-}, H_2S, CO_2 and large amounts of silica, boron, arsenic, and some other metals. The vents of chloride-sodic waters are often accompanied by vapour jets and by the appearance of acid sulphate hot springs. Their origin is related to the degassing and boiling of deep-seated alkaline thermal solutions with the subsequent near-surface oxidation of sulphide compounds. The chemical composition of deep-seated thermal waters is probably determined by the complex interaction of several factors. Among these factors one may suggest the influence of endogenetic emanations, admixing of underground waters of the upper part of the crust, interactions with wall rocks. The isotopic composition of sulphur testifies in particular to the complicated genesis of thermal waters (Vinogradov, 1964, 1966, 1970).

The isotopic composition of sulphate sulphur from Apapel'skie and Dvukhyurtochnye springs (δS^{34} + 12.0 and + 12.5‰) is typical for underground waters forming within the massifs of crystalline rocks. According to their chemical composition and isotopic composition

a b

Fig.4: Structure of the film of metacinnabar from Apapel'skie springs under the electron microscope. (a); cellulose-coal replica, magnification × 15.000. Detail of the structure of the surface of spherical particle (b); cellulose-coal replica, magnification × 45.000.



a b

Fig. 5: Oolites of pyrite from Dvukhyurtochnye springs (a); magnification × 30. Internal structure of oolite (b); polished section, magnification × 375.

of sulphur, they are similar to typical "nitric springs" widespread in many regions of the world (Vinogradov, 1964). It is not ruled out that in the origin of thermal waters of the Median Kamchatsky Range, where Apapel'skie and Dvukhyurtochnye springs are situated, abyssal factors played a subordinate role. The genesis of sulphate sulphur in these waters may be readily explained by the oxidation of sulphides disseminated in rocks (δS^{34} + 4 to + 6) in the regions of alimentation of the thermal systems with subsequent reduction of part of the sulphates. The content of H_2S in the waters of Apapel'skie and Dvukhyurtochnye springs is too low to retard the migration of quicksilver dissolved in thermal waters. Its reaction with sulphide-ion and the precipitation of cinnabar is related to the additional generation of H_2S directly inside the gryphon. Cinnabar is frequently deposited on the colonies of algae or plant debris. The isotopic composition of sulphur in cinnabar is equal to −9.6‰; the difference in isotopic composition of sulphate and sulphide sulphur corresponds to the separation during single-phase reduction of sulphate. The isotopic composition of the sulphur from pyrite of Dvukhyurtochnye springs is equal to −41.1‰. Such a light sulphur might have been derived from its cyclic participation in oxidation-reduction processes.

The complex character of the formation of volcanic thermal waters is particularly clearly exhibited on Kunashir Island. Here at the foot of the eroded structure of the Mendeleev volcano along several hundred meters of the coast line of Goriachiy Pliazh (Hot Beach), mineralized thermal Cl-Na waters are issuing. In the deep bore holes their mineralization reaches 26 grams per litre, and according to the ratio Cl/Na they exactly correspond to the composition of oceanic water. In the upper horizons and natural vents the mineralization of thermal waters is lower, but the relation between net mineralization and Cl and Na contents remains unchanged, which points to the participation of the waters of marine origin in the recharge of the hydrothermal system. It may proceed both at the expense of the water of the present ocean, and at the expense of mobilized connate waters from sedimentary deposits. The complex of marine volcanic-sedimentary deposits is revealed by bore holes drilled within the boundaries of Goryachiy Plyazh. The isotopic composition of sulphate sulphur in water of one of the springs issuing among the shore drifts of Goriachiy Plyazh turned out to be similar to the sulphur composition of oceanic sulphate near the coast of the island (+18‰). In the other spring coming out of a fissure in the young dacite extrusion sulphur was found to be heavier (+28.6‰). Such a heavy isotopic composition of sulphur may easily be explained by the marine origin of the sulphate of the thermal water with subsequent enrichment in heavy isotopes due to high-temperature reduction of sulphate. Correspondingly, the sulphur of H_2S in vapour jets of Goriachiy Plyazh is characterized by a δS^{34} value close to zero. Sulphide sulphur with this isotopic composition might have been formed during the abiogenic reduction of the sulphate of abyssal hydrothermal solutions. The basin of the development of chloride-sodic alkaline thermal waters of Goriachiy Plyazh is rimmed by the vents of acid springs along the slopes of the Mendeleev volcano, and in the caldera of the volcano there are typical solfataric fields.

Table: Isotopic Composition of Sulphur in Modern Hydrothermal Solutions and Minerals

Thermal springs	Form of sulphur	δS 34‰
Dvukhyurtochnye springs, Kamchatka	Pyrite	− 41.1
	SO_4^{2-} from solution	+ 12.0
Apapel'skie springs, Kamchatka	Cinnabar	− 9.6
	SO_4^{2-} from solution	+ 11.7
Goriachiy Plyazh, the Mendeleev volcano Kunashir Island	Cinnabar	− 2.4
	Pyrite + marcasite	− 1.5; − 1.4; + 1.2
	Barite	+ 5.2
	Alunite	+ 22.3
	Jarosite	+ 11.6; + 14.1; + 17.4
	Native sulphur	+ 1.2; + 5.4
	H_2S from gaseous phase	− 0.3; + 1.2
	SO_4^{2-} (Cl-Na waters)	+ 17.0; + 28.6
	SO_4^{2-} (acid waters)	− 1.6
Caldera Uzon, Kamchatka	Realgar	+ 1.1
	Orpiment	− 1.2
	Pyrite	− 6.1; − 5.2; − 4.6; − 4.4; − 2.8; − 2.4; + 1.1
	Native sulphur	− 3.3; + 1.3
	H_2S from gaseous phase	− 1.6; 0.0
	SO_4^{2-} from solution	− 2.5; − 0.5; + 1.1; + 3.6; + 5.6; + 22.4

All this diversity of chemical types of volcanic waters is acounted for by the phenomena of evaporation, degassing, and recondensation of abyssal waters, which are intermixed near the surface with ground waters and undergo oxidation by atmospheric oxygen. The origin of sulphate sulphur may be two-fold. The major part of sulphate is probably formed by oxidation of sulphidic sulphur, and its isotopic composition remains unchanged. The other part of sulphate can be derived at the expense of deep-seated sulphates due to involvement of deep-seated chloride waters. Admixing of abyssal oxidized sulphur should lead to the enrichment in heavy isotopes of the sulphur from sulphates of near-surface volcanic thermal waters. The acid sulphate thermal springs of the Mendeleev volcano are good examples, where the isotopic composition of sulphur from sulphates ranges from + 11.6 to 18‰.

Systematic investigations of the isotopic composition of sulphur in the caldera of the Uzon volcano has just been started. The isotopic composition of sulphidic sulphur at this locality is close to zero. The same or nearly the same isotopic composition is characteristic for sulphur of sulphates. The greater part of the sulfate is probably due to oxidation of H_2S. Only one of the springs gave an isotopic composition of sulphate sulphur equal to + 20‰. If this value reflects the isotopic composition of the sulphate sulphur from deep-seated chloride-sodic waters, we may postulate the involvement of sulphur from water-saturated rocks of the earth is crust. The existence of relict water in the rocks of the extensive tectonic depression, where the Mendeleev volcano is situated, is quite likely, although this problem needs special investigations. At the same time, the thermal waters of Uzon, according to the geological conditions of their issuing, fit the idea of typical magmatic waters. Their discharge is along large deep-seated faults, and the total amount of heat flow permits us to speak about ascending endogenetic fluids (Naboko, 1970).

The question of the sources of metals in volcanic hydrothermal solutions is open for further studies. Part of these metals could be undoubtedly extracted from wall rocks, while the other part is brought with the volcanic emanations. This problem has been best investigated for the Mendeleev volcano. Here the origin of two major ore components of the pyritic lode is different. Iron is extracted from volcanic rocks during their opalization and then is deposited by hydrogen sulphide of sulphate solutions (Naboko, Sil'nichenko, 1959). For quicksilver its gain during the hydrothermal process is obvious (Ozerova *et al.*, 1969). If quicksilver like iron were taken from wall rocks during their opalization, the mercury content of opalites should be diminished compared with unaltered volcanic rocks, while in fact it increases tens of times, and in pyritic ores it rises tens and hundreds of times compared with opalites (Fig. 6). A significant gain of metals including arsenic, antimony, and mercury might be suggested for volcano-tectonic caldera Uzon.

For Apapel'skie and Dvukhyartochnye springs the solution of this problem is much more complicated. Whether mercury mineralization is the result of the redeposition of mercury ore manifestations known in the Median-Kamchatka ore belt, or results from continuation of the ore process which is responsible for this ore mineralization, is not possible to resolve unambiguously on the basis of available data. Depending upon the answer to this problem the scale of the ore-forming activity of these thermal springs should be evaluated in different ways.

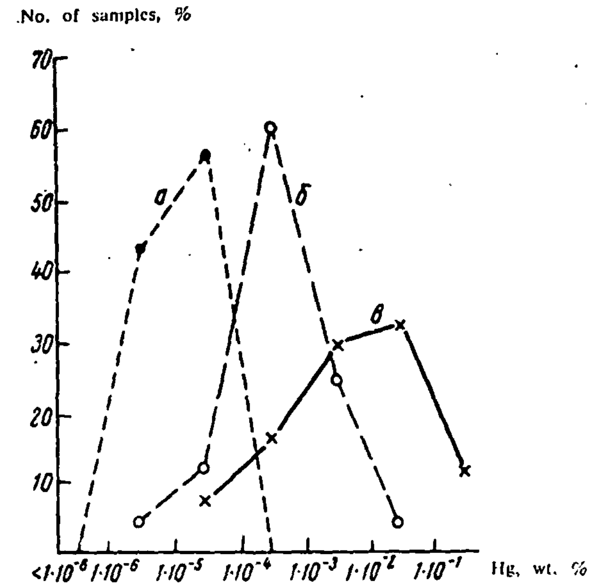


Fig. 6: The diagrams of mercury distribution in lavas (a), opalites (b), and pyritic ores (c).

On the other hand, mercury-pyritic mineralization of the Mendeleev volcano might be of practical interest as an object for concomitant mining, in case the mining of sulphur is resumed and the production of sulphuric acid from pyritic ores is started.

* * *

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Alteration of Rock by Volcanic Gas in Japan.*

IWAJI IWASAKI, MITSUEI HIRAYAMA, TAKASHI KATSURA
Tokyo Institute of Technology
TAKEJIRO OZAWA, JYOYO OSSAKA
Kagoshima University
MASAAKIRA KAMADA
HATAO MATSUMOTO
Kumamoto University

Introduction

Alteration of rocks and minerals in the geothermal regions has been studied by many investigators (1) in various localities since last century, but in none of these, so far as the authors are aware, the inclusive study of the processes of alteration under different conditions has been carried out except for the reports of LOVERING (2). Lovering had compared the halogen-acid alteration of ash at Ten Thousand Smokes, Alaska with the sulfur-acid alteration at Solfatara, Italy, studied by RITTMANN (3) (1934) and at Lassen Peak, U.S.A. reported by ANDERSON (1935) (4). After the comparison of the three studies, Lovering concluded that the halogen-acid alteration and the sulfur-acid alteration are similar in most respects and that probably all constituents of the rocks are leached in zones of intense alteration, but that alumina and magnesia are more subject to hydrolysis and precipitation in a sulfuric acid medium, whereas silica is more mobile in the halogen acids.

The purpose of the present work is to make clear in more detail the processes of alteration under different conditions by the comparison of variation in chemical compositions of the series of alteration products from several localities issuing volcanic gases in Japan, and by the model experiments, which are carried out by putting small pieces of rocks and minerals in active fumaroles and also hot springs and various solutions containing various salts, acids, and concentrations of them.

Many onion-structured rocks as an alteration product are in com-

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* Paper read at the IAV scientific session of Aug. 22, 1963 (XIII General Assembly, I.U.G.G.).

mon near the fumaroles at active volcanoes in Japan. Although the size of one onion-structured rock is given by the distance among joints of the original rocks, it seldom exceeds several meters, but most onions are usually less than one meter in diameter. If we collect a series of samples from the outermost to the inner part of a suitable onion carefully selected, it should be considered that the variation of chemical composition within the series of the samples from one onion would show each stage of the process of alteration, and also we can avoid unreliability derived from different alteration products of different kinds of rocks at one locality assumed usually to one series of alteration products. In addition, preparation of samples for chemical analysis is very easy because the shells of the onion can be easily exfoliated.

Two types of the fumarolic alteration of rocks were found in this study on the onion-structured rocks. Some of the results obtained are reported in this paper.

Materials and Experiments

For the study of the mechanism of process of alteration, four onion-structured rocks are collected from the geothermal regions at Volcano Hakone, Volcano Esan, Volcano Kusatu-Sirane, and at Higasimori in the Tamagawa Hot Spring Region.

As all the onions are located very near the fumaroles, it would be considered that the variation of chemical composition in each onion have been caused by volcanic gases as like that issuing from the fumaroles.

Several samples prepared from the outermost to the inner part of each onion of the altered rocks have been analysed for the main chemical components. Analytical methods used in this work are given separately in the previous papers (5) (6).

Results Obtained and Discussion

Change of Chemical Composition by Alteration. — The chemical composition of the samples prepared as described above are shown in Table 1 - 4.

It is said that figures giving weight percent are unsuitable for the discussion of the process of alteration. However, the use of such a constant component as alumina, silica, or of bulk density seems to be practically needless in this discussion.

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As shown in Table 1, the most remarkable changes in the main components are the continuous increase of silica, water and ignition loss, and the continuous decrease of alumina through all courses of the alteration process.

TABLE 1: Chemical Composition of Alteration Products from Higashimori, Tamagawa Hot Spring.

	(surface)		T-3	T-4	T-5	T-6	T-7	T-8	(Core)
	T-1	T-2							T-9
SiO_2	86.06	85.85	85.87	85.62	84.85	84.13	84.10	61.15	59.13
TiO_2	1.05	0.94	0.94	1.10	1.01	0.99	0.95	0.69	0.64
Al_2O_3	2.16	3.37	1.95	2.93	2.82	1.61	3.48	15.03	16.04
Fe_2O_3	0.14	0.13	0.60	0.14	0.66	0.57	0.86	3.57	4.28
FeO	—	—	—	—	—	—	—	3.00	3.45
MnO	0.002	0.002	0.019	0.007	0.009	0.006	0.029	0.199	0.226
CaO	0.05	0.05	0.05	0.05	0.05	0.05	0.30	6.53	7.27
MgO	0.05	0.05	0.05	0.05	0.05	0.05	0.34	3.72	4.12
K_2O	0.07	0.07	0.17	0.08	0.06	0.05	0.50	1.35	1.31
Na_2O	0.19	0.18	0.15	0.20	0.14	0.23	0.41	2.22	2.48
P_2O_5	0.07	0.06	0.05	0.05	0.06	0.05	0.07	0.09	0.10
H_2O (—)	5.61	6.65	6.54	6.55	6.59	6.16	4.63	0.77	0.58
Ig. loss	4.49	3.23	3.02	2.88	3.79	5.00	5.76	2.26	0.87
Free S	2.08	0.14	0.16	0.04	0.17	—	—	—	—
Total	99.84	100.47	99.31	99.55	99.98	99.79	100.42	100.40	100.50

In the specimens from Higasimori, Tamagawa Hot Spring, although the chemical compositions of the samples, T-1 ∾ T-5, which are pale-orange-colored white shells about 20 cm. thick in all of the onions, showed a small difference among them, they are very similar, as a whole, except for the most outward member, T-1, containing 2.08 percent of free sulfur. It is certainly an end product of alteration, and characterized by consisting mainly of silica, water. These increases of the components would be brought by leaching of the other components such as alumina, magnesia, lime and alkalies.

The behavior of sodium shows a very similar pattern to that of aluminium and iron (III), but potassium shows the reverse pattern to that of sodium (Fig. 1). This peculiar behavior of potassium suggests a potassium fixation by adsorption or formation of new minerals. Calcium and magnesium are extremely decreased in the early stage (T-8 and T-7), being different from all other components.

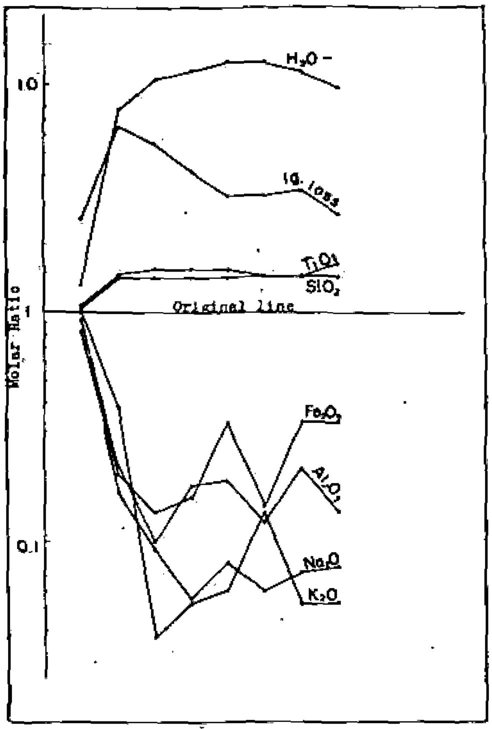

Fig. 1 - The variation of chemical composition of onion from Higasimori, Tamagawa Hot Spring Region.

As will be seen in Table 2, the most noteworthy change in the chemical compositions of the samples from Owakidani, Volcano Hakone is the increase of silica, water, ignition loss (greater part is probably water) and titanium, and the decrease of aluminum, iron (II and III), calcium, magnesium, sodium and potassium. The pattern of changes in chemical-compositions are very similar in all respects to that of the specimens from Higasimori, Tamagawa Hot Spring.

On the other hand, the onion of altered andesite at Volcano Esan,

TABLE 2: Chemical Composition of Alteration Products from Hakone Owakidani.

	Ol - 1	Ol - 2	Ol - 3	Ol - 4
H_2O (—)	6.54	6.16	4.97	1.54
Ing. Loss	3.80	4.83	4.52	2.60
SiO_2	86.02	83.34	76.74	58.06
TiO_2	1.17	1.08	1.02	0.77
Al_2O_3	1.29	2.36	2.33	14.07
Fe_2O_3	0.19	0.73	1.85	3.38
FeO	< 0.03	< 0.03	2.43	4.85
MnO	—	—	—	—
CaO	< 0.05	< 0.05	1.75	7.00
MgO	< 0.03	0.58	3.18	4.80
K_2O	0.11	0.25	0.57	0.73
Na_2O	0.23	0.24	0.34	2.25
Free S	—	—	—	—
Total	99.35	99.57	99.70	100.05

Hokkaido, as will be seen in Table 3 and Fig. 2, shows remarkable difference in the behavior of silica and alumina. In this type of alteration, the behavior of both components is quite different from the former type. Silica content decreases at the early stage of alteration, but after reaching a minimum value, the silica content gradually increases toward the outermost intensely altered shell (E-1) of the onion which consists mainly of silica. The behavior of aluminum shows the reverse relation to silica in the course of alteration of this type. Silica content had a minimum value in the course of alteration of this type, but aluminum content had a maximum. A maximum content of aluminum was usually observed at nearly the same zone where silica content was minimum.

It is very interesting that so far as the loss of silica and the gain of aluminum at the early stages of alteration (E-6, E-5, E-4) are concerned, this pattern of alteration is similar to that of process of weathering. But the behavior of ferric oxide and potassium in this « silica-minimum and alumina-maximum type of alteration » shows marked difference from that in weathering and also in « the continuous silica-increase and alumina-decrease type » of alteration as shown in Tables 1 and 2. The loss of total iron content is observed in the early stages (E-5 and E-4) and in the later stages (E-2 and E-1), but the maximum content of iron is seen in the zone E-3, where the formation of iron minerals are expected. The behavior of potassium is more peculiar than that of iron. The maximum content of potassium is observed in the zone E-4, where the potassium content shows larger value than that of the fresh original rock (E-6).

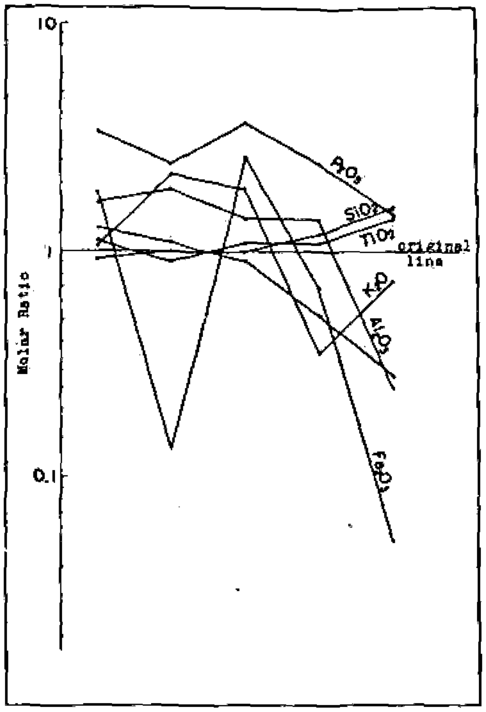

Fig. 2 - The variation of chemical composition of onion from Volcano Esan.

At Volcano Kusatu-Sirane, a suitable onion for this study could not be found. Chemical composition of fresh andesite could not be obtained, because the core of the onion collected was clearly altered. Furthermore, a specimen which is considered to be the end product of alteration also could not be collected. Although the chemical compositions of the samples from this onion in Table 4 show only a part of the alteration products, the pattern of alteration in this onion also seems to be the type of silica minimum and alumina maximum.

Thus two types of the processes of alteration were recognized in alteration of rocks near fumaroles in Japan.

Character of fumarolic gases. — Fumarolic gases have been issued at all localities where the onions were collected. It is expected that the patterns of alteration of rocks described above must be brought by different kinds of volcanic gases having different chemical compositions. Then, chemical analyses of the gases collected at various localities were carried out to find a relationship between the chemical compositions of the volcanic gases and the two types of alteration.

TABLE 3: Chemical Composition of Alteration Products from Esan.

	E-1	E-2	E-3	E-4	E-5	E-6
SiO_2	85.47	61.42	47.36	45.09	40.22	63.33
TiO_2	0.63	0.41	0.38	0.30	0.34	0.46
Al_2O_3	3.79	14.94	17.15	22.36	18.53	16.33
Fe_2O_3	0.14	1.57	5.61	0.27	5.46	2.85
FeO	—	—	—	—	—	3.66
MnO	0.001	0.001	0.001	0.001	0.001	0.13
CaO	0.05	0.05	0.05	0.05	0.05	6.57
MgO	0.05	0.05	0.05	0.05	0.05	1.74
K_2O	0.58	0.25	1.19	1.30	0.64	0.85
Na_2O	0.78	1.28	2.10	2.30	2.55	3.00
P_2O_5	0.15	0.22	0.30	0.19	0.25	0.11
H_2O (—)	0.68	0.52	0.64	0.60	0.69	0.14
Ig. Loss	7.32	18.91	24.57	27.87	30.95	0.45
Total	99.54	99.52	99.30	100.28	99.63	99.62

The sampling and analytical methods of fumarolic gases were reported briefly in the previous paper (7).

As the orifice temperatures of fumarolic gases in question are distributed from 100° to 196° C, which are just or over the boiling point of water, as shown in Table 5, the alteration in the gaseous phase is suggestive.

As more than 94.4 % of these volcanic gases are water vapor,

TABLE 4: Chemical Analyses of Fresh and Altered Andesites at Geothermal Regions, Volcano Kusatu-Sirane.

	101	102	103
H_2O (—)	4.00	0.28	1.09
Ig. Loss	9.67	2.19	7.12
SiO_2	70.21	58.46	57.31
TiO_2	0.69	0.73	0.75
Al_2O_3	6.17	19.05	16.21
Fe_2O_3	3.67	2.71	6.26
FeO	—	3.59	—
MnO			
CaO	2.87	7.57	7.24
MgO	0.26	0.35	0.33
K_2O	1.21	1.54	1.32
Na_2O	1.23	3.05	2.45
Total	99.98	99.52	100.08

there is no difference among them in respect of water content. However, the chemical compositions of these gases exclusive of water vapor are clearly different from each other. The use of this difference is very effective to classify these volcanic gases. According to the classification proposed by the present authors (7) (8), all these volcanic gases belong to two types of gases (Type IIA and Type IIB).

The fumarolic gases from Higasimori, Tamagawa Hot Spring, and

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Owakidani, Volcano Hakone contain neither hydrogen fluoride nor hydrogen chloride. A small amount of sulfur dioxide is found in both gases as will be seen in Table 5 (8). As they consist mainly of carbon dioxide and hydrogen sulfide, they can be expressed in the same gas formula proposed by the present authors (7) (8) as $[CO_2, H_2S]$. On the other hand, in the gases from the geothermal regions at Volcano Esan and Volcano Kusatu-Sirane, carbon dioxide, hydrogen sulfide, hydrogen fluoride, hydrogen chloride and sulfur dioxide were found (8). Hydrogen chloride and sulfur dioxide are the main components in these gases exclusive of water vapor. Then, the gas formulas of this type of volcanic gases are expressed as $[CO_2, H_2S, SO_2]_{HCl}$ for the gas from Volcano Kusatu-Sirane and $[CO_2, H_2S, HCl]_{SO_2}$ for that from Volcano Esan. This formal difference between $[CO_2, H_2S, SO_2]_{HCl}$ and $[CO_2, H_2S, HCl]_{SO_2}$ is not so essentially much as the difference between these two formula and $[CO_2, H_2S]$ as described above.

TABLE 5: Chemical Composition of Volcanic Gases.

	Higasimori, Tamagawa Hot Spring	Volcano Kusatu-Shirane	Geothermal Region Volcano Esan	Owakidani Volcano Hakone
Temperature	104	148	196	110
H_2O (%)	99.0	94.4	97.3	98.7
Date	Oct. 5, (1956)	June 19, (1960)	July 23, (1960)	Apr. 8, (1960)

Chemical Composition of Gases (exclusive of water).

HF	—	0.9	0.10	0.0
HCl	0.0	9.2	16.5	0.0
SO_2	0.2	22.2	2.2	<0.1
H_2S	31.8	32.8	17.2	22.2
CO_2	67.2	34.5	62.4	76.0
R	0.8	0.4	1.6	1.8
Rn (10^{-10}c/l)	—	1.2	1.8	15.1

Now we can classify the gases from chemical composition of the gases into two types; one is the weakly acidic type of gases which are characterized by the absence of hydrogen chloride and the presence of a very small amount of sulfur dioxide, as observed at Higasimori and Owakidani, the other is the strongly acidic type of gases which are characterized by the presence of hydrogen chloride and sulfur dioxide, as observed at Volcano Esan and Volcano Kusatu-Sirane.

Model experiments. — Although alteration of rocks described above would be caused mainly by volcanic gases, some of the chemical changes in them must have also the chemical reactions in liquid phase. Furthermore, as properties of volcanic gases issued are generally changed with time, altered rock collected at a certain locality and time may be formed by the gas which might have changed its properties such as temperature, chemical composition, issuing velocity (discharge), etc. during the alteration period. Moreover, weathering by meteoric waters has been added to this system of alteration, especially to the alteration products near an extinct fumarole. Therefore the precise explanation of the processes of all phenomena is very hard because of their complicated nature. If studies of alteration are carried out under various conditions of several simple factors governing the system such as temperatures, pressures, concentrations, and reaction time, the complicated phenomena must be explained. For realizing this expectation, various kinds of model experiments would be possible. One of these model experiments is reported in the followings.

A small piece, about 10 cm in diameter, of augite-olivine-basalt from Kamimasuki district in Kumamoto Prefecture was put for about 8 months in an artificial path of fumarolic gas, which has been made for industrial collection of native sulfur. Temperature of this gas was 97° C, which was measured on May 28, 1958. No seasonal or annual variation of temperature seems to be observed at present time.

After the reaction period, the test piece was sharply lined with a whitish-gray layer about 1.0 cm thick from the surface (outer zone). The next zone inward was a pinkish-gray less than 0.5 cm thick (intermediate zone), which was followed with moderately sharp contact by a zone of dark-gray altered part about 0.5 cm thick (inner zone), which transfered gradually inward into the unaltered part.

Chemical compositions of altered zones are shown in Table 6 and Fig. 3, with that of the unaltered zone and gas. As shown in Table 6, silica shows minimum in the zone IK-3, on the other hand, aluminum and iron show maximum in the zone both IK-3 and IK-2. Magnesium, calcium, manganese, sodium, potassium and phosphorus decrease continuously, and water content increases gradually toward the later stage of alteration. It is very interesting that this pattern of alteration obtained is very similar to the silica-minimum and alumina-maximum type of alteration observed in the onions from Volcano Esan and Volcano Kusatu-Sirane.

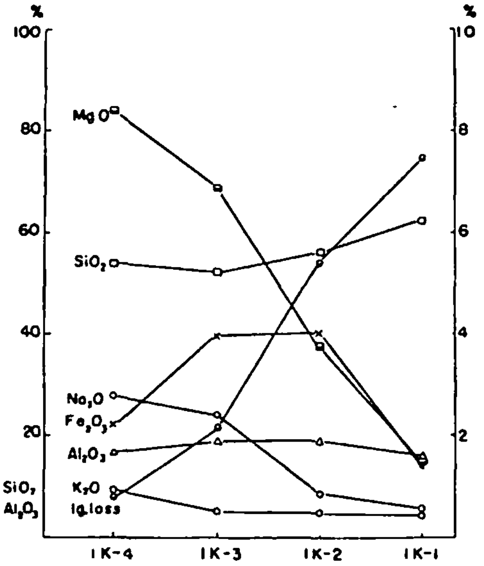

Fig. 3 - The variation of chemical composition of Test Piece (Basalt) hold for about 8 months in active fumaroles at Volcano Iwojima.

In the fumarolic gas as a reactant at this spot, H_2O, HF, HCl, SO_2, H_2S and CO_2 are found, and this type of gases is expressed with its temperature as $_{97}[SO_2, CO_2]_{H_2S \cdot HCl}$.

Chemical compositions of volcanic gases and types of alteration. The study of the alteration of five sets of rocks suggests that the process of alteration is influenced by the chemical composition of the gases which attack the rocks as a reactant. It may be asserted that the chemical composition of the volcanic gases has been maintained in an approximately constant state while the alteration of rocks was completing by gases. The model experiments on alteration of rocks and minerals showed that it is not necessary so long time for the alteration of rocks, although the most altered surface of the specimen

TABLE 6: Chemical Composition of Altered Basalt Hold for about 8 months in Active Fumarole in Iwojima Volcano.

	Outmost Zone IK-1	Intermediate Zone IK-2	Inner Zone IK-3	Original (Fresh)Rock IK-4
SiO_2	62.46	55.47	52.79	53.11
TiO_2	0.24	0.46	0.72	0.73
Al_2O_3	15.27	19.17	19.48	17.60
Fe_2O_3	1.40	4.02	3.99	2.22
FeO	0.92	3.91	3.86	4.73
MnO	none	tr	0.12	0.13
MgO	1.47	3.70	6.94	8.43
CaO	2.01	2.46	5.27	7.84
Na_2O	0.69	0.91	2.44	2.76
K_2O	0.47	0.50	0.51	0.94
P_2O_5	n.d.	n.d.	n.d.	0.17
$H_2O(+)$	7.48	5.36	2.14	0.97
$H_2O(-)$	7.70	3.97	1.86	0.27
Total	99.89	100.12	99.93	100.11

Tokara Iwojima No. 4	H_2O(%)	HF	HCl	SO_2	H_2S	CO_2	R
	99.4	0.2	1.4	68.3	7.0	17.7	5.4

Temperature: 97° C

in the model experiments did not reach the latest stage as that observed at the many geothermal regions.

The close relationship between the chemical composition of volcanic gases and the patterns of alteration is clearly recognized. The silica-minimum and alumina-maximum type of alteration of rocks is correlated to the strongly acidic type of gas. On the other hand, the

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ɪt 8 months in Active

ɔne	Original (Fresh)Rock IK-4
	53.11
	0.73
	17.60
	2.22
	4.73
	0.13
	8.43
	7.84
	2.76
	0.94
	0.17
	0.97
	0.27
	100.11

H_2S	CO_2	R
7.0	17.7	5.4

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continuous silica-increase and alumina-decrease type of alteration is correlated to the weakly acidic type. Although this relationship has not been completely explained, it might be based on the different behavior of the proton between the weakly acidic type of gas and the strongly acidic type.

In order to ascertain that either the relationship described above are adapted to the other studies or not, many studies reported by other investigators were compared with the present study.

Unfortunately, as the most of these studies have not been made from the standpoint of the relation between the patterns of alteration and reactants, the available data are relatively few.

Alteration of dacite at Lassen Peak (4) which was caused by the $_{H_2S}[CO_2]$ type of gas, belongs to the continuous silica-increase and alumina-decrease type of alteration. On the other hand, alteration of ash intimately composed of mingled andesitic and rhyolitic ejecta at Ten Thousand Smokes (2) which had been brought by the action of $[HCl, CO_2, R]_{HF \cdot H_2S}$ type of gas belongs to the silica-minimum and alumina-maximum type.

These examples show good agreement with the result of the present study..

Conclusion

The study of the processes of alteration of volcanic rocks by means of variations in chemical compositions of each part of onion-structured rocks showed that the patterns of alteration is fairly influenced by the properties of the fumarolic gases. It has been found that there are two types of alteration. One is the silica-minimum and alumina-maximum type, and the other is the continuous silica-increase and alumina-decrease type. The fumarolic gases having temperatures approximately from 100 to 200° C were classified into two groups from the viewpoint of chemical compositions. One is weakly acidic type of gases which is characterized by the absence of hydrogen chloride and presence of a very small amount of sulfur dioxide, and the other is the strongly acidic type which is characterized by the presence of hydrogen chloride and sulfur dioxide. The silica-minimum and alumina maximum type of alteration might be caused by the strongly acidic type of gases, and the continuous silica-increase and alumina-decrease type of alteration might be caused by the weakly acidic type of gases.

The model experiments and the studies of the other investigators have supported the results obtained in the present study.

Acknowledgement

This study was supported by the Scientific Research Encouragement Grant from the Ministry of Education, to which the authors wish to express their thanks.

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Discussion

R. O. Fournier: Was a study made of the mineralogy of the alteration? If so, are there any differences in the mineralogy between the two alteration types?

I. Iwasaki: I am now undertaking the mineralogical study of the alteration products. The paper presented to this meeting is concerned only with the chemical aspects of the alteration.

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ANIT, Dept. Mineral Resources
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YORA, MITSUO, YASUHIKO EJIMA, and SUSUMU NAKAGAWA, Japan Geothermal Energy Development Center, Tokyo, Japan

Present Status of Geothermal Development and Utilization in Japan

There are about 200,000 hot springs in Japan and their distribution is closely related to Quaternary volcanoes. In 1976 the output of hot springs reached 1,490 cu m per minute. The heat produced by the springs has been utilized since ancient times as hot baths, and more recently has been put to various uses, such as greenhouse operation, road heating, space heating, and fish farming.

Research work on geothermal resources was started in Japan at Otake in 1953 and the first Japanese geothermal power plant started operation at Matsukawa in 1966; as of 1977, there were five operating stations in Japan. Two stations are under construction. The Matsukawa geothermal field produces superheated steam. At other fields, the steam separated from the water is introduced into turbines; at Hatchobaru the double-flash system is employed. Although the total capacity of the five operating power stations was only 118 Mw in 1977, it is envisaged that 500 to 1,500 Mw will be generated by geothermal energy in 1985.

Because Japan has an urgent need to develop domestic energy resources, such as geothermal energy, the government in 1973 started a systematic survey of geothermal resources with surface exploration followed by drilling. Of 30 areas surveyed so far, seven have been confirmed as geothermal areas with temperatures of over 150°C.

The government also promotes research and development of technology for geothermal development and utilization which covers the techniques for prospecting for and extracting geothermal energy, power generation utilizing hot water, generation of power from volcanoes, and environmental preservation and multipurpose utilization.

ZEN, M. T., Asst. Minister of State for Research, Republic of Indonesia, and Bandung Inst. Technology, Indonesia

Energy, Resources, and Environment Management—Base for Regional Cooperation for Asian Region

The world is facing a whole range of complex issues—food for an increasing population; unemployment and obstacles to industrial development; energy and resources imbalance; *resource policies and their* impact on the human environment; education, research, science, and technology in their social context; problems of international trade and the balance of payments; the role of *multinational corporations in the* developing countries. To many people these issues are temporary though interrelated "crises." In reality they are but symptoms of deep-rooted forces of a more fundamental nature. These issues are connected with the role of and the interaction among natural resources, population, economic growth, technologic development, and the natural environment. The interactions of these problems and issues force interdependence among nations. This is particularly true for people of the Asiatic countries. If the many millions of Asians are to survive, strong and sound management of energy, resources, and environment has to be applied to the Asian region. Plus, a strong input of capital and technology is necessary from the technologically advanced countries. Similarities and complementary conditions of the problems faced will have to be made a base for a closer cooperation within the Asian region.

The exploration for, and exploitation of, hydrocarbons and tin in the offshore regions of southeast Asia, the application of remote-sensing techniques for the inventory of resources, pollution control, and electric grid; the development of nuclear energy; and the development of agricultural- and resource-based industries are all items which can be developed in a more beneficial way if tackled together by the Asian countries. It is therefore imperative to speed up the regional cooperation program, especially in the development of energy and other natural resources, and the management of the environment, if Asians want to be strong and relatively "independent."

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J. Min. Coll. Akita Univ., Ser. A, Vol. IV, No. 3, pp. 19-34, April, 1970
(With 13 Figures and 1 Table)

ON THE GEOTHERMAL GRADIENT IN AKITA PREFECTURE, NORTHEAST HONSHŪ, JAPAN

By

Takeshi Ohguchi*, Kazuo Noritomi** and Takeshi Inoue*

Contribution from the Institute of Mining Geology, Mining College, Akita University, No. 224

(*Received 10 April, 1970*)

The geothermal gradients were investigated at the northern and coastal areas in Akita Prefecture, Northeast Honshū, Japan. In the northeastern area of the Prefecture, the temperature measurements were carried out in eight boreholes drilled for prospecting of ore deposits. Their hole depths were 500 m to 600 m.

For the coastal area, we collected the bottom hole temperatures in wells which drilled and surveyed with well logging for prospecting the oil and gas.

The northern and inland area of this field show higher geothermal gradient (above 4.0°/100 m) than that in the coastal area (2.0–4.0°C/100 m). A reasonable relation was found in the inland area; that is, high geothermal gradient anomaly corresponds to an upheaval tectonic movement. In the coastal area, where the oil and gas fields are distributed, the lower geothermal gradient anomalies have a close relation with the younger sedimentary deposits. A remarkable low geothermal gradient anomaly was found at Akita off shore and it extended towards Hachirō-gata. Some local anomalies in the coastal area must be considered, and one of them shows a high anomaly and the locality of that may correspond well to the zone of the geological disturbance.

INTRODUCTION

The west side of northeast Japan is well known as so-called "Green Tuff Region" where the Neogene sediments are widely developed. It has been pointed out that the west side of northeast Honshū, as well as of Akita Prefecture (Fig. 1), show greater heat flow comparing with the east side. Akita Prefecture is one of the most famous district where is rich in underground resources such as metallic ores, oil and gas. Under these circumstances, many geological and geophysical surveys were made in the district, and we are able to collect detail information concerning with surface and undergound geological structure on there.

We attempt to investigate, therefore, the known geological or geophysical phenomena from the geothermal points of views.

One of the purpose of this study is to find a relation between the geological phenomena, such as tectonic movement, mineralization and etc., and the geothermal ones. However, we have not yet sufficient geothermal data for discuss on the object in detail. In this paper, therefore, we described some evidences obtained up to date.

INLAND REGION OF THE NORTHEASTERN PART OF AKITA PREFECTURE

On the geology of the region, concerned now, excellent works have been made by many geologists since many years ago. For example, Ueda (1965) described and

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* Research Institute of Underground Resources; ** Institute of Mining Geology, Mining College, Akita University.

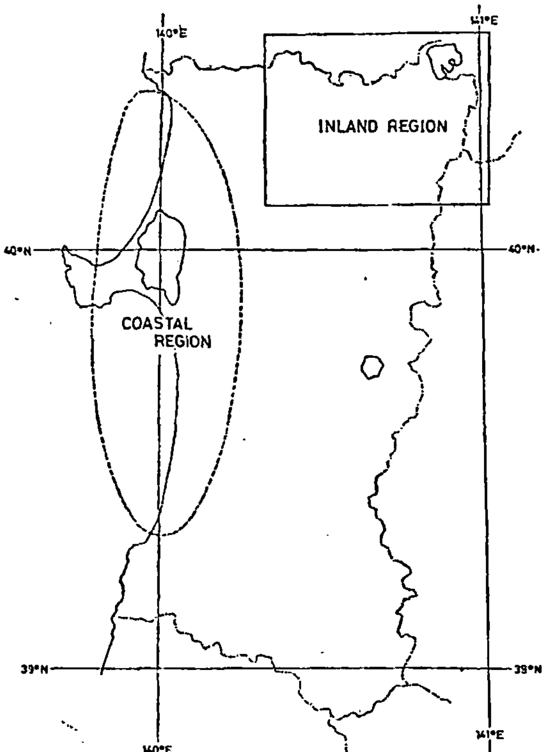


Fig. 1. Index map.

discussed in detail. According to those studies, the characteristic geological features are as follows:

In this region, Cenozoic thick pyroclastic sediments accompanied with marine clastic sediments are widely distributed, and some terrestrial deposits composed of pyroclastic rocks and lake deposits are partially developed. Along the Ôu mountain range, Recent volcanoes such as Towada caldera, Hachiman-tai and etc., are distributed. Thus, this area is characterized by the intense volcanic activities of submarine and terrestrial, from the early Miocene to Recent. In the region, such a large scale folding as appeared at oil fields in the coastal region is not observed, but a fault with N-S or E-W trend, which has close relation to the block movements of the basement rocks of the pre-Tertiary strata, is found markedly.

In the areas, a number of ore deposits are also distributed, especially, the Kita-Akita ~ Kazuno district is one of the most famous mining district in Japan. Accordingly, many boreholes were drilled for the prospecting of metallic ore deposits. We used these boreholes to measure the geothermal gradient since 1969, and eight boreholes as shown in Fig. 2 were measured up to date. The temperature was measured by means of the thermistor thermometer.

Results of these measurements are illustrated in Fig. 3. In the figure, the result of 69–2 hole was excepted because it was unable to observe at the greater depths than 180 m by collapsed accident of the hole. In Fig. 3, the depths of each borehole are substituted by their corresponding altitudes from the sea level. All temperatures, except in the 69-1,

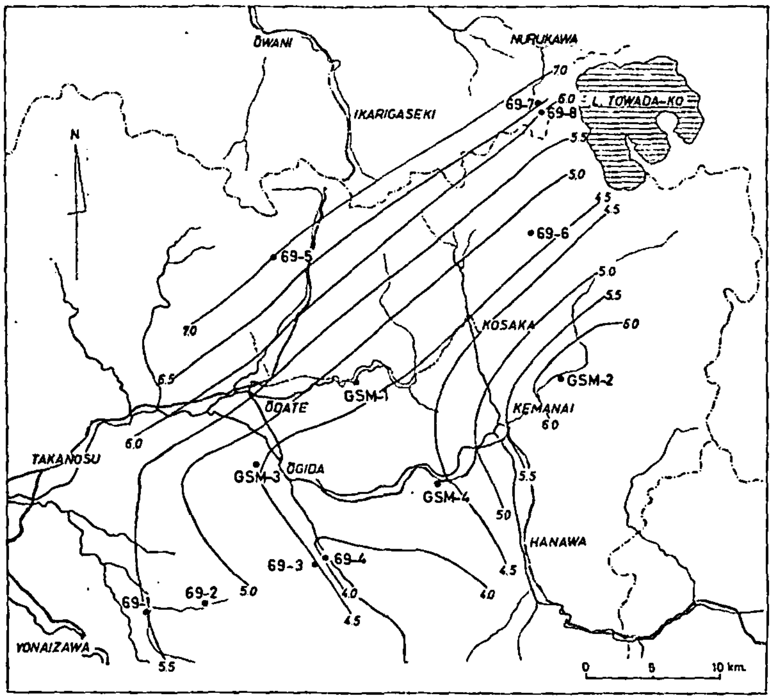


Fig. 2. The location of the drilling sites and isothermal gradient (°C/100 m) contour map of the inland region of the northeastern Akita Prefecture.

were measured in the drill pipe having an inside diameter of 35 to 60 mm, because the borehole without casing pipe was easily clogged by wall breakdown due to the fragile characteristic formation in the area. In case of the 69-1, the measurement was able to carry out in open hole without casing pipe, owing to its stable borehole.

The geothermal gradient in each borehole was estimated by the least square method from the data occupied relatively a straight part in the temperature curve. The results obtained are shown in Table 1 with other useful data from GSM-1,2,3 and 4, their locations are also shown in Fig. 2, which surveyed by the Geological Survey of Japan in 1963 and 1964 (Geological Survey of Japan, 1964 and 1965).

According to the results, some considerable local variations of the geothermal gradient must be considered. To confirm that, the results were plotted and an isothermal gradient contour map was submitted, as shown in Fig. 2. Although the numbers of data are insufficient to describe exactly, it may be said at least from the present data that the gradient contours at the northern half part of the region have parallel and NE-SW trend and the geothermal gradient increases with the distance from the low gradient area distributing along the line from Ōgida to Kosaka and Lake Towada-ko. But at the southern half, each contour turns off to the NW-SE direction, and low gradient areas, limited by 4.0°C/100 m contour, are situated at the southeast of Ōgida.

COASTAL REGION OF AKITA PREFECTURE

Many oil fields are distributed along the coast of the Japan Sea in Akita Prefecture. In this coastal region, thick marine clastic sediments, Cenozoic in age, are developed in

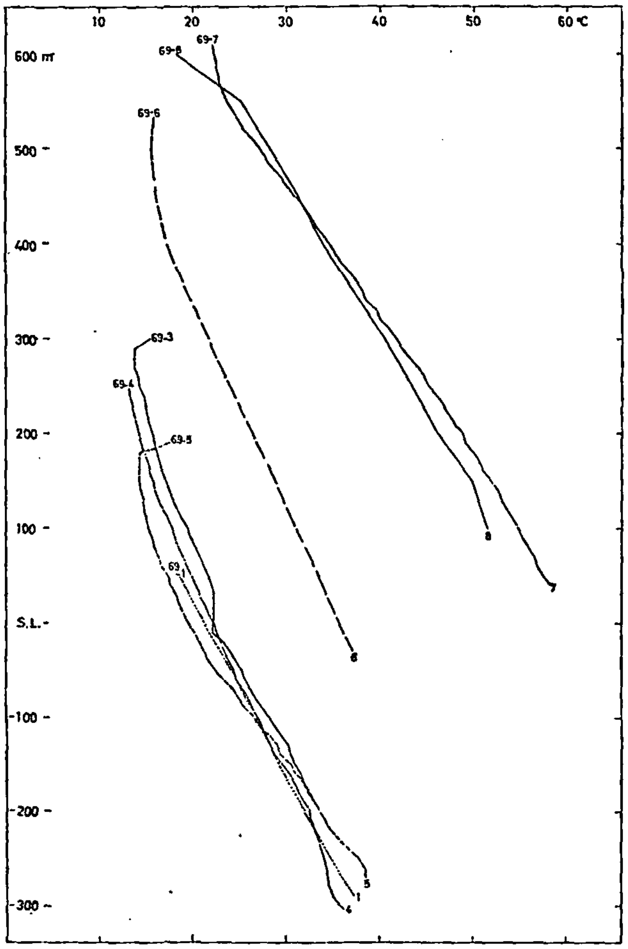


Fig. 3. Results of the temperature loggings in the inland region of the northeastern Akita Prefecture.

Table 1. Temperature gradient (°C per 100 m) in the inland regions of the northeastern part of Akita Prefecture.

Well	Gradient	Surface Temp. (calc.)
69-1	5.45	13.1
69-3	4.62	8.8
69-4	3.91	13.3
69-5	7.01	5.7
69-6	4.63	10.2
69-7	6.65	20.4
69-8	5.98	19.4
*GSM-1	4.6	
*GSM-2	6.4	
*GSM-3	4.5	
*GSM-4	4.3	

* ; after Geological Survey of Japan (1964, 1965).

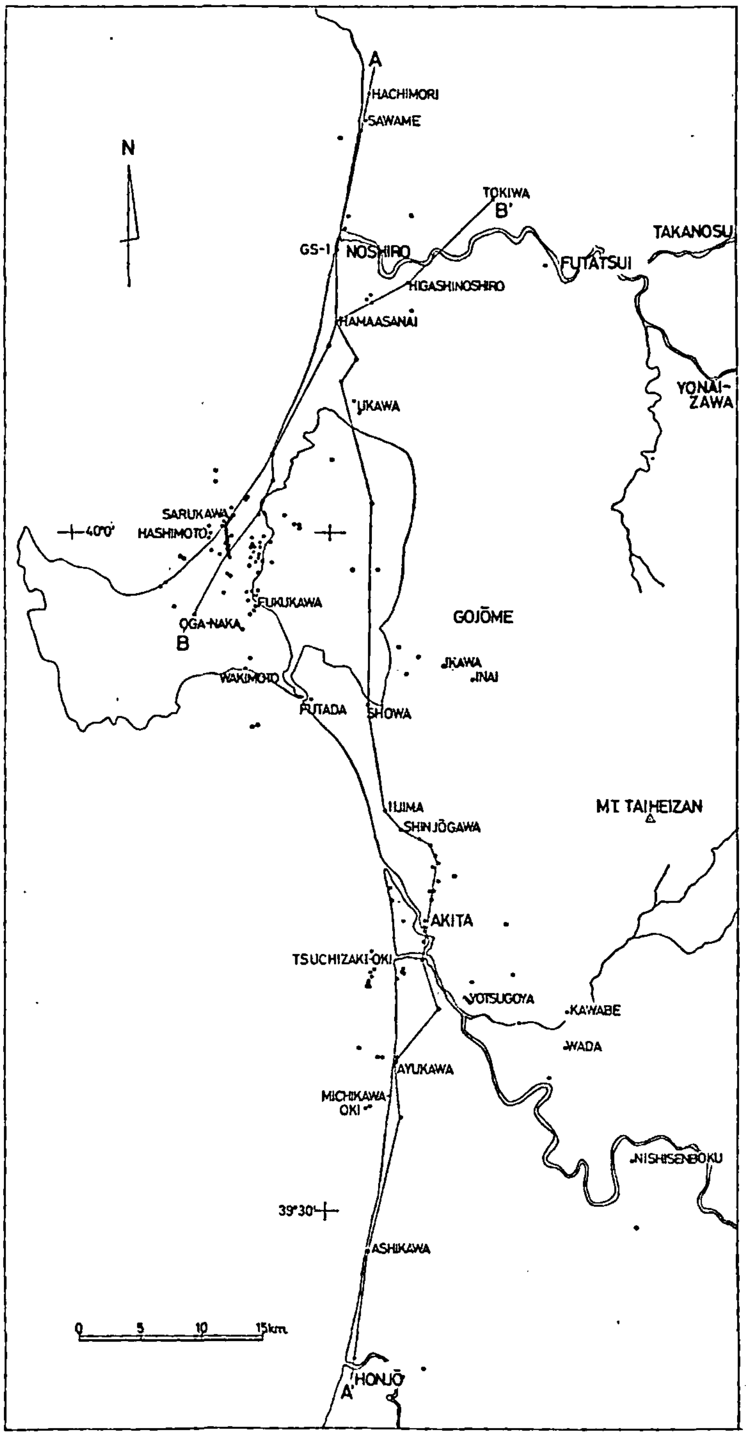
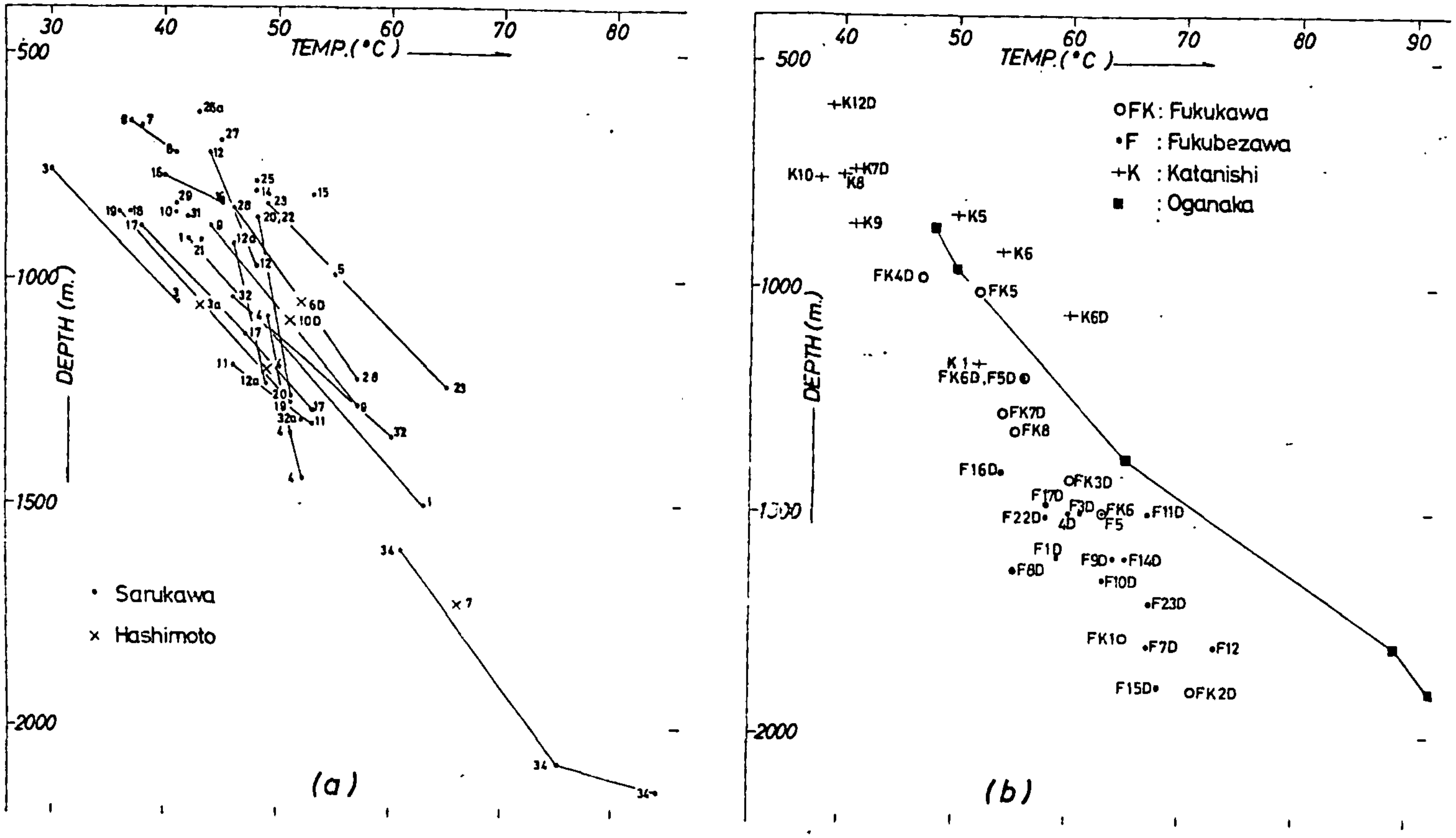
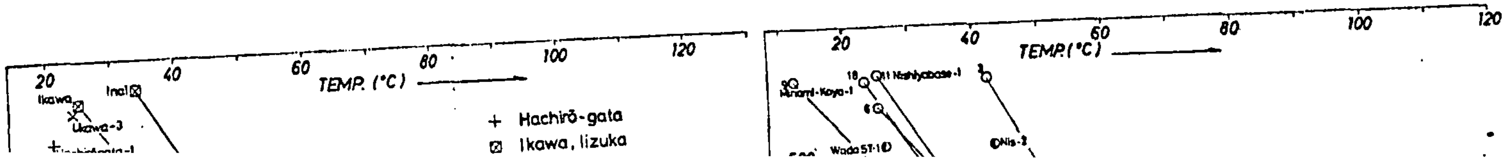


Fig. 4. Location of wells used in the present study in the coastal region of Akita Prefecture.


TEMP.(°C)
DEPTH (m.)
500
1000
1500
2000
30
40
50
60
70
80
90
• Sarukawa
× Hashimoto
(a)
○FK : Fukukawa
•F : Fukubezawa
+K : Katanishi
■ : Oganaka
(b)


TEMP. (°C)
20
40
60
80
100
120
+ Hachirō-gata
⊠ Ikawa, Iizuka
Ikawa
Inai
Ukawa-3
Minami-Koya-1
Hashiyabase-1
Wada ST-1D
Nis-3

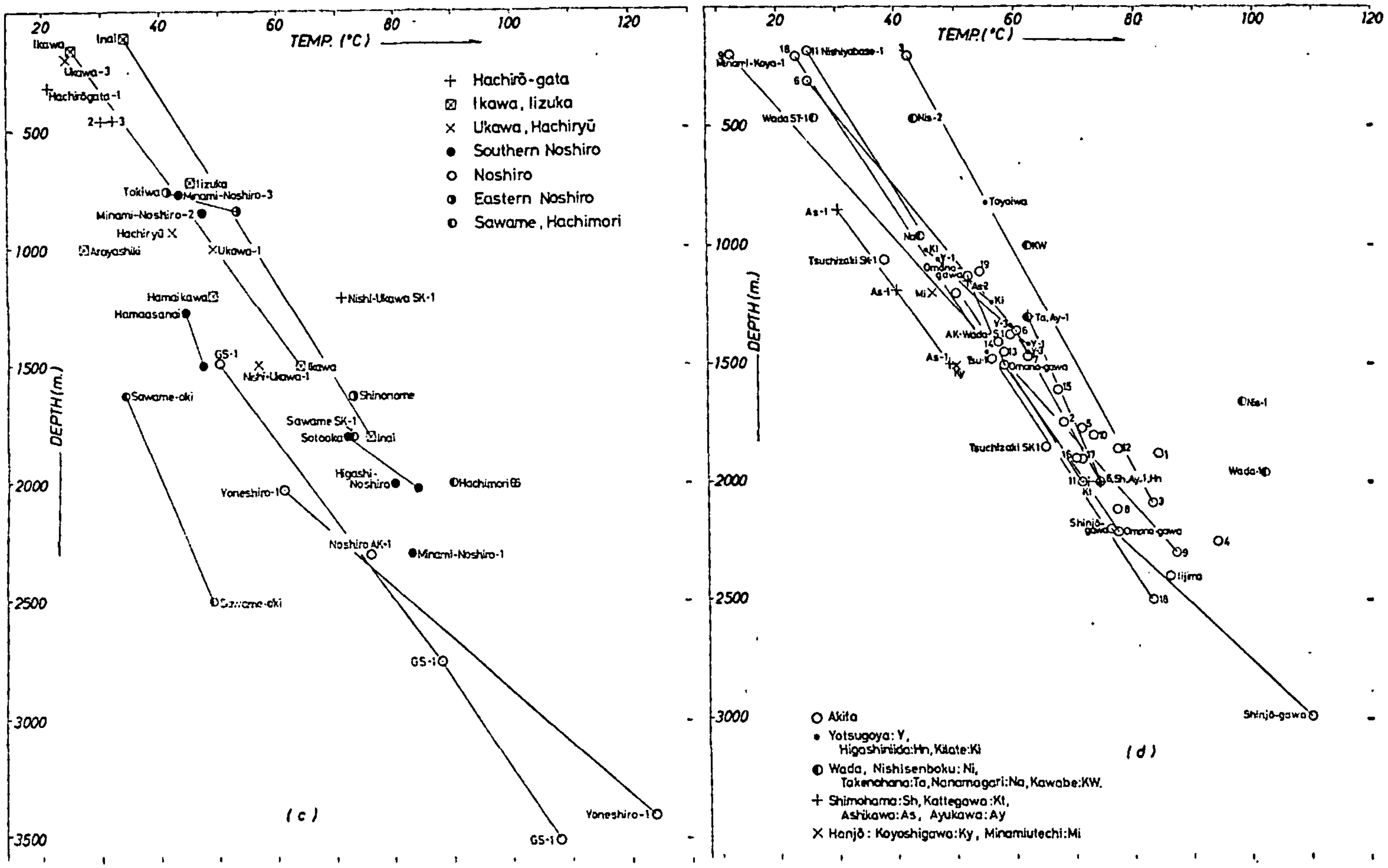


Fig. 5. Bottom hole temperatures of wells in several areas of the coastal region of Akita Prefecture, a; Sarukawa oil filed, b; Katanishi, Fukubezawa and Fukukawa oil fields, and Oga-naka, central part of Oga Peninsula, c; surroundings of Hachirô-gata and Noshiro City, d; Akita City and its surroundings.

sedimentary basins, called Noshiro, Akita and Wada basin. Geology and geological developments of these sedimentary basins were fully discussed by IKEBE (1962).

In the oil fields and surroundings, many boreholes were drilled and most of them were surveyed by means of electro-logging. The bottom hole temperatures at a few depths of a well were also measured in order to correct the electro-logging data. These bottom hole temperatures were selected from two hundreds wells and used for this study. The sites of these wells are shown in Fig. 4, but, there were so many wells at oil fields such as Sarukawa, Fukubezawa, et al., that only representative ones were plotted in the figure. Fig. 5a, b, c, d show the bottom hole temperatures in several areas. In some wells, two or more temperatures had been measured at different depths of a well, and the values corresponding to the same well, in Fig. 5, were connected each other by a straight line.

Fig. 6 and 7 are subsurface isothermal contour map, based upon the bottom hole temperatures of wells arranged on the A-A' and B-B' lines (see Fig. 4) crossing at Hama-Asanai, north of the Hachirō-gata Lagoon. In the section A-A' (Fig. 6), the contours exhibit a southwards slope in the range from Hachimori (northern end of this section) to Hama-Asanai, and they show rugged shapes at neighbourhood of Akita City. There are some ambiguities in this section at underground of Hachirō-gata, because no fine data were obtained there. Infering from the data of the surroundings of Hachirō-gata, however, the isothermal contours under there may be situated at slightly greater depths than Akita area. In Fig. 7, B-B' section, isothermal contours are deep in Momokawa and Hama-Asanai, and shallow in Oga-naka (western end of the section), Katanishi oil field and Tokiwa (the northeastern end of the section).

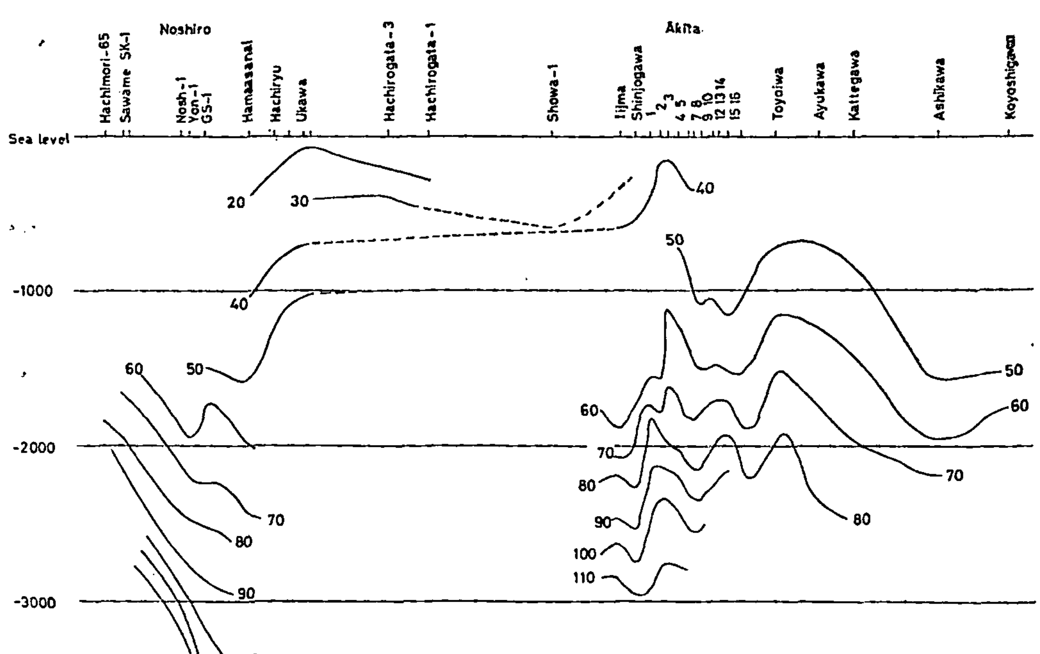


Fig. 6. Subsurface isothermal line in A-A' section.

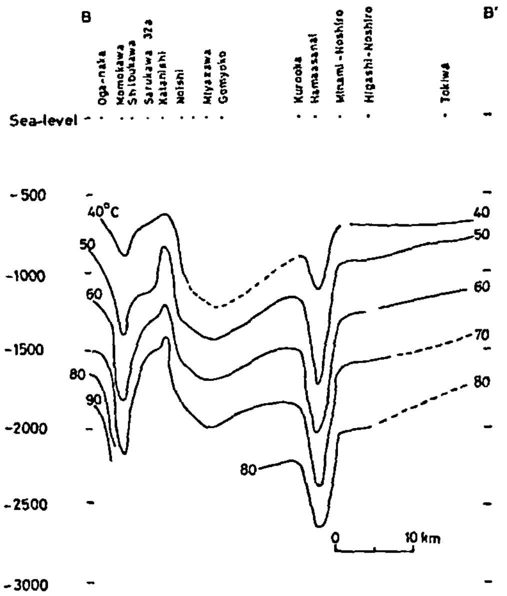


Fig. 7. Subsurface isothermal line in B-B' section.

As previous mentioned, the distribution of well was dense at oil field and the thermal gradient calculated from respective well or near wells at a field were not always the same with each other. To estimate a general geothermal gradient, therefore, an average value was determined by the least square method from a group of temperatures at various depths. In this case, the group of temperatures was set up from the wells which were distributed in the limited circle domain. The limited circle domain was selected relatively to the density of wells' distribution. In the area, concentrated with well, the radius of the circle domain was 1 km., while in area, sparsely dotted with well, it was 5 km to 10 km, and the average geothermal gradient, obtained in each domain, was defined as the geothermal gradient at the central point of the concerned domain. As an example of this procedure, the case in Sarukawa oil field is shown in Fig. 8, where the domains have the radius of 1 km. These gradients deduced from the above method are listed and illustrated in Fig. 9, together with several gradients of the inland region. As seen evidently from the Fig. 9, the geothermal gradients are in the range of 2.0 to 2.5°C/100 m for most oil fields, excepted Katanishi and Fukubezawa oil field where the gradients are 4.1 and 3.2°C/100 m, respectively.

According to the data listed above and all others, an isothermal gradient contour map are described in Fig. 10. It is obvious from the figure that a low gradient anomaly lies at Akita off shore and it extends towards Hachirô-gata. In general, the thermal gradeint increases with the eastwards distance from the coast, but isothermal gradient lines are not always parallel to the coastal line as seen in Noshiro area. The northern part of Noshiro shows a higher gradient as if there were some high geothermal anomaly in the north distance. A local high anomaly is seen at Oga Peninsula and the center of anomaly may be lied near Kitaura. The isothermal gradient contours exhibit some irregularities due to local anomalies. The remarkable local anomaly at the neck of Oga Peninsula corresponds well to oil fields such as Katanishi and Fukubezawa.

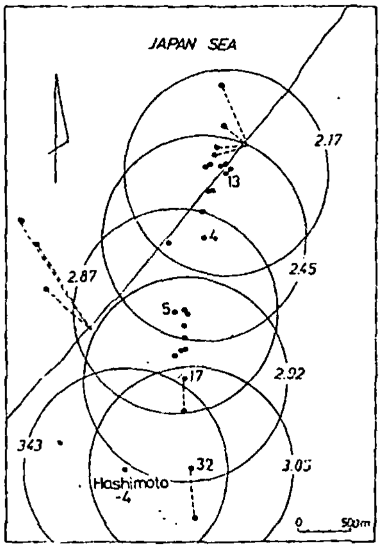


Fig. 8. Distribution of wells (black dot) and the circle domain for determining the average geothermal gradient in Sarukawa oil field. Numeral on each circle shows calculated gradient (°C/100 m) in each domain.

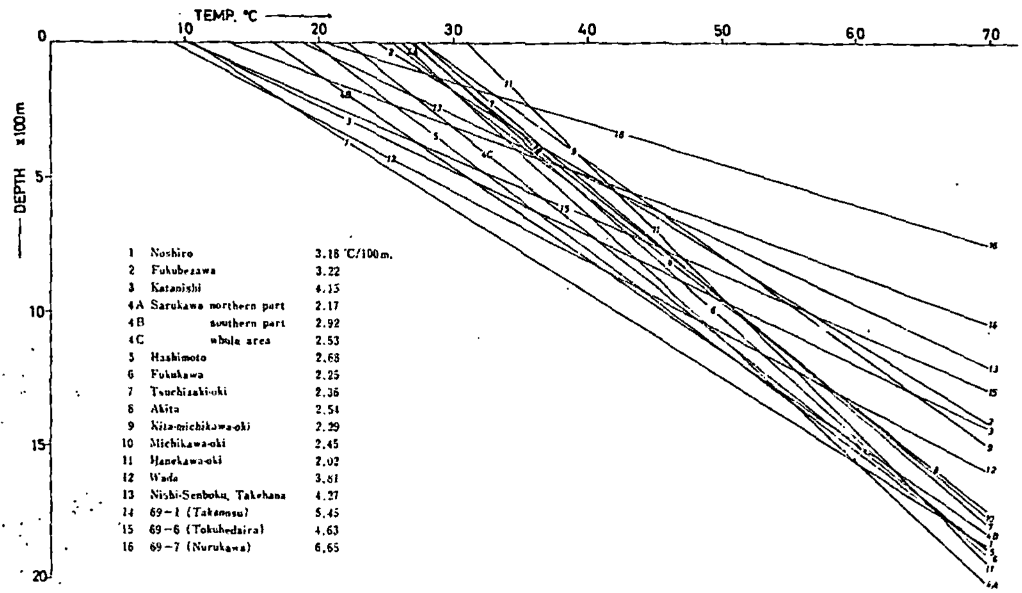


Fig. 9. Geothermal gradient for defferent oil fields and other representative areas.

CONSIDERATIONS

Based upon the above mentioned geothermal gradient and published geological data, we attempt to discuss on a few close relations among them.

The geology of the inland region, as mentioned previously, was studied by Ueda (1965) and Hashiguchi, et. al. (1966), and their geological maps are shown in Fig. 11 and 12, where the area is limited to the part concerned with present study.

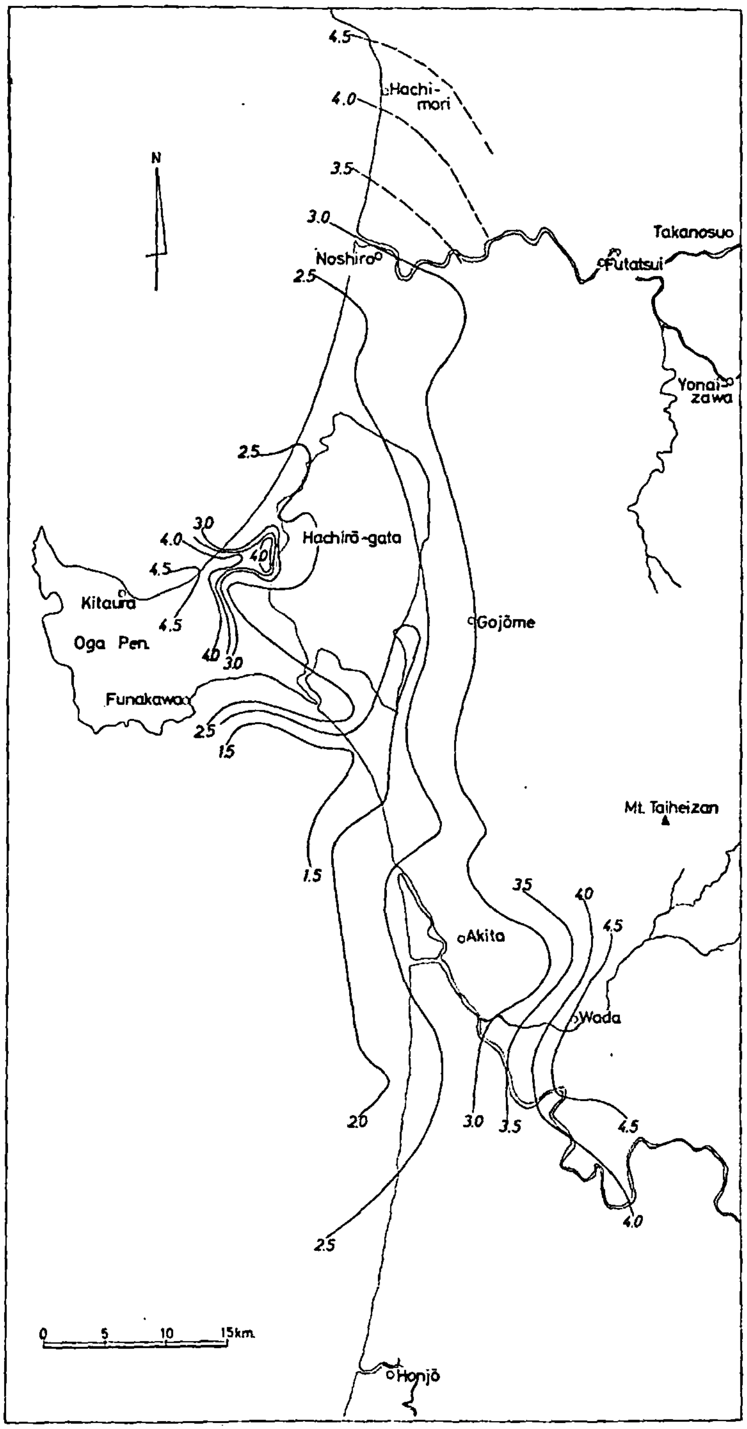


Fig. 10. Isothermal gradient (°C/100 m.) contour map in the coastal region of Akita Prefecture.

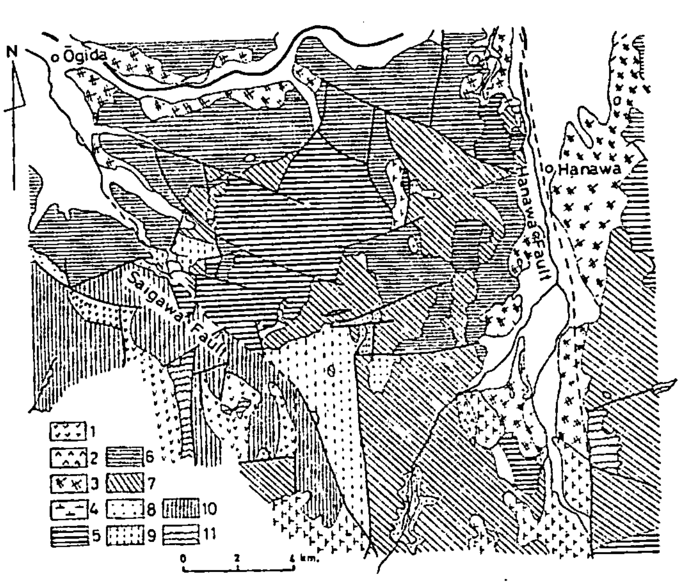


Fig. 11. Geological map of the inland region of the northeastern Akita Prefecture (after UEDA, 1965). 1; holocrystalline rocks, 2; dolerite, 3–10 shows Cenzoic sediments in descending order; 3; volcanic detritus of Towada caldera, 4; Kashinai, 5; Tobe, 6; Ōtaki, 7; Ōkuzu, 8; Sunakobuchi, 9; Senosawa, which is marine equivalent, 10; Ōya formation, a terrestrial equivalent of the Senosawa formation, and 11; Palaeozoic strata.

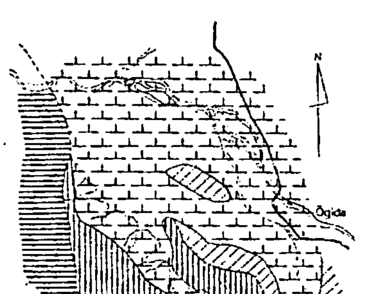


Fig. 12. Geological map of the southern part of Ōdate basin (after HASHIGUCHI, et al., 1966, simplified). 1; Ittôri, 2; Ōtaki, 3; Ōkuzu and 4; Ôya formation in descending order.

Characteristic features appeared in the isothermal gradient contour map of the inland region (Fig. 2) are as follows; in the northern half of the region, each contour have NE-SW trend, and the lowest gradient zone with the same trend is found as if it were a valley: on the other hand, in the southern half, each contour line bends to NW-SE direction.

In the northern half of the region, we do not found any relationships between the geological events and the features in geothermal gradient. But, in the southern half,

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there is a correspondence between two phenomena. In the area, the trend of the gradient contour line corresponds with the trend of the major fault, called "Sai-gawa fault" by UEDA (1965, see Fig. 11). In the paper, UEDA described about this fault as well as about others with the same feature that, "These faults with N-S trend are the same as the intermittent faulting of BILLINGS, which are resulted from the geostructural movements in a long period of time. . . ." and then "these faults may be related to the change of lithofacies of sediments, producing an upheaval area in some stage and the differentiations of sedimentary basins."

As the evidential phenomena for his consideration on the fault, he pointed out that in the southwestern side of the fault, which has NNW-SSE trend, the Ōya formation accompanied with terrestrial sediments (early Miocene) is widely developed, on the contrary, in the northeastern side, the Senosawa formation which deposited in marine condition in the same age are distributed. As a farther fact to justify his argument, he pointed out that the Tobe formation, late Miocene in age, is developed mainly in northeastern side, but, it becomes thin abruptly in another side.

The northwestern extension of the Sai-gawa fault is found in the southwestern part of Ōdate basin, and it has a trend of NNW-SSE to NW-SE (HASHIGUCHI, et al., 1966, see Fig. 12). The fault had played important roles in differentiation of sedimentary basins and tectonic developments during Miocene Epoch as same as the Sai-gawa fault.

Furthermore, active geothermal areas of the northern foot of Hachiman-tai volcanoes are located at the southern extension of the Sai-gawa fault.

From a considerable coincidence of geological and geothermal phenomena, some relations may have been existed between the geothermal gradient and the geostructural movements, occurring all through the geological time. The same relations are recognized in the coastal region, as described later.

As same as the Sai-gawa fault, the Hanawa fault (INOUE, et al., 1965) in the Hanawa basin (Fig. 11) had contributed to form the frameworks of geological structure and to differentiate of sedimentary basin during Miocene epoch. However, no anomalies can be recognized along the Hanawa fault, it may be due to insufficient numbers of measurement point.

The characteristic features in the isothermal gradient contour map of the coastal region were described in previous section.

Comparing the geothermal data with the geological ones, it was found on the whole that the pattern of the geothermal contour map resembles to the isopach map of the Shibikawa formation (Pliocene) (Fig. 13) and to the contour map of the depth of erosion surface of the Tertiary rocks after KANO (1968). Speaking broadly, the thermal gradient tends to low in the areas where the younger sediments (the Shibikawa and Katanishi formation) are developed thickly, while it becomes high in the marginal areas of the sedimentary basin, consisted of the younger sediments. This suggests that some relations exist between the characteristics, and the thickness of the younger sediments and the geothermal gradient. We considered the relation among them as the results of that the younger sediments contain relatively a large amount connate water than older ones, and the mobility of water in younger sediments is also greater than that in older, so these two originate a low thermal gradient in younger sediments.

The lump-like shaped high anomaly at the west side of Hachirō-gata corresponds to the sinking area in the late Miocene to Pliocene, after IKEBE (1962). And, in the late Pliocene (the Shibikawa formation) to Pleistocene (the Katanishi formation), the east side of the area subsided, and the west was uplifted. From the above evidence, it was

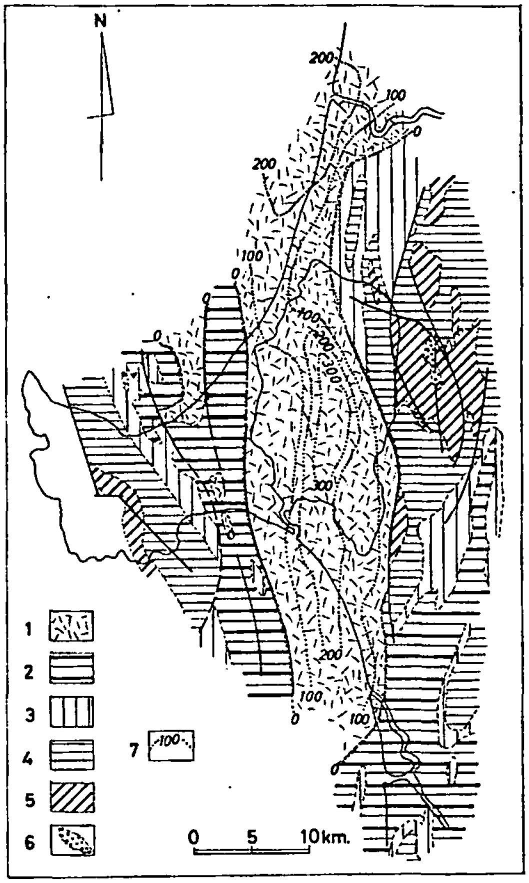

Fig. 13. Geological map at the erosion surface of the Neogene sediments and the isopach map of the Shibikawa formation (after Kanō, 1968, partially modified).
1; Shibikawa, 2; Wakimoto, 3; Kitaura, 4; Funakawa, 5; Onnagawa, 6; Nishikurosawa formation in descending order. 7; isopach contour line of the Shibikawa formation (thickness in meter).

deduced that the tectonic line which has the same characteristics as the Sai-gawa fault in the inland region had been existing in this zone, and the geothermal anomaly may be caused by a origin related with the geological movement.

As is generally known, the Neogene sediments in the "Green Tuff Region" are altered to green rocks, having the mineral assemblages of the prehnite-pumpellyite and zeolite facies, by the hydrothermal alterations and burial metamorphism.

Degree of the geothermal gradient may be an important factor to control these alteration process. We have been interested in these processes, however, we have not sufficient data to discuss thoroughly the problems at present.

Huzioka et al., (1969) studied on the zeolite alteration of vitric tuffs in the Neogene oil bearing formation in Akita oil field, and distinguished them into two types of zeolitization such as upheaval and depression type, by a connecting with the geological developments in the region. Between the depth of the appearance of analcime, based upon their

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study, and the geothermal gradient, estimated in our study for several boreholes, following relations are found;

Boreholes	Depth of the appearance of analcime (m)	Thermal gradient (°C/100m)
Minami-Kōya R-1	1450	2.9
Nishi-Yabase R-1	1760	2.5
Shinjō-gawa AK-1	1800	2.5
Higashi-Wakimoto SK-1	2100	2.7
Higashi-Noshiro R-1	1810	2.8

Limiting to the narrow area where includes only Minami-Kōya R-1, Nishi-Yabase R-1 and Shinjō-gawa AK-1, some significant relations may be seen among them, but over the whole area, no reasonable one can be found. There are so many factors which have the influence to rock alteration, such as tectonic movement, physical and chemical properties of rock and connate water, and etc., that it is unable to be considered from present data that the geothermal gradient as a most predominant factor for the rock alteration in this field.

On the other hand, the distribution of the geothermal gradient, on the whole, fully corresponds to the Bouger anomaly distribution (Ikebe, 1962) in the coastal region of Akita Prefecture. From this, it may be confirmed that the geothermal gradient is closely relating with geological structure and characteristics of sediments, as mentioned before.

SUMMARY

In this preliminary report, authors described on the geothermal gradient, measured in the boreholes for a prospecting of the ore, oil and gas in the inland and the coastal region of Akita Prefecture, and pointed out that the geothermal gradient is reflecting the large scale geological structures which were acting intermittently during long geological time and affected the differentiation of sedimentary basins and changes of lithofacies. From the present data, we can not discuss on the mechanism of the heat generation and loss along the main local tectonic line. Also, the effect of geothermal gradient to the alteration in the Neogene sediments can not be explained from the present data.

In the future, we intend to increase the observation point for many boreholes in systematically, and to measure thermal conductivity of various rocks. Then, we shall be able to know on the local geothermal structure in detail, and to thoroughly discuss the relations with geological events.

In concluding, authors wish to express their thanks to Mitsubishi Metal Mining Co. Ltd., Dōwa Mining Co. Ltd., Nippon Mining Co. Ltd. and Mining Division of Akita Prefecture office for giving the chance to measure the temperature in boreholes. We also wish to thank Japan Petroleum Exploration Co. Ltd. and Teikoku Oil Co. Ltd. for their grant admission to use the bottom hole temperatures of many wells. The authors are deeply indebted to Dr. Y. Ōki, Mr. M. Moriya and other members of the Hot Spring Research Institute of Kanagawa Prefecture for their considerable assistance in the setting up the thermistor thermometer, used in this study. The present study has been partly supported by a Grant-in-Aid for Scientific Research from the Ministry of Education.

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Fumarolic hot lakes on Hokkaido: geochemical mineralogical and biochemical investigations of their significance for the formation of massive sulfide-deposits

By

A. Wauschkuhn (Heidelberg), W. Schwartz (Braunschweig-Stöckheim)
G. C. Amstutz (Heidelberg) and K. Yagi (Sapporo)

With 14 figures and 6 tables in the text

Wauschkuhn, A., Schwartz, W., Amstutz, G. C. & K. Yagi: Fumarolic hot lakes on Hokkaido: geochemical, mineralogical and biochemical investigations of their significance for the formation of massive sulfide-deposits. – N. Jb. Miner. Abh. 129, 171–200, Stuttgart 1977.

Abstract: In fumarolic hot lakes of the Nasu volcanic zone of Hokkaido, N-Japan, present-day formation of massive and disseminated sulfur and sulfide deposition takes place. Four of these lakes were investigated geochemically, mineralogically and bacteriologically. A classification of sulfur/sulfide formation according to physico-chemical and ecological parameters is given. In all four lakes microorganisms start or even accelerate and carry through, geochemical processes which, in organic systems, with identical Eh–pH and P–T conditions, would not take place or only at a very slow rate leading at the most to trace amounts of sulfur or sulfides in lake sediments.

The geochemical and microbiological processes taking place in the lakes are described in order to elucidate the possible beginning of exhalative-sedimentary ore forming processes. Indentical or similar processes are most likely responsible for the formation of most massive sulfide deposits of volcanic parentage.

Key words: Fumarole, lake, temperature (50–130 °C), sulphur, pyrite, marcasite, Eh, pH, geochemical process, biochemical process, genesis of deposit (massive sulfide deposit), chemical analysis; Hokkaido (Nasu Zone).

Auszug: In der vulkanischen Nasu-Zone auf Hokkaido sind rezente Schwefel- und Sulfidbildungen in heißen, von Fumarolen und Oberflächenwässern gespeisten Seen zu beobachten. Vier dieser Seen und ihre Umgebung wurden geochemisch, mineralogisch und bakteriologisch untersucht. Entsprechend den im Wasser der Seen herrschenden physiko-chemischen und ökologischen Bedingungen sind verschiedene Formen von Schwefel- und Sulfid-Ablagerungen in den Seen zu unterscheiden.

Für die untersuchten Seen zeigt sich, daß Mikroorganismen geochemische Prozesse sowohl einleiten als auch beschleunigen und biochemisch durchführen, die unter den gegebenen geochemischen Bedingungen von Druck und Temperatur nicht oder nur mit einem hohen Zeitfaktor möglich sind.

Die in den Seen ablaufenden geochemischen und mikrobiellen Prozesse werden aufgezeigt, um so Aufklärung über die Anfänge der Bildung exhalativ-sedimentärer Lagerstätten zu erhalten. Letztere bilden wohl einen großen Teil der heute allgemein als „massive sulfide deposits" bezeichneten, weitverbreiteten Lagerstätten.

The Problem

The massive sulphide deposits represent one of the most important type of deposits both, from an economic and a geologic point of view. Probably more than half of these wide spread deposits are linked to volcanic rocks. Except in a few cases or a few portions this link may be termed congruent, stratigraphically as well as paleogeographically. Geochemical congruencies were also observed in many localities, indicating thus a genetic link between wall rock and ore minerals.

The confirmation of the genetic role of congruence and the explanation of the details of the mode of formation of massive sulfide deposits results on the whole only from studies of recent processes of formation still going on. (An actualistic principle is certainly applicable in this case.)

Compared with recent volcanic deposits of oxides and hydroxides, those of sulfides are apparently more rarely found. In recent years, the work of BERNAUER (1933, 35, 39) has been continued (so to say) by the studies of HONNOREZ (1969), HONNOREZ, HONNOREZ-GUERSTEIN, VALETTE & WAUSCHKUHN (1973), and WAUSCHKUHN & GRÖPPER (1975). BROWNE (1971) investigated the ore mineral content of the volcanic zone of Taupo, New Zealand. OZEROVA et al. (1971) described the formation of sulfides in volcanic hot lakes on Kamchatka and the Curiles. Similar volcanic lakes are known on Hokkaido, Japan (WAUSCHKUHN, 1973, 1974). The present paper attempts to demonstrate the formation of massive exhalative volcanic sedimentary sulfide deposits on the basis of observation made on four lakes on Hokkaido. These observations include geochemical, mineralogical, and biochemical investigations on the waters and the sediments. The authors realize that their studies deal only with the first phase of formation of ore deposits, i.e., the transport and deposition of material. The second phase is diagenesis and this had to be left essentially to a later investigation.

1. The geologic framework

The Japanese islands belong to the circumpacific volcanic arcs and are traversed by various volcanic belts active since Miocene time. On Hokkaido, the northernmost island of Japan, two such volcanic arcs are still active at present:

a) the Kurile-zone, originating in the Kurile-islands; and
b) the Nasu-zone, extending from Honshu to Sachalin, crossing over South-Hokkaido.

The rocks of the Kurile-zone consist essentially of pyroxene-andesites, whereas those of the Nasu-zone contain in addition also pyroxene-dacites

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(MURAKOSHI & HASHIMOTO, 19
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(MURAKOSHI & HASHIMOTO, 1956, p. 108). The volcanic rocks of the Nasu-zone were formed as submarine units in Miocene time and propylitized by the ocean water. The ensuing green color gave large areas of North-Honshu and Hokkaido the name "Green Tuff Region" (ISHIHARA, 1974).

Parts of the Nasu-zone emerged from the ocean since Pliocene time and the present shape of the Japanese islands formed essentially at the transition from Tertiary to Quaternary times. In connection with the volcanism various submarine and subaerial deposits of Fe-sulfide, sulfur and limonite formed. The formation of similar deposits can be observed also today at or near active volcanoes, for example the formation of recent sulfide deposits in connection with fumarolic activities in lakes. In most of these lakes sulfides occur associated with native sulfur. At the same time masses of native sulfur occur on the slopes or crests of the volcanoes as sublimates of fumarolic gases. At the bottom of volcanoes recent limonite deposits are found in source water basins.

In Northern Japan the Kuroko-deposits occur within the Green Tuff Region. It appears logical to assume that these deposits formed from volcanic and postvolcanic activities, as presently observed in the Nasu-zone. Consequently, the investigation of four volcanic lakes heated by fumarolic activity may provide some clues as to the mode of formation of this young massive exhalative-sedimentary type of ore deposits.

2. The lakes in the volcanic area of Niseko

2.1 The volcanologic situation

Two of the lakes under discussion are the lower and the upper Yumoto lakes. They are located in the Niseko volcanic area which lies at the southwestern end of the Shakotan-Peninsula of West Hokkaido and belongs to the Green Tuff Region (Fig. 1). After the submarine deposition of the green tuffs during early Miocene the volcanic activity set in again during Pleistocene time, (after a period of relative calmness during Pliocene time), with repeated eruptions of andesitic lava and intercalations of tuffaceous breccia in the subaerial parts. According to HIROKAWA & MURAYAMA (1955) the five youngest volcanoes (Mekunnai, Shagnagi-yama, Chisenupuri, Iwaonupuri and Nisekoannupuri) are sitting on an East-West fault zone.

On the flanks of these volcanoes postvolcanic processes are observed. South of the lava dome of Chisenupuri are located the two lakes with fumaroles with a distance of only 600 m between the lakes. The gases of the fumaroles are noticed already at considerable distance because of the H_2S-content. The fumaroles rise on a fault between the older tuff breccia of Shakunagi-yama and the younger Yumoto-lava. They enter to a good part into the lakes and change the chemical composition of the water and of the sediments. The fumarole gases increase the alteration and weathering of the neighbouring wall rock. Its fast decomposition is also due to the high

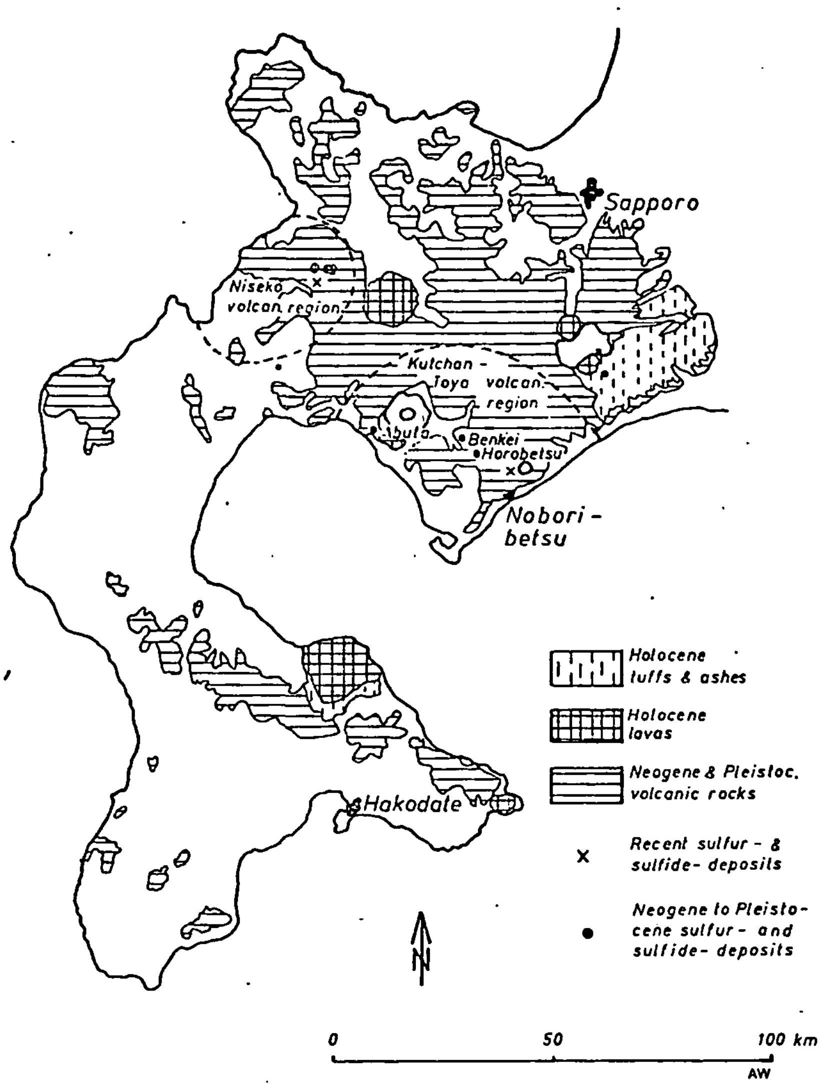

Fig. 1. The distribution of volcanic rocks in the Nasu-zone of South-Hokkaido (modified after Saito et al., 1967).

temperatures of the fumaroles, in addition to the surface weathering agents which include biological factors. The temperatures measured in the fumaroles at the lake shore rise up to 70 °C. The H_2S of the fumarole gases is oxidized to sulfuric acid with the aid of microorganisms. This acid in turn attacks the country rock and produces deep weathering. Most of the weathering products are transported into the lakes. Reddishbrown precipitates of iron hydroxide which are seen in many streamlets or water gullies, indicate

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Table 1. Temperature, pH- and

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2.2 The lakes and thei

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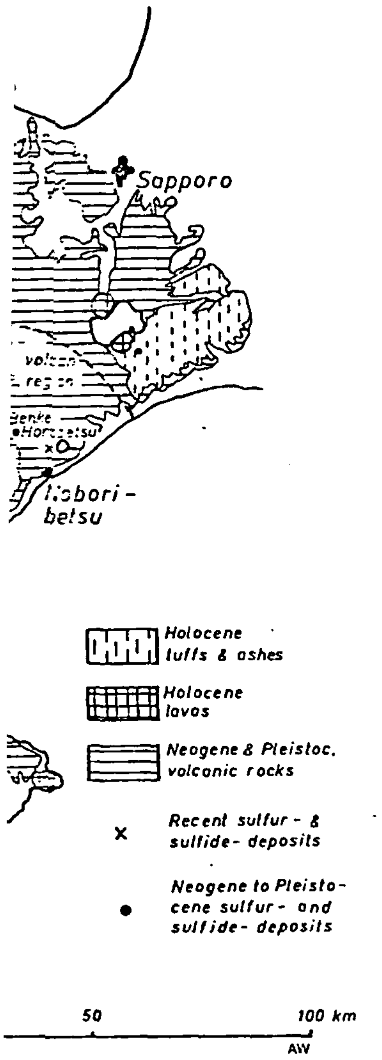

ı the Nasu-zone of South-Hokkaido

Table 1. Temperature, pH- and Eh-values of the water from the different lakes.

	depth (m)	T °C	pH (1971)	pH (1973)	Eh (mV)
upper Yumoto lake	0	42	4.9	4.6	+
lower Yumoto lake	0	64	4.4	3.9	+
	4	67	5.1		
	8	71	4.3		
Ojunuma lake	0–14	49.5	2.2–2.6	2.6–3.1	+50 – +105
	15	53.5	2.3	3.0	–40
	16	90.0	2.3	3.0	–95
	18	120.5	2.5	3.0	–100
	20	122.0	2.4	3.0	–150
	25	131.5			
Okunoju lake	0	80.0	5.6	4.8	–200
	2	81.5		5.4	–250
	3	82.0	4.7		
	4	104	4.8		
	5	111	4.6		

a to the surface weathering agents aperatures measured in the fuma- The H_2S of the fumarole gases is microorganisms. This acid in turn p weathering. Most of the weather- kes. Reddishbrown precipitates of treamlets or water gullies, indicate a transport of iron into the lakes. The water and the sediments of the lakes are thus not only changed by the fumaroles in the lakes, but also by the weathering solution containing sulfuric acid. The area surrounding both lakes is heavily vegetated so that the streamlets not only bring in weathering products of the rock but also large quantities of organic compounds and micro-organisms.

2.2 The lakes and their sediments

For technical reasons the two lakes could not be sampled with a boat; consequently the water and sediment samples originate only from the shores and near shore areas.

The upper Yumoto lake is located 600 m above the lower Yumoto lake and is smaller than the latter. Its shape is elliptical and its dimensions are 45 by 20 m, with an estimated depth of about 4 m. At the northern tip a streamlet enters and water vapor from the fumaroles condensates and also feeds the lake. Its water is milky-white. At four places the lake bubbles or effervesces, which indicates four strong fumaroles at the lake bottom. At the surface, a water temperature of 48 °C was measured and a pH-value of 4.9 (Table 1). As indicated in Table 2, the water contains the abnormally high amount of 140 ppm of SO_4.

The overflow of this lake enters the lower Yumoto-lake. The pH-value of the overflow lies here as in other lakes between 4 and 5 or even below and rises with increasing distance from the lake to values between 6 and 7. In many places iron hydroxide is precipitated.

The lower Yumoto lake has an average diameter of 60 m and an estimated depth of 9 m at the most. In the middle of the lake about 10

Table 2. Ions solved in the water of the volcanic lakes (ppm) (Cl measured titrimetrically, SO_4 gravimetrically, Fe and As colorimetrically, and the remaining elements by AAS).

	depth	Cl	SO_4	Na	K	Ca	Mg	Fe	Mn	Zn	As
upper Yumoto lake	0 m	7.6	140	7.3	2.5	15	4	tr	0.2	tr	tr
lower Yumoto lake	0 m	8.9	140	6.8	2.0	15	4	tr	0.2	tr	tr
	4 m	8.2	1850	11	4.8	20	10	25	0.6	0.2	tr
Okunoju lake	0 m	131	456	47	13	20	3	1	0.2	0.1	0.2
	3 m	131	740	54	15	70	31	8	2.0	0.5	tr
	4 m	138	770	54	17	60	23	27	1.6	1.0	tr
	5 m	157	493	64	15	20	3	32	0.3	0.2	0.3
in the upper water-layer of Ojunuma lake	0 m	120	600	66	13	60	8	13	0.5	0.1	0.1
	5 m	120	800	64	13	60	7	13	0.5	0.1	0.2
	10 m	120	725	68	15	50	8	13	0.5	0.1	0.2
	14 m	120	900	66	12	50	8	16	0.5	0.1	0.3
above the fumarole-funnel of Ojunuma lake	0 m	120	600	64	12	50	7	11	0.5	0.1	0.1
	5 m	120	792	67	13	50	8	11	0.5	0.1	0.2
	10 m	127	1150	66	13	50	7	13	0.5	0.2	0.5
	15 m	120	1430	66	12	50	7	31	0.5	0.2	1.0
	17 m	131	1680	70	15	50	8	17	0.5	0.1	0.5
	20 m	304	1930	129	26	145	24	290	1.2	1.1	0.1

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in the upper water-layer of Ojunuma lake	0 m	120	600	66	13	60	8	13	[illegible]	[illegible]	[illegible]
	5 m	120	800	64	13	60	7	13	0.5	0.1	0.2
	10 m	120	725	68	15	50	8	13	0.5	0.1	0.2
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	10 m	127	1150	66	13	50	7	13	0.5	0.2	0.5
	15 m	120	1430	66	12	50	7	31	0.5	0.2	1.0
	17 m	131	1680	70	15	50	8	17	0.5	0.1	0.5
	20 m	304	1930	129	26	145	24	290	1.2	1.1	0.1

fumaroles enter the water and cause the water to look boiling. The temperatures, however, are only 71 °C at the bottom and 64 °C at the surface. The pH values from bottom to top vary between 4.5 and 5. This lake is fed by three tributaries, one of which brings the water down from the upper Yumoto lake. The two others carry normal surface waters from the hills. Here too the fumaroles probably contribute to the influx of water. The color of the water corresponds to that of the upper lake, but a difference consists of the sulfur balls floating on the surface of the Lower lake and accumulating on the shore. The ionic composition of the water on the surfaces of the two lakes is almost identical. The concentration increases considerably towards the depth especially regarding the content in SO_4 and Fe.

The sediments of both lakes consist mainly of allothigenic quartz, authigenic native S and a clay fraction from the weathering products of the country rocks. Fe-sulfides give the mud a grey to dark grey color. In addition smaller quantities of authigenous Fe-oxides and opal are found. Quartz stems from the andesitic lavas and tuffaceous breccias from the surrounding areas. S is formed from oxidation of the H_2S of the fumarole gases and occurs in the lakes in two forms, a) in a mud which is colored gray by Fe-sulfide contents, and b) as pure yellow ball-shaped concretions up to 1 cm in diameter, which are found only in the immediate vicinity of the fumaroles. These variable forms of S are caused by three factors, 1) the variable degrees of agglomeration (which in the case of the grey mud is practically nil, probably due to the separation properties of clay or other particles), 2) the time factor available for crystal growth of S crystals, and 3) the stepwise oxidation of H_2S after its exit into the lake water; a part of the H_2S is oxidized immediately after it comes out of the fumarole opening. Here, the pure S-ooids (which were found by the third author in 1970 upon which this project was started) are formed by the violent motion of the water. These S-spheres which often form around quartz grains or around organic remains, perform a circular movement in the fumarole stream and grow at the same time. Finally the more massive balls fall on the ground of the lakes around the openings of the fumaroles, while the lighter ones which often display holes in the middle, are drifted on the shore (Fig 2).

If shallow water surround fumarole openings, enough O is present to permit a strong microbiological oxidation of H_2S which also leads to an accumulation of S-ooids. The remaining H_2S either escapes into the air or is finely dispersed into the water where it will also oxidize. As mentioned above, it will mix with suspended particles brought in by the tributaries of the lakes and is then precipitated as a sediment together with Fe-sulfides formed from H_2S in the lakes.

In the sediments of both lakes the following elements were detected by spectral analysis: As, Co, Cu, Cr, Mg, Mn, Mo, Ni, Pb, Sb, Si, Sn, Ti, V and Zn. Six quantitative analyses for Cu, Zn, Pb, Co, Ni, Mn, Sb, Cr,

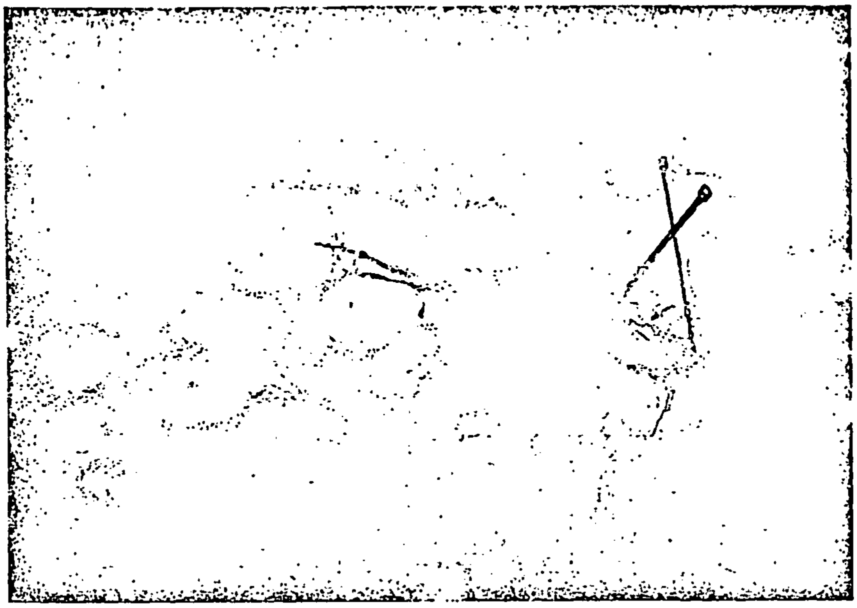

Fig. 2. Fumaroles in the lower Yumoto-lake. The mouths of the fumaroles are surrounded by pure S-ooids, and the sediment consist of gray sulfur-sulfide-mud. Scale given by the grab-instrument (base measures approx. 25 × 15 cm).

As, Fe and native S of sediment samples taken at a depth of 0, 2, 3, 4, 6 and 8 m respectively in the lower Yumoto lake yielded similar values excepting Fe and S. The values for these two elements increase with increasing water depth.

3. The lakes near Noboribetsu-Onsen

3.1 The volcanic setting

The two other hot volcanic lakes are located in the Kutchan-Toya volcanic district which, likewise, forms part of the "Green-Tuff-Region". The lakes lie 800 m north of Noboribetsu-Onsen, a suburb of Noboribetsu (Fig. 1) which is located 6 km to the north. Here, also, following the formation of the "green Tuffs" during the early Miocene, again active volcanism took place during the Pleistocene with the appearance of andesite and dacite lavas and submarine tuff breccias; this volcanism followed a relatively quiet period during the Pliocene (Ota, 1954).

The Hiyori-Yama Dome on the west side and at the foot of the Kutara Volcanoe was squeezed out during the Holocene (Yagi & Hunahashi, 1970). According to Ishikawa (1967) an explosion crater formed at the south foot of the Hiyoriyama-Dome as a result of high steam pressure; another crater, the Jigokudani, formed 800 m to the south.

Table 3. Analyses of the native sulfur free sediments and the S-content of the sediments (S measured titrimetrically, As colorimetrically, and the remaining elements by AAS).

Cu	Zn	Pb	Co	Ni	Mn	Sb	Cr	As	Fe	S

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result of high steam pressure;
ı to the south.

Table 3. *Analyses of the native sulfur free sediments and the S-content of the sediments (S measured titrimetrically, As colorimetrically, and the remaining elements by AAS).*

		Cu ppm	Zn ppm	Pb ppm	Co ppm	Ni ppm	Mn ppm	Sb ppm	Cr ppm	As %	Fe %	S %
upper Yumoto lake	mean of 2 samples	35	40	40	35	15	180	65	35	tr.	3.33	29.2
lower Yumoto lake	mean of 6 samples	30	65	75	45	30	530	180	50	tr.	6.11	65.9
	foam from the water-surface	200	490	3390	90	270	220	160	70	0.88	9.75	82.2
Ojunuma lake	mean of 15 samples from 0–15 depth	96	136	262	75	360	140	320	45	0.38	4.4	38.7
	mean of 6 samples from 16–25 m depth	213	242	573	114	348	203	608	62	1.08	12.0	71.9
	mean of 2 samples from the consolidated layer	330	280	1255	145	115	145	660	50	2.28	24.7	52.2
Okunoju lake	mean of 6 samples from 0–5 m depth	93	138	47	48	58	635	263	152	0.11	7.9	10.1

Postvolcanic features may be observed in both craters. In the southern most crater are two hot lakes with fumaroles: Ojunuma lake and Okunoju lake. An enormous number of fumaroles have perforated the surface in the Jigokudani crater. In addition, several hot springs rise in Noboribetsu-Onsen.

This post-volcanic action – fumaroles in the hot lakes and in the Jigokudani crater as well as hot springs in Noboribetsu-Onsen – is to be acribed to the Kutara volcanism just as MUROZUMI (1976 a) had proven on the basis of geochemical comparisons. Nevertheless, differences are noted too, despite their common origin. As a result of the high H_2S content, which is partly oxidized to sulfuric acid, the Ojunuma lake water and the small pools around the exhalation vents of the fumeroles are very acidic; The pH values in the fumeroles in the Jigokudani crater lie between 1.2 and 2.4; those for the Ojunuma water lie between 2.2 and 2.6 while the pH values in the Okunoju lie between 4.6 and 5.6. The hot spring water is more or less neutral (pH values between 6.1 and 7.5) and contains only traces of sulfur (MUROZUMI, 1961 a).

The appearance of adjacent neutral hot springs and acid, H_2S and SO_4 bearing fumaroles, is ascribed to exomagmatic differentiation of the primary hydrothermal solution to a liquid Na, K, Ca, Mg, Cl bearing phase and a gaseous volatile phase with constituents such as H_2S and CO_2 (MUROZUMI, 1961 a), which reach the surface as fumaroles (Tab. 4).

Table 4. Composition of the fumarole gases near Noboribetsu-Onsen (parts most accessible) (WAUSCHKUHN, 1973).

Locality	H_2S	CO_2	O_2	rest	Remarks
Jigokudani	29*	47	6	18	water condensate included
	14	46	9	31	
	32	68	–	–	water condensate not included
Ojunuma	29	68	–	3	
Okunoju	7	68	2	23	

* $H_2S + SO_2$.

During transportation of gases to the surface, parts of the rocks are dissolved along the channelways of the fumaroles. The Hiyori-yama dacite, through which the fumaroles pass, indicates a depletion in the trace elements of Co, Cr, Ca, Fe, Mn, Ni, Pb and Zn on a comparison with unaltered dacite; the rocks are, however, enriched in As and S (Tab. 5). The transported elements mentioned above are partly concentrated in the lake sediments as a result of physico-chemical changes (t, p, pH, Eh, p_s) on reaching the lake environment. In both Ojunuma lake and Okunoju lake, recent

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organisms in the surface wate

Table 5. Content of trace elem
metrically, As colorimetrically, a

	Cu ppm	Zn ppm	Pb ppm
unaltered	9	35	23
dacite	11	32	27
altered	5	8	19
dacite	2	3	16
	4	17	16

3.2 Ojunuma lake and

Ojunuma lake is elliptical i
fumaroles perforate the surf
temperatures reach 130 °C.

The temperature of the w
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During the summer of 1971,
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Ojunumu lake obtains so
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A special boat was used f
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- b) a zone extending from a d

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near Noboribetsu-Onsen (parts most

rest	Remarks
18 31	water condensate included
– 3	water condensate not included
23	

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in As and S (Tab. 5). The trans-
tly concentrated in the lake sedi-
ges (t, p, pH, Eh, p_s) on reaching
lake and Okunoju lake, recent

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sulfur and or metal sulfides are deposited. The areas around both lakes are densely vegetated giving rise to abundant organic substances and micro-organisms in the surface waters reaching the lakes.

Table 5. Content of trace elements in the Hiyori-yama-dacite (S measured titrimetrically, As colorimetrically, and the remaining elements by AAS).

	Cu ppm	Zn ppm	Pb ppm	Co ppm	Ni ppm	Mn ppm	Sb ppm	Cr ppm	As ppm	Fe %	S %
unaltered	9	35	23	24	9	310	65	55	3	2.7	0.15
dacite	11	32	27	25	12	335	50	60	4	2.7	0.17
altered	5	8	19	6	7	33	40	16	14	1.6	3.25
dacite	2	3	16	8	9	18	40	16	7	1.2	5.06
	4	17	16	13	5	100	70	24	tr	0.5	0.88

3.2 Ojunuma lake and sediments

Ojunuma lake is elliptical in form, 200 m by 90 m in diameter. Numerous fumaroles perforate the surface along the shore and on the lake bottom; temperatures reach 130 °C.

The temperature of the water remains at a nearly constant 50 °C from the surface to a depth of 15 m; deeper, at a depth of 18 m an increase in temperature to over 120° was noted and at a depth of 25 m the bottom of the deepest part of the lake, the temperature was noted to be 131.5 °C. During the summer of 1971, the pH varied from 2.2 to 2.6. Again, in the summer of 1973, pH-measurements of the water were made which varied from 2.6 to 3.0 but the temperature of the water had remained almost constant (Tab. 1). This change in hydrogen ion concentration is traced directly to a variation in the intensity of fumarolic activity. Regionally, less fumarolic activity was observed during the summer of 1973 than during the summer of 1971.

Ojunumu lake obtains some of its waters from Okunoju lake by a connecting stream. According to MUROZUMI (1961 b), determinations of the isotope composition of hydrogen in the hot springs near Noboribetsu-Onsen indicates the presence of both juvenile and meteoric water in the fumaroles at the surface. Excess water in the lake is drained by a stream on the south side of the lake.

A special boat was used for taking the water and sediment samples and for making various measurements. Based on quantitative analyses of the water soluble substances, as well as Eh readings, two distinct zones could be determined in the lake (Tab. 1 and 2):

a) a zone extending from the surface to a depth of 15 m with a temperature of 50 °C and positive Eh readings; water soluble substances relatively uniformly distributed:
b) a zone extending from a depth of 15 m to a depth of 25 m with tempera-

ture increasing to over 100 °C with increasing depth; reducing conditions prevail; rapid increase in water soluble substances. When compared with the ionic concentrations of sulfate lakes in the United States (HUTCHINSON, 1957, p. 569), the Ojunuma lake waters contain a very high ionic concentration.

The lake sediments are comprised mainly of authigenic sulfur detrital quartz and pumice derived from the surrounding volcanic rocks. The surface of the lake carries a grayish black foam composed of sulfur; such sulfur is washed up into the shore in the form of spheres and hemispheres (Fig. 3); they contain, in addition to sulfur, pyrite, marcasite, quartz, opal and pumice in aggregates up to 1.5 cm in diameter.

A funnel has developed around a main group of fumeroles at the bottom of the lake, deepening the lake from 15 m to 25 m locally. Investigation of the sediments in the funnel revealed the presence of dark sulphur spheres, as well as quartz and pumice. The sediment in the shallow parts of the lake is composed of gray sulfur-sulfide mud with included quartz, opal and pumice.

As in the Yumoto lakes, two forms of sulfur occur in Ojunuma lake. These include the following:

a) mud composed of sulfur, discolored gray by iron sulfide;
b) dark sulfur concretions up to 1.5 cm in diameter, with fine-grained iron sulfide distributed throughout.

The origin of concretions composed of a mixture of sulfur and iron sulfide instead of pure yellow sulfur ooides as found in the Yumoto lakes is explained in the following text.

Reducing conditions prevail in the fumarole funnel such that fumarolic hydrogen sulfide does not oxidize to sulfur directly in the openings of the fumaroles as is the case in the Yumoto lakes. Oxidation to sulfur first takes place in the top 15 m of water in the lakes; precipitation commences here with formation of a gray sulfur-sulfide mud containing iron sulfide formed by reaction with H_2S and suspended substances transported by the streams. Part of this gray mud drops back into the fumarole funnel wherein the temperature exceeds 119 °C, the melting point of sulfur. Melting and agglomeration of the fine-grained sulfur particles and Fe-sulfides proceeds with the formation of fumarole gas bearing spheres. These, as observed, are carried upward with the formation of a foam floating on the lake surface (Fig. 3). Some of the spheres, on the journey upward, deposit on the walls of the fumarole funnels and solidify where the temperature is lower. A third fraction forms a fluid, black, sulfur-sulfide mixture which collects at the bottom of the fumarole funnel.

Using the grid spectrograph the following elements were detected to be present in the sediment:

As, Co, Cr, Cu, Mg, Mn, Mo, Ni, Pb, Sb, Si, Sn, Ti, V and Zn (Co, Cr, Cu, Mn, Ni, Pb, Sb and Zn were also determined quantitatively [see

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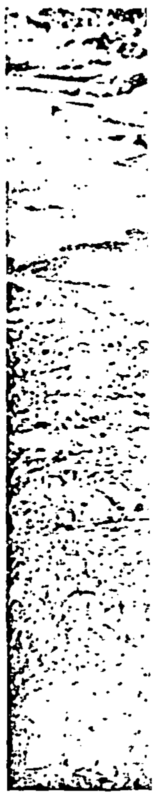

Fig. 3. Foam of

Tab. 3]). Sulfur increases
creasing lake water depth.
Cr, Cu, Pb, Zn, Co, and
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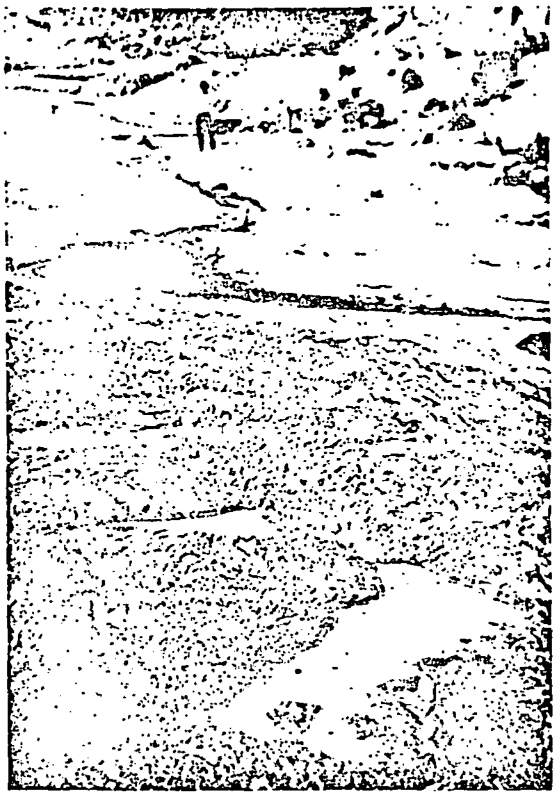

Fig. 3. Foam of sulfur floating on the Ojunuma-lake.

Tab. 3]). Sulfur increases to 89.4 % in the lake bottom sediment with increasing lake water depth. Likewise, the concentrations of Fe, As, Sb, Mn, Cr, Cu, Pb, Zn, Co, and Ni increase in the sulfur free sediment fraction with increasing water depth. If average concentrations of samples from the 0–25 m are compared with those from the 16–25 m depth, it is unmistakably clear that the fumarole funnels between a depth of 16 m and 25 m contain most of the metallic sulfides. At the 16 m depth a consolidated layer containing up to 52 % sulfur has formed in the transition zone between the fumarole funnels and shallow parts of the lake. Samples were taken from this zone and the consolidated layer was found to be especially enriched in Fe and As. A comparison of values determined in the sulfur foam with the averages determined from samples from the 16–25 m depths (see above) proved rewarding. The sulfur, Fe, Cu, As and Mn concentrations in the foam differ little from the averages but are almost exactly the same as those values determined from a depth of 23 m–25 m. However, Zn and especially Pb is more enriched in the foam (Tab. 3).

These results support the hypothesis that the sulfur spheres remove lead and zinc ions from the water on reaching the water surface and then form sulfide and sulfate. This the more so as the lake water contains up to 0.6 ppm lead and up to 1.1 ppm zinc (Tab. 2).

3.3 Lake Okunoju and sediments

Lake Okunoju, the smaller of the two lakes, is more circular in form with a diamater of 25 m. The surface water was determined to have a temperature of 80 °C and pH of 5.6. The temperature increases with water depth to the deepest part of the lake. The lake is 5 m deep in its deepest part and the temperature at the bottom is 111 °C with a pH of 4.6 (a drop in pH). Reducing conditions prevail in the whole water-body (Tab. 1). In parts of the lake, the surface is covered with a thin coating of sulfur (Fig. 4). A mountain spring which flows through a small, acid iron bearing spring (pH about 5) empties into the lake. Fumarole water, in addition, is transported to the lake. Overflow is removed by a stream floating to lake Ojunuma. Aside from the lower iron and sulfur content in the water of lake Okunoju, the concentrations of soluble constituents are just as high as in lake Ojunuma (Tab. 2).

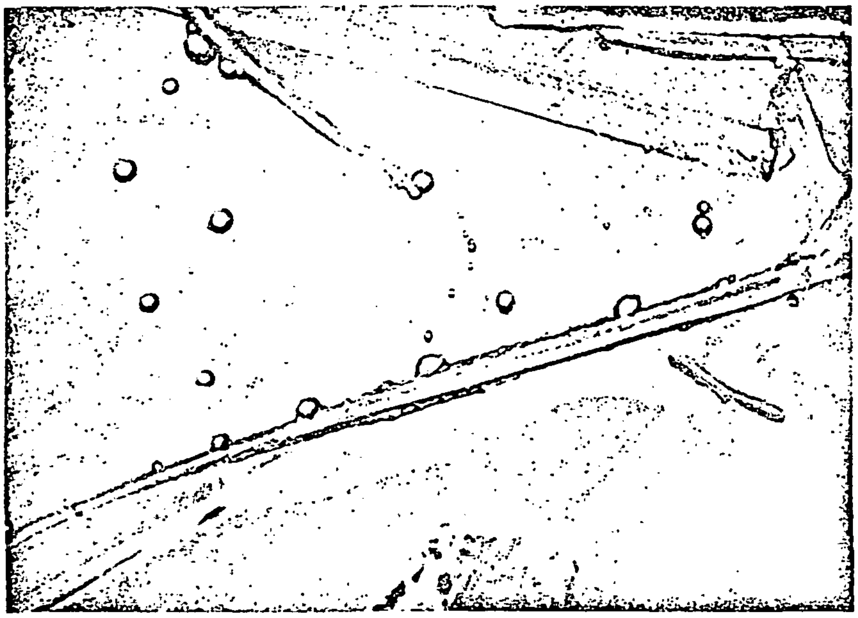

Fig. 4. A thin iron-sulfide-skin floating on Okunoju lake (width of area about 1 m).

The lake sediments consist of pyrite coated (and more thickly encrusted) quartz grains in which marcasite also sometimes occurs. To orient the reader,

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the following trace elements
Co, Cr, Cu, Mg, Mn, Mo, Ni,
Though both lakes are only
history, the deposits in the
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order of magnitude whereas
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4. Microscopic observations
of the sediments

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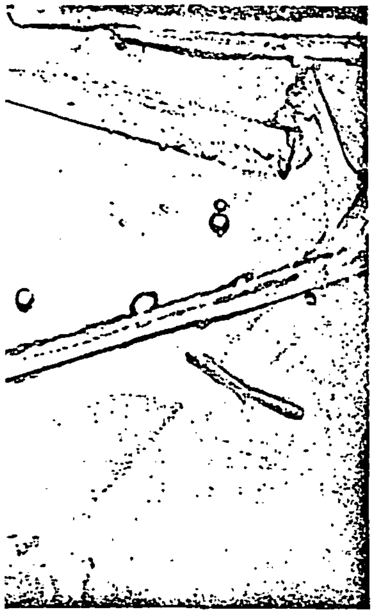

noju lake (width of area about 1 m).

ted (and more thickly encrusted)
imes occurs. To orient the reader,

the following trace elements were determined spetrographically and include Co, Cr, Cu, Mg, Mn, Mo, Ni, Pb, Sb, Si, Sn, Ti, V and Zn.

Though both lakes are only 100 m apart and indicate similar postvolcanic history, the deposits in the lakes show marked differences. Although the fumaroles transsect the same rock formations and the same concentrations of trace elements and temperatures are indicated at the exhalation openings, concentrations of the elements in the sediments differ. The average concentrations of Fe, Cu and Zn from deposits in both lakes are of the same order of magnitude whereas Pb, As, Ni, Mn and particularly sulfur differ greatly (Tab. 3).

No native sulfur and considerably less Pb is to be found in lake Okunoju (average content of Pb in the foam in lake Ojunuma not weighed); furthermore, less As and Ni and more Mn were found in lake Okunoju than in lake Ojunuma. The variation is attributed to differences in oxidation reduction conditions which prevail in both lakes. Reducing conditions exist in the fumarole funnels of both lakes so that hydrogen sulfide cannot oxidize to sulfur; oxidizing conditions in the upper parts of lake Ojunuma, however, allow for sulfur formation.

Hydrogen sulfide in the fumarole is oxidized by oxygen contained in the lake water. At Ojunuma, oxygen is carried in by the streams accounting for the oxidizing environment in the upper near surface parts of the lake. SO_3^{2-} and SO_4^{2-} form in addition to sulfur and account for the strong acidity in lake Ojunuma. At Okunoju, there being no oxygen available, dissociation of H_2S to HS^- and S^{2-} ions takes place and impacts only a weak acidity to the water. Yet parts of these ions react with iron with the formation of iron sulfide. The pH-Eh region wherein the reactions occur is indicated in Fig. 5. In the existing environment in Okunoju and in the fumerole funnels at Ojunuma, only sulfide may form; native sulfur will not form.

4. Microscopic observations on thin sections and polished sections of the sediments

The formation of ore minerals was investigated with particular care. The main sulfide ore minerals in the four lakes are pyrite and marcasite, but pyrrhotite, arsenopyrite, chalcopyrite, galena, and sphalerite are also present. All these phases formed authigenically.

Pyrrhotite is always surrounded by pyrite and is replaced by it. While pyrrhotite in xenomorphous masses or as needles is more abundant in the two Yumoto lakes, it is rare and is observed as tiny inclusions within pyrite in the Ojunuma and Okunoju lakes, where its oxidation and transformation into pyrite has progressed very far. The "birds-eyes" textures, which are often observed when pyrrhotite is transformed into pyrite (RAMDOHR, 1969, p. 593 etc.), were not found. Arsenopyrite is rather abundant in the sedi-

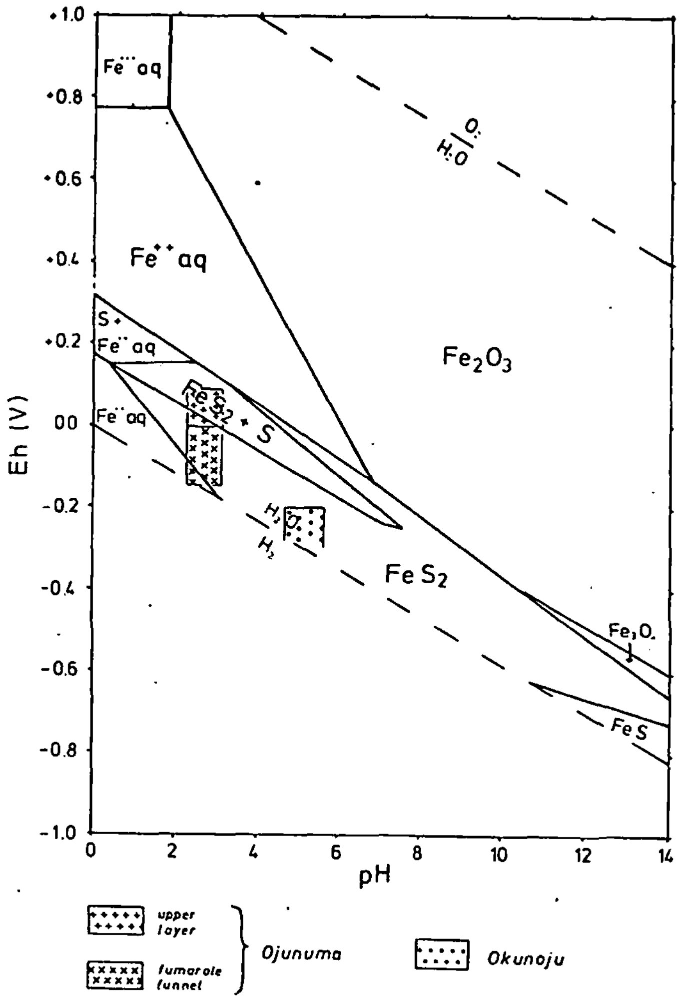

Fig. 5. Stability relations of iron-oxides and sulfides in water at 25 °C and 1 atmosphere total pressure at an activity of dissolved sulfur of 10^{-1} (after GARRELS & CHRIST, 1965). The different pH-Eh-conditions in the lakes are marked.

ments from the Ojunuma, less abundant in the sediments from the Okunoju, and was not found at all in the Yumoto lakes. It is always intergrown with pyrite, and is often surrounded by it.

Chalcopyrite, galena, and sphalerite are found only rarely, and occur as tiny inclusions intergrown with pyrite in the sediments of the lakes at Noboribetsu-Onsen. Pyrite and marcasite are the most abundant sulfides in the volcanic lakes. They do not show any textural differences in the four lakes. Three types can be distinguished under the microscope and will be discussed in the following sequence:

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a) iron sulfide without intergr
b) iron sulfide surrounding otl
c) iron sulfide in close intergr

a) Iron sulfide without interg

Idiomorphous pyrite is a
according to AMSTUTZ (1963
form of pyrite.

Pyrite is weakly anisotropi
color varying from red to g
inclusions which form irregul
probe analysis has proven, th
lattice, up to a concentration

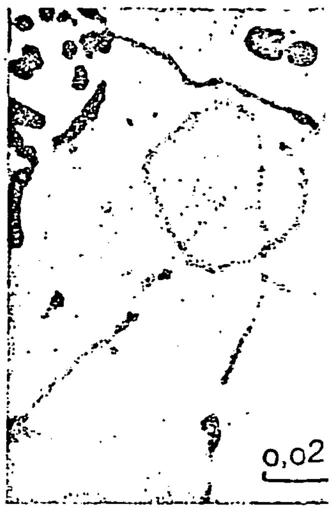

Fig. 6 a

Fig. 6 a. Pyrite (light) with C
Polished section, oil immersion.
the area of fig. 6 a.

Framboids were identified
According to the classificatio
can be classified as "unorder
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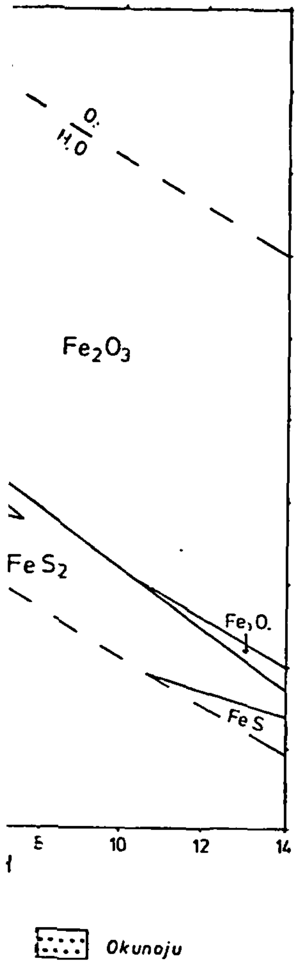
surrounded by a marcasite-rir
marcasite to such an extent t
boids. Sometimes they are also

The degree of intergrowth
Many framboids whose interg



nd sulfides in water at 25 °C and
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a) iron sulfide without intergrowths with other minerals;
b) iron sulfide surrounding other minerals;
c) iron sulfide in close intergrowth with other minerals.

a) Iron sulfide without intergrowths with other minerals:

Idiomorphous pyrite is almost always crystallized in cubes, which, according to AMSTUTZ (1963), generally represent the lowest-temperature form of pyrite.

Pyrite is weakly anisotropic in the sediments from the volcanic lakes, its color varying from red to green. Some pyrites contain brownish-colored inclusions which form irregular spots or zonations in the pyrites. As microprobe analysis has proven, this coloration is due to Co entering the crystal lattice, up to a concentration of 0.8 % by weight (Fig. 6).

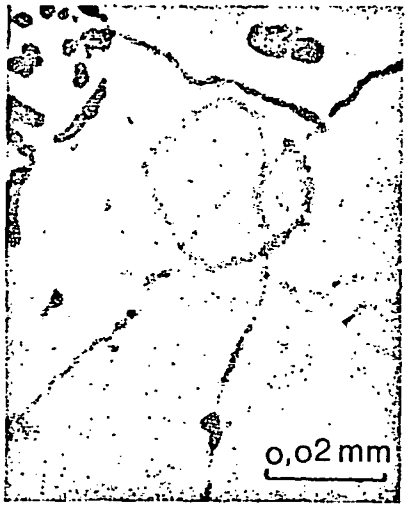

Fig. 6 a

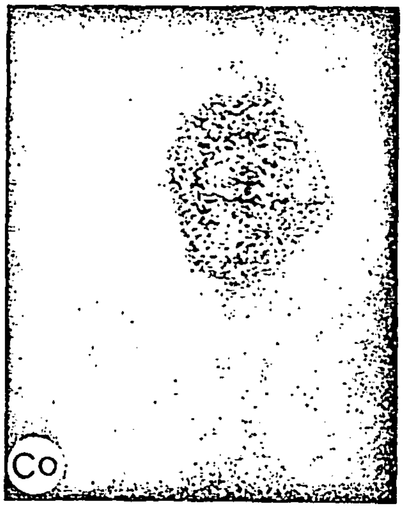

Fig. 6 b

Fig. 6 a. Pyrite (light) with Co-containing zones (gray), lower Yumoto lake. Polished section, oil immersion. – b. Scanning-photograph of Co corresponding to the area of fig. 6 a.

Framboids were identified in all sediment samples from the lakes. According to the classification suggested by LOVE & AMSTUTZ (1966), they can be classified as "unordered". The framboids occur exclusively in irregular aggregates, and only rarely as isolated spherules. They are frequently surrounded by a marcasite-rim (Fig. 7 a, b), and are often intergrown with marcasite to such an extent that it is difficult to recognize them as fromboids. Sometimes they are also rimmed by pyrite.

The degree of intergrowth in the framboids varies in the different lakes. Many framboids whose intergrowth with marcasite is not very pronounced

Fig. 7 a

Fig. 7 b

Fig. 8

Fig. 9

Fig. 7 a. Framboidal pyrite, rimmed by marcasite, Okunoju lake. Polished section, oil immersion. – b. Picture corresponding to fig. 7 a, Nicols almost crossed. Isotropic pyrite gray, anisotropic marcasite black and white.

Fig. 8. Marcasite-zone in pyrite, Ojunuma lake. Polished section, oil immersion, Nicols almost crossed.

Fig. 9. A ball of marcasite rimmed by a rosette of marcasite. Polished section, oil immersion, Nicols almost crossed.

were observed in the sediments from the Yumoto lakes, while they are so tightly intergrown with marcasite in the lakes at Noboribetsu-Onsen that their texture is often obliterated and they are rarely recognized at all. Framboidal diameters were determined from more than 400 framboids from

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the lower Yumoto lake. (Comj
the framboids from the lakes a
intergrowths with marcasite, a
with a maximum between 8 ar
was 30 μ in diameter. Overall
sponds to the range of sizes g
described to date. The size disi
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These rosettes and spherules of
by WAUSCHKUHN & GROEPPER
Levante at Vulcano, Italy.

b) Iron sulfide surrounding oth

Particularly pyrite framboids
by iron sulfide. Formation of su
of lake Okunoju that a large r
to form a sulfide layer.

These crusts, observed maci
marcasite with pyrite-framboids
over quartz grains in the sedime

c) Iron sulfide in close intergro

This type of iron sulfide is
main iron oxide is magnetite,
that may point to the presence
p. 895). Here like at Vulcano,
(1975), a brownish rim can s
where titanomagnetite is sulfid
was analyzed under the microp
of this zone. Iron, sulfur, and ti
to illustrate the distribution of
Ti-content in the magnetite-zc
zone (Fig. 10).

.7 b

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site, Okunoju lake. Polished section,
fig. 7 a, Nicols almost crossed. Iso-
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Yumoto lakes, while they are so
lakes at Noboribetsu-Onsen that
ey are rarely recognized at all.
m more than 400 framboids from

the lower Yumoto lake. (Comparable measurements could not be made on the framboids from the lakes at Noboribetsu-Onsen, because of their strong intergrowths with marcasite, as mentioned above.) A normal distribution with a maximum between 8 and 10 μ was measured. The largest framboid was 30 μ in diameter. Overall, the size of these framboidal pyrites corresponds to the range of sizes given by Kalliokoski (1974) for framboids described to date. The size distribution of the framboids from the volcanic lakes resembles the distribution curves for framboids from the Chattanooga-Shale and from the layered Rammelsberg ores published by Love & Amstutz (1966), with the difference that the framboids from these deposits are slightly smaller, the curve maxima being between 5 and 6 μ, and that they frequently show internally ordered textures. In addition to pyrite, also marcasite occurs in all of the lakes, generally in intergrowths with the former. The marcasite zones that can occasionally be observed in pyrite (Fig. 8) point to changes in the environment of deposition during crystal growth. These changes may be due to variations in fumarolic activity, or to a change in supply of meteoric water to the lakes. Both factors affect the pH-Eh values in the lake water. Figure 9 shows a "rosette" of marcasite with radiating texture, the likes of which are frequently found in the lake sediments. Occassionally, pyrite occupies the center of the rosettes, or a spherule of marcasite which in turn is composed of much smaller crystallites. These rosettes and spherules of marcasite are very similar to those described by Wauschkuhn & Groepper (1975) from the sediments of the Porto di Levante at Vulcano, Italy.

b) Iron sulfide surrounding other minerals:

Particularly pyrite framboids and quartz grains are frequently surrounded by iron sulfide. Formation of sulfide overgrowths was so strong in one place of lake Okunoju that a large number of quartz grains was cemented so as to form a sulfide layer.

These crusts, observed macroscopically, correspond to intergrowths of marcasite with pyrite-framboids, and to sulfide coatings of varying thickness over quartz grains in the sediments, observed microscopically.

c) Iron sulfide in close intergrowths with other minerals:

This type of iron sulfide is generally intergrown with iron oxides. The main iron oxide is magnetite, which often shows faint brownish-pink hues that may point to the presence of Ti in the crystal lattice (Ramdohr, 1969, p. 895). Here like at Vulcano, as described by Wauschkuhn & Groepper (1975), a brownish rim can sometimes be recognized around the oxide, where titanomagnetite is sulfidized. A partially sulfidized titanomagnetite was analyzed under the microprobe to determine the chemical composition of this zone. Iron, sulfur, and titanium were detected. Scanning-photographs to illustrate the distribution of these three elements show distinctly that the Ti-content in the magnetite-zone is as high as in the brown iron-sulfide zone (Fig. 10).

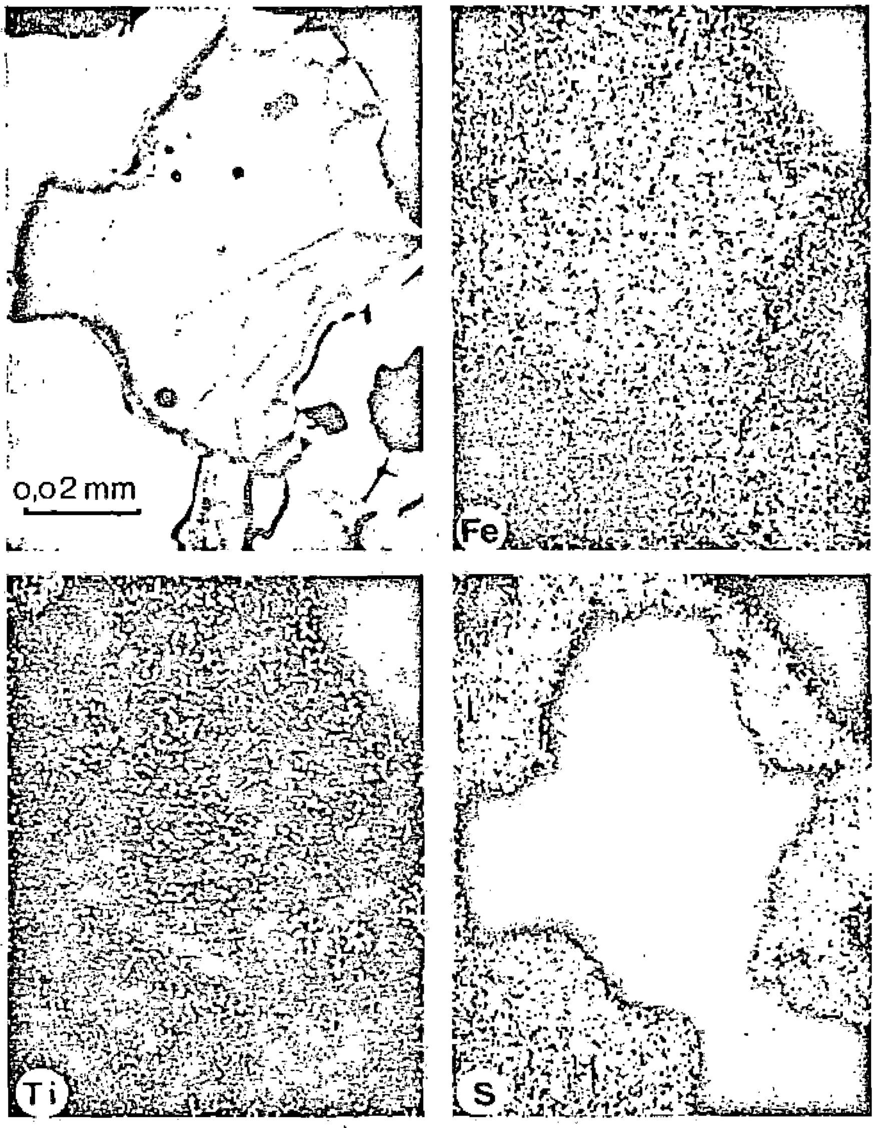

Fig. 10. Titano-magnetite rimmed by a Fe–Ti–S-zone, lower Yumoto lake, polished section, oil immersion, and the corresponding scanning-photographs of Fe, Ti, and S.

A step-scanning traverse was performed for a better determination of the nature of the brownish mineral or mineral mixture: with three spectrometers, the X-ray intensities of $Fe_{K\alpha}$, $S_{K\alpha}$, and $Ti_{K\alpha}$ were measured simultaneously in steps of 3 microns. The percent composition of the three elements was calculated by comparison with the X-ray intensities of standards. The

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sulfur- and iron contents s
content in the brownish zone
The analytical results sugges
position of the zone:

α) a submicroscopic mixture
leucoxene;

β) a very unstable titanium-i

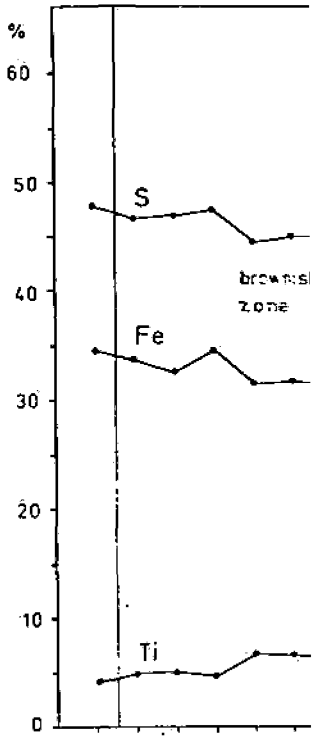

Fig. 11. Microprobe-profile acr
of Fig. 10.

The marcasite-leucoxene i
ments of the volcanic lakes
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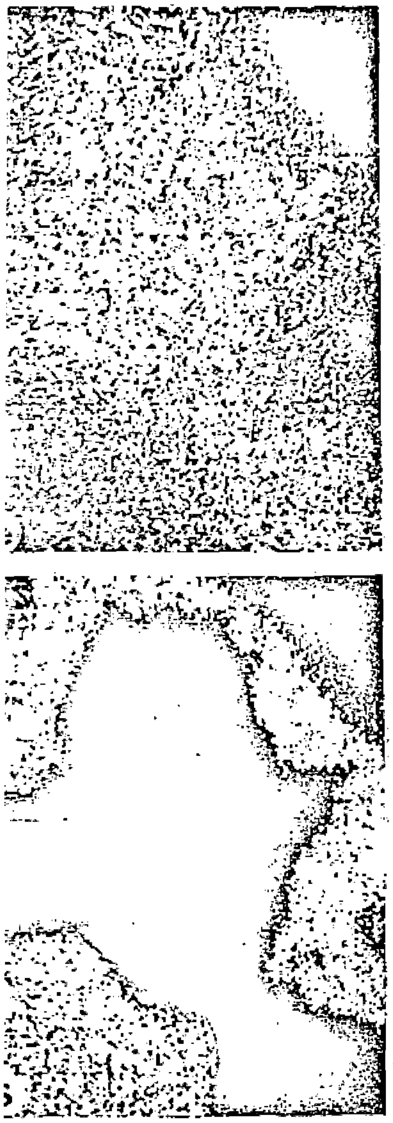

·S-zone, lower Yumoto lake, polished
ng scanning-photographs of Fe, Ti,

l for a better determination of the
·ral mixture: with three spectro-
and $Ti_{K\alpha}$ were measured simulta-
composition of the three elements
-ray intensities of standards. The

sulfur- and iron contents show parallel variations, while the titanium content in the brownish zone is relatively constant at around 6 % (Fig. 11). The analytical results suggest the following two possibilities for the composition of the zone:

α) a submicroscopic mixture of finely disseminated iron sulfide, sulfur, and leucoxene;

β) a very unstable titanium-iron-sulfide.

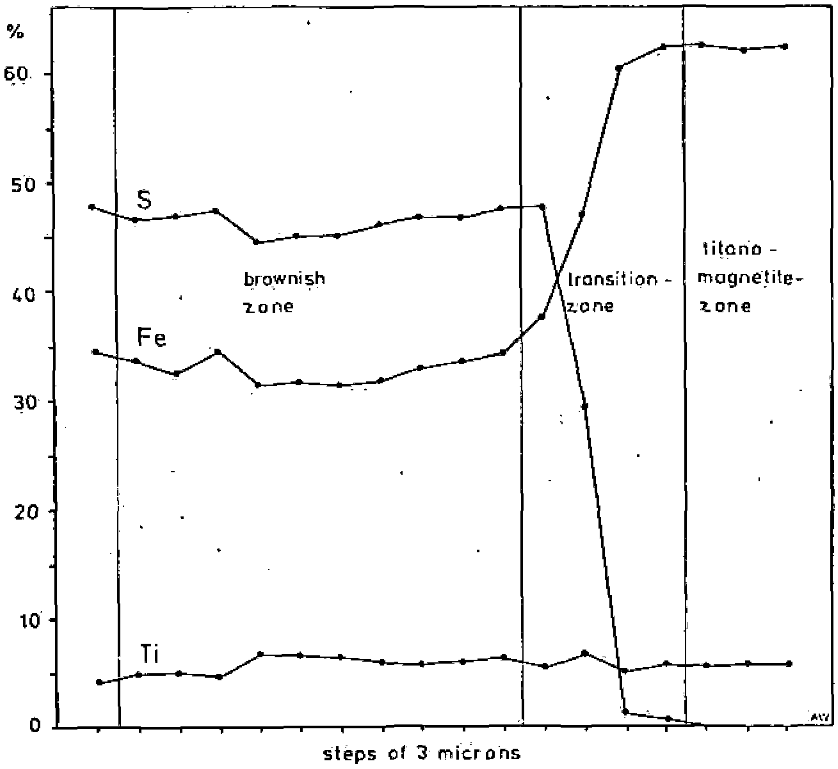

Fig. 11. Microprobe-profile across the Fe-, Ti-, and S-containing zone of the grain of Fig. 10.

The marcasite-leucoxene intergrowths (Fig. 12) often found in the sediments of the volcanic lakes form by way of this brownish, intermediate product from the titanomagnetite.

Apart from the sulfidization, some grains of titanomagnetite are also decomposed by the hot, acid waters in the lakes. The mineral grains are corroded from the rim; part of the iron is removed, another part forms iron sulfide, and all the titanium remains as leucoxene. The decomposition of titanomagnetite continues along cleavages and fractures in the grains,

Fig. 12. Titano-magnetite substitution by pyrite-lamellae and then by pyrite, Okunoju lake. Polished section, oil immersion.

leading to the complete destruction of the grains. Only leucoxene and small amounts of iron sulfide remain as relics, indicating that titanomagnetite was the primary mineral.

Colloform pyrite forms by sulfidization of titanium-free magnetite; zonation in the pyrite indicates the presence of impurities or submicroscopic inclusions. They stem from inclusions and solid solution "impurities" and may contain e.g. Mg, Mn, Ca, or Ni, which take the place of iron in the crystal lattice of magnetite and are distributed zonally during sulfidization. Excepting its intergrowths with iron oxides, iron sulfide is only intergrown interstitially with pumice.

Microscopic observation of ore textures and intergrowths allow distinction of three types of sulfide formation, as was also described from the sediments of the Porto di Levante at Vulcano, Italy (Wauschkuhn & Groepper, 1975). This genetic interpretation corresponds with the previously given descriptive classification. Therefore the same letters a), b), c) can again be given:

a) Formation of sulfide by precipitation (without formation of coatings or of replacements);
b) Sulfide coating of minerals;
c) Sulfidization of minerals.

Sulfide framboids, idiomorphous pyrite cubes, and marcasite spherules and rosettes, formed by precipitation from the hot, lacustrine waters, are nearly identical in the volcanic lakes and in the Porto di Levante at Vulcano. In the two recent depositional environments, sulfide accretions over framboids, quartz, and sand grains are found, and the sulfidization of titanomagnetite involves a titanium-iron-sulfide stage, which later passes into the characteristic, lamellar intergrowths of leucoxene-iron sulfide. Only

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pyrrhotite, which was occa
Hokkaido was not found in t
There is, however, a qua
three genetic types of sulfide
Porto di Levante: While sulfi
Porto di Levante, sulfides pr
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in the hot volcanic lakes. Acc
are relatively rare in the la
elements dissolved by the fu
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elements supplied to the wa
by marine currents.

5. Microbiological investigati

Samples of water and sedi
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laboratory. Slides were expo
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at the Yumoto lakes.
In both groups of sulfur
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pH-values were not so low.
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mentioned later).
All these micro-organisms
and energy-source organic ca
transported in solution or as
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[1] Cf. A. & W. Schwartz, Zt
[2] Nutrient Agar, Merck, M
Chase, 1943).

rite-lamellae and then by pyrite,

the grains. Only leucoxene and
is relics, indicating that titano-

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and intergrowths allow distinc-
as was also described from the
Vulcano, Italy (WAUSCHKUHN &
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erefore the same letters a), b), c)

without formation of coatings or

e cubes, and marcasite spherules
m the hot, lacustrine waters, are
in the Porto di Levante at Vul-
ronments, sulfide accretions over
found, and the sulfidization of
sulfide stage, which later passes
ns of leucoxene-iron sulfide. Only

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pyrrhotite, which was occasionally observed in the volcanic lakes of Hokkaido was not found in the sands from Vulcano.

There is, however, a quantitative difference in the importance of the three genetic types of sulfide formation between the volcanic lakes and the Porto di Levante: While sulfide accretion and sulfidization dominate in the Porto di Levante, sulfides precipitated from the lacustrine waters, like the framboids, pyrite cubes, and marcasite spherules and rosettes predominate in the hot volcanic lakes. Accretions, and particularly sulfidization textures, are relatively rare in the latter. The reason for this difference is that the elements dissolved by the fumaroles are concentrated in the water of the volcanic lakes and precipitate when these become saturated, while the elements supplied to the water in the Porto di Levante are carried away by marine currents.

5. Microbiological investigations[1]

Samples of water and sediments were collected at the different ecological habitats of the lakes and their surroundings for further examination in the laboratory. Slides were exposed after the Cholodny-Rossi technic for 1 to 7 days in water and sediment; scum and films from the surface of the lakes were taken off by slides and both prepared for microscopic examination in the laboratory (Fig. 13 a, b). A first microscopic control was made at the Yumoto lakes.

In both groups of sulfur lakes the temperatures near the surface of the water and of the sediments were between 45 and 70 °C, that means within the range of mesophilic and thermophilic micro-organisms. Because of the low pH values of the water in the lakes acid-sensible micro-organisms, especially acid-sensible bacteria could not grow. Nevertheless, the numbers of acid-tolerant bacteria and fungi were relatively high and reached under aerobic conditions in the average 10^3 to 10^5 cells/ml water or wet sediment with higher or lower levels in relation to pH and temperature and with more bacteria than fungi, as far as both may grow on the media, which were used for these experiments[2]. The highest numbers, up to 10^8, were found in pools and rivulets near the shore of the lakes, where the pH-values were not so low. Under strictly anaerobic conditions only a few bacteria were growing (except the desulphurizing bacteria, which will be mentioned later).

All these micro-organisms are carbon-heterotrophic and want as carbon- and energy-source organic carbon compounds. Compounds of this kind are transported in solution or as organic detritus to the lakes with water from the surrounding hills, which are covered with rich vegetation.

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[1] Cf. A. & W. SCHWARTZ, Ztschr. Allg. Mikrobiol. 16, 1977 (under press).

[2] Nutrient Agar, Merck, Malt-Agar Merck, Agar B +S, 3 : 1 (LOCHHEAD & CHASE, 1943).

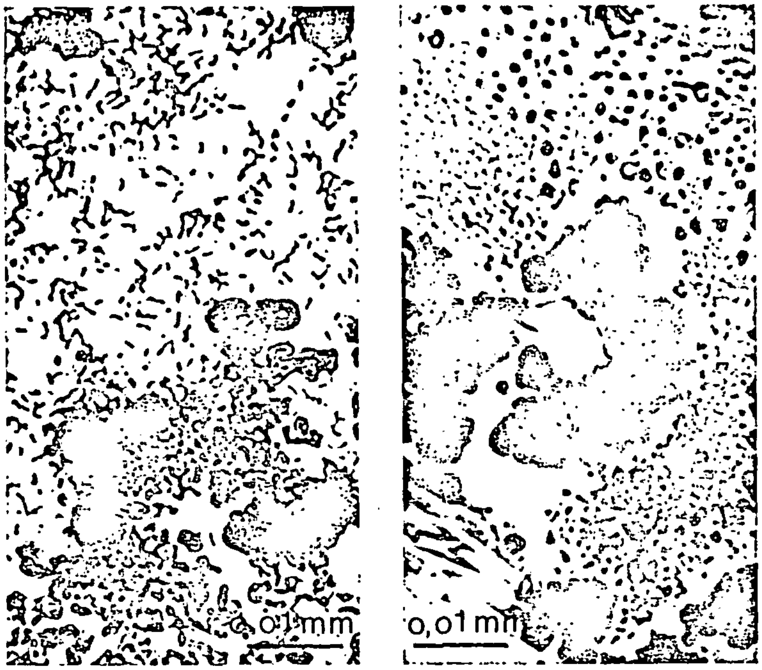

Fig. 13 a, b. "Aufwuchs"-culture from the Ojunuma lake. The black parts seem to be sulfur-aggregates. Slide exposed for 24 h in the lake, depth about 1 m. Fixation by heating. Stained with erythrosine, 24 h.

At all ecological habitats of the lakes, e.g. water, scum at the surface of the lakes, sediments, solfatares, sulphur-accumulations, acid- and metal-tolerant mesophilic to thermotolerant and thermophilic strains of *Thiobacillus thiooxidans*, *Th. thioparus/neapolitanus*[3], and *Th. ferrooxidans* were the prevalent micro-organisms (Table 6). In the water of Lake Oyunuma, we also found a thermophilic Sulfolobus strain at about 70 °C. A single species, *Sulfolobus acidocaldarius*, has been described by BROCK et al. (1972) and MOSSER et al. (1973), which oxidizes S° to $''SO_4$ at a pH optimum of 2–3 and an optimal temperature of 70–75 °C. In a hot spring in Yellowstone Park, BRIERLEY & MURR (1973) have found a strain, belonging likely to *Sulfolobus*, which had a high molybdenum tolerance and is said to oxidize Fe^{2+} besides S°.

Desulfurizing bacteria (*Desulfovibri, Desulfotomaculum*) are growing in the sediments under anaerobic conditions up to about 70 °C but not below pH 4.5. They are carbon-heterotrophic; some strains are hydrogenase-active and may assimilate CO_2 besides organic C-compounds, especially salts

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[3] We have not differenciated between these two species.

Table 6. Thiobacilli and desu

	Scum at the water surface
Th. thiooxidans	+
Th. thioparus/ neapolitanus	O
Th. ferrooxidans	O
Desulfurizing bacteria	(+)

of organic acids. The Thio
ecological conditions, carb
ferentially S° to $''SO_4$ and
neapolitanus oxidize H_2S to
to $''SO_4$, lowering the pH to
oxidizes FeS, FeS_2, $FeSO_4$ to

Thermophilic and acidopl
anaerobic purple sulfur ba
which are elsewhere found
groups, or only sporadicall
because of the combination
the water of the lakes.

The same restrictions as f
iron-cycle, which is represe
Gallionella, Leptothrix and
besides other reasons becaus
pools near the shore of the
of about 5.5–7 iron, which
was oxidized to hydroxide
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There were no essential mi
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[4] We are still occupied with
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, water, scum at the surface of
cumulations, acid- and metal-
thermophilic strains of *Thio-*
*itanus*³, and *Th. ferrooxidans*
e 6). In the water of Lake
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ulfotomaculum) are growing
up to about 70 °C but not
some strains are hydrogenase-
: C-compounds, especially salts

species.

Table 6. Thiobacilli and desulphurizer in the Yumoto- and Noboribetsu-Lakes.

	Scum at the water surface	Water of the lakes	Solfa-taras	Black sulfur/ FeS_2 crusts	Ooids and concretions of sulfur	Sediments
Th. thiooxidans	+	+	++	O	+	+
Th. thioparus/ neapolitanus	O	+	+	O	+	+
Th. ferrooxidans	O	O	O	+	O	+
Desulfurizing bacteria	(+)	O	O	O	O	+

of organic acids. The Thiobacilli and *Sulfolobus* are aerobic and, under ecological conditions, carbon-autotrophic. *Th. thiooxidans* oxidizes preferentially S° to $''SO_4$ and produces the lowest pH-degrees. *Th. thioparus/ neapolitanus* oxidize H_2S to S° which accumulates, but may also be oxidized to $''SO_4$, lowering the pH to about 3–4. Besides S° and $''S$, *Th. ferrooxidans* oxidizes FeS, FeS_2, $FeSO_4$ to $Fe_2(SO_4)_3$, which is a strong chemical oxidans.

Thermophilic and acidophilic *Cyanophyceae, Beggiatoaceae,* phototrophic anaerobic purple sulfur bacteria and other microbes of the sulfur cycle, which are elsewhere found in sulfur springs, are missing in the two lake groups, or only sporadically growing in the water of the shore region because of the combination of high metal contents and low pH degrees in the water of the lakes.

The same restrictions as for the sulfur cycle concern the specialists of the iron-cycle, which is represented in the lakes only by *Th. ferrooxidans. Gallionella, Leptothrix* and the *Siderocapsaceae* are missing in the lakes, besides other reasons because of the low pH degrees. Only in some water pools near the shore of the lakes and in the surroundings at pH degrees of about 5.5–7 iron, which was transported with weathering solutions, was oxidized to hydroxide and precipitated, and *Siderocapsaceae* may have participated in this process[4]). When iron hydroxyde is transported to the lakes, it will be reduced at last and precipitated as FeS.

There were no essential microbiological differences between the four lakes but quantitatively the cell numbers per ml were lower in Oyunuma lake and the lowest in Okunoyu lake of the Noboritbetsu-group, where the temperatures and the metal contents of the water and the sediments were higher, but even there, water and sediments were not sterile within the temperature limit of the biosphere.

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[4] We are still occupied with experiments on the role of *Siderocapsaceae* in iron oxidation and accumulation under different conditions.

6. Discussion of the results and conclusions

The lakes of Niseko as well as those of Noboribetsu-Onsen are located in active volcanic areas. The countryrock of these lakes consists of volcanic products of andesitic or dacitic composition in the forms of lavas, lava domes and pyroclastic covers and flows. In the lakes and in their vicinity hot gasses with H_2S emanate from below. These fumaroles contain water vapor, H_2S, CO_2 and trace elements, expecially As and S. They alter the country rock through which they percolate and remove certain principal and trace elements from it and carry them in solution to the surface. In the altered country rock they often leave part of the As and S (sulfidization of mafics etc.).

The H_2S of the fumaroles reacts with the O of the atmosphere by way of micro-organisms, if and when there is enough humidity. The oxidation includes the formation of native S and the formation of sulfuric acid which in turn increases the weathering process of the country rock considerably. The solved material is carried to the lakes by the streamlets and contributes to the formation of the recent deposition of sulfur and sulfides. In the lakes both, the material solved by the fumarolic weathering agents as well as the weathering products are precipitated under favourable conditions. These depend on various factors, such as changes of the climate and of the fumarolic activity, producing frequent depositional variations. Comparative studies revealed that in the area affected by fumarolic activities, the processes forming mineral deposits and those destroying them alternate or take place simultaneously in different places. In the lakes the positive, ore deposit forming processes finally predominate.

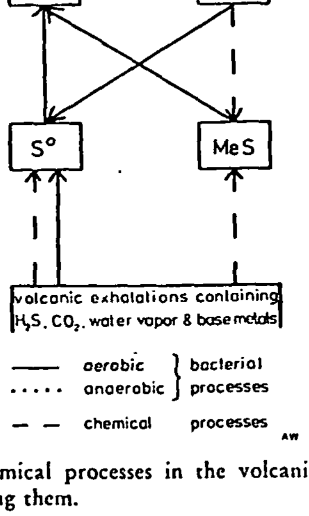

Fig. 14. Bacterial and chemical processes in the volcanic lakes, forming mineral deposits and those destroying them.

The latter consist of c
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formation of ore deposits. D
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can alternate in the course
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place or would require very
With regard to the pro
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forming processes. Ore min
the oxidation of S° to $SO_4^{=}$
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a) Yellow ooids of native S

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b) Grey mud or ooze of na

This material forms in t
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the sulfide which is formed
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with this mud.

c) Grey concretions of nat

These concretions or oo
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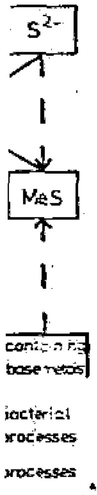

the volcanic lakes, forming mineral

The latter consist of chemical and microbiological processes, which contribute to the deposition of the material which may later lead to the formation of ore deposits. Distructive are those processes in this first phase of the formation of ore deposits which cause the solution of material so that it enters the geochemical cycle again (Fig. 14). Precipitation and solution can alternate in the course of the physico-chemical and ecological changes. Within the given ecological limits micro-organisms can accelerate geochemical processes; or they start and carry through processes which under the given geochemical conditions of pressure and temperature, would not take place or would require very much more time.

With regard to the processes in the four hot sulfur lakes, precipitation and enrichment of S^0 from H_2S and from alkalisulfides (dissolved in the water) by the *Thiobac. thioparus/neapolitanus* group belong to the ore forming processes. Ore mineral destroying processes are, on the other hand, the oxidation of S^0 to SO_4^{2-} by *Thiobac. thiooxidans* and bei *Sulfolobus*, as well as the oxidation of iron sulfides by *Thiobac. ferrooxidans* to $FeSO_4$ and $Fe_2(SO_4)_3$. In this process Fe(III)sulfate can oxidize additional sulfides of base metals to sulfates. A process of renewed sulfide and sulfur formation (recycling) is kept up by the activity of desulfurizers which reduce freshly formed sulfates brought in from the surrounding. The H_2S which thus forms exogenetically contributes to the precipitation of base metals or of S^0, the latter by way of the activity of the *thioparus/neapolitanus* group.

Four forms of precipitation can be differentiated in function of the physico-chemical and ecological conditions existing in the lake waters:

a) Yellow ooids of native S:

These globules form at the mouths of fumaroles, if the conditions at these places are oxidizing. H_2S is oxidized immediately at the mouths of the fumaroles chemically and by bacterial activity by *Thiobac. thioparus/neapolitanus* group to S^0 which, due to the water motion produced by the leaving gases, accumulates in form of ooids in the surroundings of these fumaroles, for example in the two Yumoto lakes.

b) Grey mud or ooze of native S and sulfides:

This material forms in the presence of the *Thiobac. thioparus/neapolitan.* group during oxidation of H_2S partly to S^0, whereby the rest of H_2S is finely dispersed in the lake water. The S^0 then precipitates together with the sulfide which is formed by reaction of H_2S with metal cations. The floor of the Yumoto lakes and the shallow parts of the Ojunuma are covered with this mud.

c) Grey concretions of native S and sulfides:

These concretions or ooidal globules form, if reducing conditions exist at the mouths of fumaroles and if the temperature exceeds the melting point of S (119 °C); if, however, in the upper layers of a lake the conditions are oxidizing and the temperature low; H_2S is, consequently, converted to S° chemically and by the *Thiobac. thioparus/neapolitanus* group in the upper layer and precipitates with sulfides which formed from the reaction of H_2S with cations of base metals. If this ooze or mud reaches deeper, hotter zones, it agglomerates and forms grey concretions in the water streams of the fumaroles. The sediments in the fumarole funnels of the Ojunuma consist of such gray concretions.

d) Deposits of sulfides:

Sulfide precipitates which are not mixed with native S form in lakes with reducing conditions throughout. H_2S reacts with the metal ions in the water to form sulfides or escapes from the water. This type of sulfide formation was observed at Okunoju.

The total belance of deposition thus consists of the material which is brought in from below by the fumaroles, plus the H_2S forming in the lakes, plus the mineral constituents (dissolved or undissolved) and thus the major and trace elements from weathering processes in the area, and in addition of the organic compound from the vegetal detritus which enters the lakes through tributary streamlets. The superficial influx is reflected in the activity of the desulfurizers and in the iron cycle. At least a part of the iron brought in from the surrounding areas is precipitated as Fe(III)hydroxide in waterholes and waterchannels; the precipitate reaches the lakes with the sreamlets and is later reduced and precipitated as sulfides in the zones of desulfurizers or of solfataras with H_2S. The necessary energy is provided by the inorganic oxidation processes and by the organic compounds in the chemolithotrophic and chemoorganotrophic metabolism.

For the later diagenetic processes which may form sulphide deposits those sedimentations are available which enter into domains in which on one hand no bacterial processes exist which are able to destroy ore mineral deposits and in which on the other hand no physical and no chemical weathering processes dominate. Bacterial activities are, according to the present geomicrobiological knowledge inhibited in temperature ranges of $\overset{\sim}{>}$ 100 °C or in anaerobic domains at pH values of $\overset{\sim}{<}$ 4.5 (Desulfurizer). Chemical stability of metal sulfides is as a rule existing in volcanic exhalative temperature ranges at reducing conditions and pH values of $\overset{\sim}{>}$ 2.

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Authors' addresses:

A. Wauschkuhn und G. C. Amstutz, Mineralogisch-petrographisches Institut der Universität, Postfach 104040, D-6900 Heidelberg.

W. Schwartz, Institut für Molekularbiologie, Gastabteilung Geomikrobiologie, Mascheroder Weg, D-3300 Braunschweig-Stöckheim.

K. Yagi, Dept. Geology and Mineralogy, Hokkaido University, Sapporo, Japan.

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Resistivity Exploration for Altered Zone at Otake Geothermal Area - Japan *

T. NOGUCHI and S. ONODERA
Geophysical Exploration Laboratory
Kyushu University, Japan

Abstract

Geothermal electric power plant with a capacity of 10 mw has been now constructed by the Kyushu Electric Power Co. Ltd. at Otake, northern part of the Kyushu Island. Resistivity exploration, one of geophysical prospecting applied to this field in order to investigate the subsurface structure accompanied with natural steams, indicated low resistivity layer corresponding to altered zone of andesite due to hydrothermal agents.

For the rapid interpretation of resistivity sounding curves, a method of calculating the standard curve for the multiple layered earth is developed in the utilization of an electronic digital computer. Some examples to show the application of this method are given, and finally the result is described of resistivity measurement at Otake geothermal area.

Introduction

The Otake Geothermal Field is located in the Kujyu Volcano Group, approximately 30 km southwest of the hotspring city of Beppu, Oita Prefecture. This area shows a basin topography surrounded by such dome-shaped volcanoes as Mt. Waita, Mt. Misokobushi, Mt. Ichimoku, Mt. Ryoshi-dake, Mt. Gotoh, Mt. Kuroiwa, Mt. Kami-sensui and Mt. Sensui forming the west part of the Group. The Kusu River, which flows north through the central part of this area, has cut everywhere through altered zones. In addition, drilling loggs had shown the exist-

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ence of many cracks in altered zone providing active channels through which natural steams raise.

In fact, the observed resistivity values of pyroxine andesite and augite andesite are in the range of 6000-8000 ohm.m and 2000-3000 ohm.m respectively. While calculated values of low resistivity layer which corresponds to altered zone is of order 4-50 ohm.m. Consequently it is possible to investigate the subsurface distribution of altered zone by resistivity method of exploration.

In general we usually use the standard curve prepared by C.G.G (1965) and MOONEY (1956) for the application of curve matching method to the interpretation of resistivity sounding curves. However as far as the writers' aware, it does not always follow that these curves may be applied for all practical purposes. Stricktly speaking there is no curve in the case that the depth ratio, h_i/h_1 is greater than 25 and the deepest layer as a definite resistivity. From a point of view we developed a metod of calculating the resistivity for multiple layer problems. For rapid numerical calculations a digital computer has been utilized.

The subject of the present paper will be divided into two parts. Part I deals with fundamentals in the computation of the standard curve, procedures used in computer calculation and its practical application. In part II the result of resistivity exploration will be described for altered zone at Otake geothermal area.

Part I - A Method of the Interpretation

§ 1. BASIC EQUATIONS

The resistivity computation formula for the n-layer problem is given by the STEFANESCO and SCHLUMBERGER's integral equation of the form (1930):

$$\rho^*(a) = \frac{\rho(a)}{\rho_1} = 1 + 2a\int_0^\infty K_n(k_i, h_i; \lambda)\, J_0(\lambda a)\, d\lambda \qquad (1$$

where $\rho^*(a)$ is the relative resistivity defined by the ratio of the apparent resistivity, $\rho(a)$ to the resistivity of the upper layer, ρ_1, a is the

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$$\int_0^\infty K_n(k_j, h_j; \lambda) J_0(\lambda a)\, d\lambda \quad (1$$

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vity of the upper layer, ρ_1, a is th

stance between current and potential electrodes for the two elec-ode method, $K_n(k_j, h_j; \lambda)$ is the kernel function which is expressed as

$$K_n(k_j, h_j; \lambda) = \frac{G_n}{H_n - G_n} \tag{2}$$

which k_j is the reflection coefficients and is expressed by

$$k_j = (\rho_{j+1} - \rho_j) \,/\, (\rho_{j+1} + \rho_j), \; j = 1, 2, \ldots, n-1$$

which n denotes the number of layer, h_j is the depth of interface of vers, J_0 is the Bessel function of zero order and λ is a parameter.

The functions G_n and H_n are given by the FLATHE's recursion for-ula (1955):

$$\left.\begin{aligned} G_n &= G_{n-1} + k_{n-1}\, x_{n-1}\, H'_{n-1} \\ H_n &= H_{n-1} + k_{n-1}\, x_{n-1}\, G'_{n-1} \end{aligned}\right\} \tag{3}$$

here

$$H'_{n-1} = H_{n-1}\Big|_{\substack{x \to y \\ y \to x}} \quad \text{and} \quad G'_{n-1} = G_{n-1}\Big|_{\substack{x \to y \\ y \to x}}$$

ith the abbreviations

$$x_j = e^{-2\lambda h_j} \quad \text{and} \quad y_j = e^{2\lambda h_j}$$

or particular expressions we have

$$H_2 = H'_2 = 1, \; G_2 = k_1 x_1 \quad \text{and} \quad G'_2 = k_1 y_1$$

In numerical calculations of exponential functions by utilizing the mputer OKITAC-5090H, the magnitude of mantissa in real type a-thmetic of the object program must lie between the approximate mits of 10^{+77} and 10^{-77}, or be zero. Therefore, in the case that nu-erical values of the kernel function against a given model with eater depth of interfaces, we cannot use the recursion formula (3).

On the other hand, the ONODERA's recursion formula (1960)

$$\left.\begin{aligned} G_n &= G_{n-1} + k_{n-1}\, x_{n-1}\, k_{n-2}\, y_{n-2}\, G^{*}_{n-1} \\ H_n &= H_{n-1} + k_{n-1}\, x_{n-1}\, k_{n-2}\, y_{n-2}\, H^{*}_{n-1} \end{aligned}\right\} \tag{4}$$

here

$$G^{*}_{n-1} = G_{n-1}\Big|_{k_{n-2} \to k^{-1}_{n-2}}$$

$$H^{*}_{n-1} = H_{n-1}\Big|_{k_{n-2} \to k^{-1}_{n-2}}$$

es not be affected by such a limitation.

For numerical calculations, we write

$$F(a) = 2a \int_0^\infty K_n(k_j, h_j; \lambda) J_0(\lambda a)\, d\lambda \tag{5}$$

and make the transformation

$$e^{-2\lambda} = z$$

Here we write $K_n(z)$ for $K_n(k_j, h_j; \lambda)$ with $e^{-2\lambda}$ replaced by z. Then $K_n(z)$ is a function of z continuous on (0,1), and the particular values of $K_n(z)$ are

$$K_n(0) = 0 \quad \text{at } z = 0$$

$$K_n(1) = \frac{1}{2}(\rho_n/\rho_1 - 1) \quad \text{at } z = 1$$

If $K_n(z)$ is approximated by power series or a polynomial, $A_N(z)$ of degree N, then we have

$$K_n(z) \fallingdotseq A_N(z) = \sum_{\nu=1}^{N} A\nu\, z^\nu \tag{6}$$

where $A\nu$ are coefficients of power series or a polynomial, and may be determined by a method of undetermined coefficients. Substituting (6) in (5), and applying the Lipschits integral formula, we obtain the ulimate approximate formula for computing the integral (5):

$$F(a) = \sum_{\nu=1}^{N} A\nu \;\; \Delta\nu(a) \tag{7}$$

where

$$\Delta\nu(a) = \frac{2a}{\sqrt{4\nu^2 + a^2}} \tag{8}$$

If we denote the maximum error in $|A_N(z) - K_n(z)|$ *by* δ_N and the maximum error of relative resistivities by ε_N, then the fundamental formula for estimating the error of relative resistivities to be calculated is given by

$$\varepsilon_N = 2\delta_N \tag{9}$$

Strictly speaking, the problem of computing the numerical values of F(a) with preassigned amount of the limit of errors, denoted by

M' becomes that of determining the degree N of approximate polynomial satisfying the inequality

$$\delta_N \leqq \frac{M'}{2} \tag{10}$$

This may only be determined by trial and error methods. For a more detail in the deduction of equation (9) see ONODERA (1963).

Referring to Fig. 1, Δ-function for Schlumberger electrode arrangement are given by

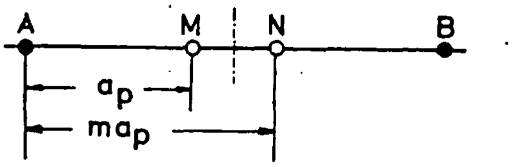

FIG. 1 - Schlumberger Electrode Arrangement.

$$\Delta v(a_p, ma_p) = \frac{m}{m-1}\,\Delta v(a_p) - \frac{1}{m-1}\,\Delta v(ma_p) \tag{11}$$

where

$$m = AN/AM$$

and the resistivity computation formula becomes

$$\rho^*(a_p; ma_p) = \frac{\rho(a_p, ma_p)}{\rho_1} = 1 + \sum_{v=1}^{N} Av\Delta v(a_p, ma_p) \tag{12}$$

If we put $m = 2$ in (11), then we get Δ-function for Wenner configuration.

2. PROCEDURES IN COMPUTER PROGRAM

The program was written in Kyushu Daigaku ALGOL for the OKITAC-5090H at the Computation Center of Kyushu University. Fig. 2 shows the flowchart of the program No. 15 in which numerical values of relative and apparent resistivities are computed against the separate electrode spacing of 60 for both Wenner and Schlumberger electrode arrangements or only each one of them. In Fig. 2, TITLE indicates the print of the title of the program. Δ-functions for Wenner and Schlumberger systems are calculated at the labels *D*1 and *D*2 respectively. LNEQ indicates the derivation of simultaneous equations, of which the solution is obtained by procedure RENRITU. CALRES indicates the calculation of relative and apparent resistivities. These values for Wenner electrode arrangement are computed at the label *C*1 and those for Schlumberger system at the lable *C*2.

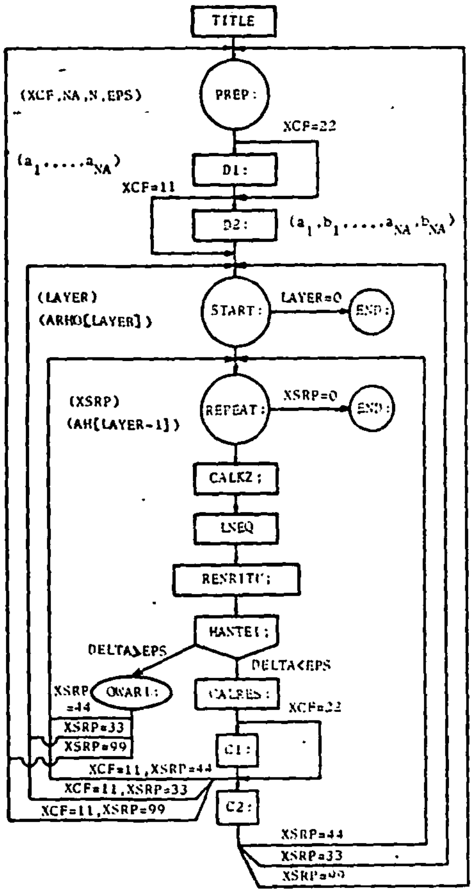

FIG. 2 - Flowchart of the Program No. 15.

The input data consist of

XCF, integer of changing curves to be calculated. If *XCF* = 12, then both Wenner and Schlumberger curves can be calculated. If *XCF* = 11, then only Wenner curve, and if *XCF* = 22, then only Schlumberger curve;

NA, the n

N, the de
func

EPS, the a

LAYER, th

RHO[I], a

XSRP, int

H[I], arra

which are pun
the program ta
Some proc

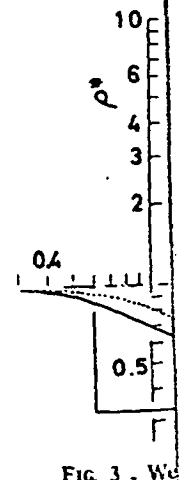

FIG. 3 - We

§ 3. THE OUTPU

After the ti
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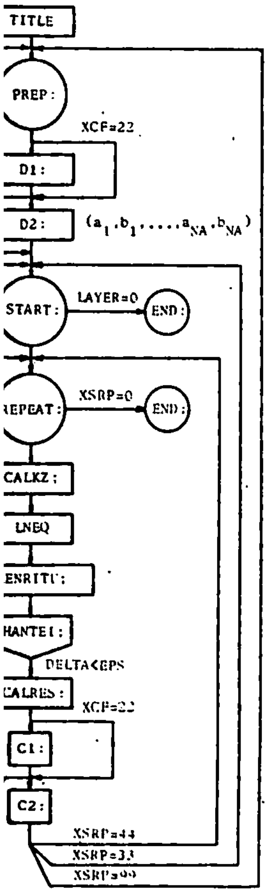
easily seen from

calculated at the labels *D*1 and
derivation of simultaneous equati
ed by procedure RENRITU. CALRES
ive and apparent resistivities. Th
angement are computed at the la
system at the lable *C*2.



of the Program No. 15.

rves to be calculated. If *XCF* =
Schlumberger curves can be cal
ıen only Wenner curve, and if M
mberger curve;

NA, the number of electrode spacing;

N, the degree of a polynomial for approximating the kernel function;

EPS, the accuracy of resistivity to be calculated;

LAYER, the number of layer in a given model;

RHO[I], array of resistivity of the model;

XSRP, integer indicating the go to statement;

H[I], array of depth of interfaces;

hich are punched onto cards in turn. These cards continued from
program tape are supplied to the computer.

Some procedures used in the program are listed in Table 1.

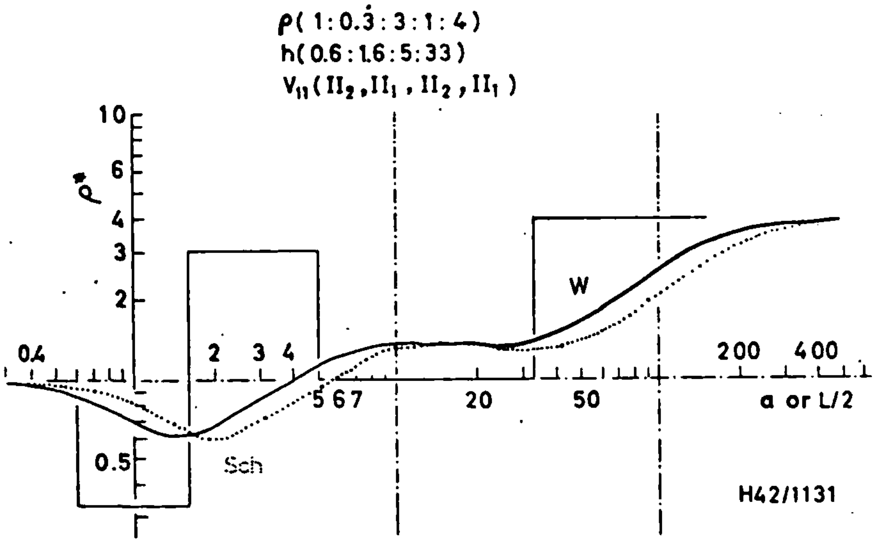


FIG. 3 - Wenner and Schlumberger Curves for a Five Layered Earth.

3. THE OUTPUT

After the time of 57 seconds in comuter processing, we can get
e output, as shown in Table 2, for a given five layer example. It is
sily seen from this table that the accuracy in relative resistivity

Table 1 - Some Procedures used in the Program. For the purpose of reference procedure CALKZ based on the Flathe's recursion formula is listed.

```
procedure COEFFK;
   begin for J: =1 step 1 until LAYER-1 do
            AK [J] : = (ARHO [J+1] - ARHO [J]) / (ARHO [J+1] + ARHOL [J])
   end;

procedure CALKZ; comment Onodera's Recurrence Formulas;
   begin real BH, Z, LNZ, PZ, KI, KIS, HI, EHL; array PH, PHS, PG, PGS [1:49];
      BH: =1.0/FLOAT(N); PH[2]: =PHS[2]: =1.0; I: =0;
      for Z: =BH step BH until 1.01 do
         begin I:=I+1; AZ[I]: =Z; LNZ: =LN(Z);
            PG[2]: =AK[1]*EXP(AH[1]*LNZ); PGS[2]: =EXP(AH[1]*LNZ) / AK[1];
            if LAYER = 2 then go to L1;
            for J: =3 step 1 until LAYER do
                 begin KI: =AK[J-2]*AK[J-1]; KIS: =AK[J-2] /AK[J-1];
                         HI: =AH[J-1]-AH[J-2]; EHL: =EXP(HI*LNZ);
                   PH[J]: =PH[J-1]+KI*EHL*PHS[J-1];
                  PHS[J]: =PH[J-1]+KIS*EHL*PHS[J-1];
                   PG[J]: =PG[J-1]+KI*EHL*PGS[J-1];
                   PGS[J]: =PG[J-1]+KIS*EHL*PGS[J-1]
                 end;
            L1:  PZ: =PG[LAYER] / PH[LAYER]; PZ: =PZ / (1.0-PZ); AKZ[I]: =PZ
         end
   end; halt

procedure CALKZ: comment Recurrence Formula presented by Flathe;
   begin real BH, Z, LNZ, PZ; array PH, PHD, PG, PGD [1 : 49];
      BH: =1.0/FLOAT(N); Z: =0; for I: =1 step 1 until N do
      begin Z: =Z+BH; AZ[I]:=Z; LNZ: =LN(Z); PH[2]: =PHD[2]: =1.0;
            PG[2]:=AK[1]*EXP(AH[1]*LNZ):
            PGD[2]: =AK[1]*EXP(-AH[1]*LNZ);
         if LAYER=2 then go to L1;
        for J: =3 step 1 until LAYER do
         begin PH[J]: =PH[J-1]+AK[J-1]*EXP(AH[J-1]*LNZ)*PGD[J-1]:
                  PG[J]: =PG[J-1]+AK[J-1]*EXP(AH[J-1]*LNZ)*PHD[J-1];
                PHD[J]:=PHD[J-1]+AK[J-1]*EXP(-AH [J-1]*LNZ)*PG[J-1];
                 PGD[J]:=PGD[J-1]+AK[J-1]*EXP(-AH [J-1]*LNZ)*PH[J-1]:
         end;
        L1: PZ: =PG[LAYER]/PH[LAYER]; PZ:=PZ/(1.0-PZ); AKZ[I]: =PZ
      end
   end; halt

procedure CALAZ;
   begin real P; P: =AI[N]; for J: =N-1 step -1 until do
                  P:=P*Z+AI[J]; AZ[I]:=P:=P*Z
   end;

procedure HANTEI;
   begin for I: =1 step 1 until N do
      begin DELTA:=2.0*ABS(AZ[I]-AKZ[I]); ADEL[I]:=DELTA;
         if DELTA>EPS then go to OWARI
      end; I: =N; OWARI:
   end; halt
```

Table 2 - The Output of the Computer Calculation

```
LAYER =  5              EPS = 0.05000
  RHO =  1.0000000            0.3333333      3.0000000      1.0000000      4.0000000
    K = -0.5000000            0.8000000     -0.5000000      0.6000000
    H =  1.0000000            3.0000000      6.0000000     11.0000000

      I                 COEFF A          Z           K (Z)          A (Z)          ERROR
```

TABLE 2 - The Output of the Computer Calculation

LAYER = 5 EPS = 0.05000

RHO =	1.0000000	0.3333333	3.0000000	1.0000000	4.0000000
K =	−0.5000000	0.8000000	−0.5000000	0.6000000	
H =	1.0000000	3.0000000	6.0000000	11.0000000	

I	COEFF A	Z	K (Z)	A (Z)	ERROR
1	$-.497996796_{10}$ 0	0.05	$-.243187832_{10}-1$	$-.243187830_{10}-1$	$.378349796_{10}-9$
2	$.124189649_{10}$ 0	0.10	$-.470724543_{10}-1$	$-.470724538_{10}-1$	$.101863407_{10}-8$
3	$.380130589_{10}$ 1	0.15	$-.679972238_{10}-1$	$-.679972210_{10}-1$	$.547152013_{10}-8$
4	$-.504402778_{10}$ 2	0.20	$-.868671502_{10}-1$	$-.868671341_{10}-1$	$.321306288_{10}-7$
5	$.481070844_{10}$ 3	0.25	$-.103476292_{10}$ 0	$-.103476227_{10}$ 0	$.128813554_{10}-6$
6	$-.317356854_{10}$ 4	0.30	$-.117622522_{10}$ 0	$-.117622322_{10}$ 0	$.400992576_{10}-6$
7	$.150168435_{10}$ 5	0.35	$-.129092243_{10}$ 0	$-.129091729_{10}$ 0	$.102887861_{10}-5$
8	$-.526970379_{10}$ 5	0.40	$-.137645060_{10}$ 0	$-.137644018_{10}$ 0	$.208418351_{10}-5$
9	$.142116824_{10}$ 6	0.45	$-.142997084_{10}$ 0	$-.142994505_{10}$ 0	$.515626743_{01}-5$
10	$-.306472629_{10}$ 6	0.50	$-.144800377_{10}$ 0	$-.144795526_{10}$ 0	$.970158726_{01}-5$
11	$.540375888_{10}$ 6	0.55	$-.142613109_{10}$ 0	$-.142605071_{10}$ 0	$.160755590_{10}-4$
12	$-.731433048_{10}$ 6	0.60	$-.135847391_{10}$ 0	$-.135835320_{10}$ 0	$.241410453_{10}-4$
13	$.512806673_{10}$ 6	0.65	$-.123662326_{10}$ 0	$-.123642835_{10}$ 0	$.389830093_{10}-4$
14	$.644767539_{10}$ 6	0.70	$-.104720263_{10}$ 0	$-.104665067_{01}$ 0	$.110391411_{10}-3$
15	$-.269333968_{10}$ 7	0.75	$-.765962337_{10}-1$	$-.765106563_{10}-1$	$.171154796_{10}-3$
16	$.437981389_{10}$ 7	0.80	$-.342824992_{10}-1$	$-.342827349_{10}-1$	$.471394742_{10}-6$
17	$-.427407623_{10}$ 7	0.85	$.338517304_{10}-1$	$.339922830_{10}-1$	$.281105109_{10}-3$
18	$.258852408_{10}$ 7	0.90	$.158620574_{10}$ 0	$.159553641_{10}$ 0	$.186613377_{10}-2$
19	$-.901010144_{10}$ 6	0.95	$.442844682_{10}$ 0	$.445027533_{10}$ 0	$.436570216_{10}-2$
20	$.138348050_{10}$ 6	1.00	$.150000002_{10}$ 1	$.150718302_{10}$ 1	$.143660009_{10}-1$

WENNER CURVE								SCHLUMBERGER CURVE		
A	R (A)	AR (A)	AM	AN	MN/2	AN/AM	AB/MN	AO	R (AO)	AR (AO)
0.1	0.9997	0.9997	0.26	0.340	0.04	1.307692	7.5000	0.30	0.9971	0.9971
0.2	0.9973	0.9973	0.36	0.440	0.04	1.222222	10.0000	0.40	0.9930	0.9930
0.3	0.9916	0.9916	0.46	0.540	0.04	1.173913	12.5000	0.50	0.9870	0.9870
0.4	0.9811	0.9811	0.56	0.640	0.04	1.142857	15.0000	0.60	0.9788	0.9788
0.5	0.9661	0.9661	0.66	0.740	0.04	1.121212	17.5000	0.70	0.9683	0.9683
0.6	0.9468	0.9468	0.64	0.960	0.16	1.500000	5.0000	0.80	0.9565	0.9565
0.7	0.9235	0.9235	0.74	1.060	0.16	1.432432	5.6250	0.90	0.9407	0.9407
0.8	0.8972	0.8972	0.84	1.160	0.16	1.380952	6.2500	1.00	0.9236	0.9236
0.9	0.8693	0.8693	1.04	1.360	0.16	1.307692	7.5000	1.20	0.8845	0.8845
1.0	0.8406	0.8406	1.24	1.560	0.16	1.258065	8.7500	1.40	0.8405	0.8405
1.2	0.7847	0.7847	1.44	1.760	0.16	1.222222	10.0000	1.60	0.7982	0.7982
1.4	0.7334	0.7334	1.64	1.960	0.16	1.195122	11.2500	1.80	0.7551	0.7551
1.6	0.6900	0.6900	1.84	2.160	0.16	1.173913	12.5000	2.00	0.7183	0.7183
1.8	0.6563	0.6563	2.04	2.360	0.16	1.156863	13.7500	2.20	0.6803	0.6803
2.0	0.6300	0.6300	2.34	2.660	0.16	1.136752	15.6250	2.50	0.6440	0.6440
2.2	0.6118	0.6118	2.64	2.960	0.16	1.121212	17.5000	2.80	0.6127	0.6127
2.4	0.6027	0.6027	2.84	3.160	0.16	1.112676	18.7500	3.00	0.5989	0.5989
2.6	0.5982	0.5982	2.76	4.040	0.64	1.463768	5.3125	3.40	0.5888	0.5888
2.8	0.5987	0.5987	3.36	4.640	0.64	1.380952	6.2500	4.00	0.5856	0.5856
3.0	0.6012	0.6012	3.76	5.040	0.64	1.340426	6.8750	4.40	0.5966	0.5966
3.4	0.6220	0.6220	4.36	5.640	0.64	1.293578	7.8125	5.00	0.6265	0.6265
4.0	0.6638	0.6638	5.36	6.640	0.64	1.238806	9.3750	6.00	0.6869	0.6869
4.4	0.6977	0.6977	6.36	7.640	0.64	1.201258	10.9375	7.00	0.7518	0.7518
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.64	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8.0	0.9914	0.9914	11.50	16.500	2.50	1.434783	5.6000	14.00	1.1215	1.1215
9.0	1.0632	1.0632	13.50	18.500	2.50	1.370370	6.4000	16.00	1.2073	1.2073
10.0	1.1267	1.1267	15.50	20.500	2.50	1.322581	7.2000	18.00	1.2864	1.2864
12.0	1.2352	1.2352	17.50	22.500	2.50	1.285714	8.0000	20.00	1.3546	1.3546
14.0	1.3448	1.3448	19.50	24.500	2.50	1.256410	8.8000	22.00	1.4381	1.4381
16.0	1.4379	1.4379	22.50	27.500	2.50	1.222222	10.0000	25.00	1.5411	1.5411
18.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

0.9	0.8693	0.8693	1.04	1.360	0.16	1.307692	7.5000	1.20	0.8845	0.8845
1.0	0.8406	0.8406	1.24	1.560	0.16	1.258065	8.7500	1.40	0.8405	0.8405
1.2	0.7847	0.7847	1.44	1.760	0.16	1.222222	10.0000	1.60	0.7982	0.7982
1.4	0.7334	0.7334	1.64	1.960	0.16	1.195122	11.2500	1.80	0.7551	0.7551
1.6	0.6900	0.6900	1.84	2.160	0.16	1.173913	12.5000	2.00	0.7183	0.7183
1.8	0.6563	0.6563	2.04	2.360	0.16	1.156863	13.7500	2.20	0.6803	0.6803
2.0	0.6300	0.6300	2.34	2.660	0.16	1.136752	15.6250	2.50	0.6440	0.6440
2.2	0.6118	0.6118	2.64	2.960	0.16	1.121212	17.5000	2.80	0.6127	0.6127
2.4	0.6027	0.6027	2.84	3.160	0.16	1.112676	18.7500	3.00	0.5989	0.5989
2.6	0.5982	0.5982	2.76	4.040	0.64	1.463768	5.3125	3.40	0.5888	0.5888
2.8	0.5987	0.5987	3.36	4.640	0.64	1.380952	6.2500	4.00	0.5856	0.5856
3.0	0.6012	0.6012	3.76	5.040	0.64	1.340426	6.8750	4.40	0.5966	0.5966
3.4	0.6220	0.6220	4.36	5.640	0.64	1.293578	7.8125	5.00	0.6265	0.6265
4.0	0.6638	0.6638	5.36	6.640	0.64	1.238806	9.3750	6.00	0.6869	O.6869
4.4	0.6977	0.6977	6.36	7.640	0.64	1.201258	10.9375	7.00	0.7518	0.7518
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8.0	[illegible]	[illegible]	11.50	16.500	2.50	1.434783	5.6000	14.00	1.1215	1.1215
9.0	1.0632	1.0632	13.50	18.500	2.50	1.370370	6.4000	16.00	1.2073	1.2073
10.0	1.1267	1.1267	15.50	20.500	2.50	1.322581	7.2000	18.00	1.2864	1.2864
12.0	1.2352	1.2352	17.50	22.500	2.50	1.285714	8.0000	20.00	1.3546	1.3546
14.0	1.3448	1.3448	19.50	24.500	2.50	1.256410	8.8000	22.00	1.4381	1.4381
16.0	1.4379	1.4379	22.50	27.500	2.50	1.222222	10.0000	25.00	1.5411	1.5411
18.0	1.5279	1.5279	25.50	30.500	2.50	1.196078	11.2000	28.00	1.6265	1.6265
20.0	1.6163	1.6163	27.50	32.500	2.50	1.181818	12.0000	30.00	1.6932	1.6932
25.0	1.8228	1.8228	31.50	36.500	2.50	1.158730	13.6000	34.00	1.8114	1.8114
30.0	2.0092	2.0092	37.50	42.500	2.50	1.133333	16.0000	40.00	1.9970	1.9970
32.0	2.0786	2.0786	41.50	46.500	2.50	1.120482	17.6000	44.00	2.0821	2.0821
40.0	2.3189	2.3189	40.00	60.000	10.00	1.500000	5.0000	50.00	2.2003	2.2003
48.0	2.5292	2.5292	50.00	70.000	10.00	1.400000	6.0000	60.00	2.3955	2.3955
56.0	2.6913	2.6913	60.00	80.000	10.00	1.333333	7.0000	70.00	2.5713	2.5713
64.0	2.8483	2.8483	70.00	90.000	10.00	1.285714	8.0000	80.00	2.7548	2.7548
80.0	3.0916	3.0916	80.00	100.000	10.00	1.250000	9.0000	90.00	2.8710	2.8710
96.0	3.2674	3.2674	90.00	110.000	10.00	1.222222	10.0000	100.00	2.9890	2.9890
100.0	3.2984	3.2984	110.00	130.000	10.00	1.181818	12.0000	120.00	3.1765	3.1765
120.0	3.4578	3.4578	130.00	150.000	10.00	1.153846	14.0000	140.00	3.3672	3.3672
160.0	3.6591	3.6591	150.00	170.000	10.00	1.133333	16.0000	160.00	3.4081	3.4081
200.0	3.7721	3.7721	170.00	190.000	10.00	1.117647	18.0000	180.00	3.5937	3.5937
240.0	3.8252	3.8252	160.00	240.000	40.00	1.500000	5.0000	200.00	3.6025	3.6025
280.0	3.8785	3.8785	180.00	260.000	40.00	1.400000	5.5000	220.00	3.6592	3.6592
320.0	3.9246	3.9246	210.00	290.000	40.00	1.380952	6.2500	250.00	3.7439	3.7439
400.0	3.9442	3.9442	240.00	320.000	40.00	1.333333	7.0000	280.00	3.7759	3.7759
480.0	3.9729	3.9729	280.00	360.000	40.00	1.285784	8.0000	320.00	3.8452	3.8452
560.0	3.9889	3.9889	340.00	420.000	40.00	1.235294	9.5000	380.00	3.8881	3.8881
640.0	3.9977	3.9977	420:00	500.000	40.00	1.190476	11.5000	460.00	3.9277	3.9277

Table 3 - A Series of Schlumberger Electrode Arrangement used at Otake. This system shows $\overline{m}$ = 1.274038.

AM	AN	MN/2	AN/AM	AB/MN	AO
0.400	0.600	0.100	1.500000	5.000000	0.5000
0.500	0.700	0.100	1.400000	6.000000	0.6000
0.600	0.800	0.100	1.333333	7.000000	0.7000
0.700	0.900	0.100	1.285714	8.000000	0.8000
0.800	1.000	0.100	1.250000	9.000000	0.9000
0.900	1.100	0.100	1.222222	10.000000	1.0000
1.100	1.300	0.100	1.181818	12.000000	1.2000
1.400	1.600	0.100	1.142857	15.000000	1.5000
1.250	1.750	0.250	1.400000	6.000000	1.5000
1.450	1.950	0.250	1.344828	6.800000	1.7000
1.750	2.250	0.250	1.285714	8.000000	2.0000
2.150	2.650	0.250	1.232558	9.600000	2.4000
2.750	3.250	0.250	1.181818	12.000000	3.0000
3.150	3.650	0.250	1.158730	13.600000	3.4000
3.750	4.250	0.250	1.133333	16.000000	4.0000
4.750	5.250	0.250	1.105263	20.000000	5.0000
4.000	6.000	1.000	1.500000	5.000000	5.0000
5.000	7.000	1.000	1.400000	6.000000	6.0000
6.000	8.000	1.000	1.333333	7.000000	7.0000
7.000	9.000	1.000	1.285714	8.000000	8.0000
8.000	10.000	1.000	1.250000	9.000000	9.0000
9.000	11.000	1.000	1.222222	10.000000	10.0000
11.000	13.000	1.000	1.181818	12.000000	12.0000
14.000	16.000	1.000	1.142857	15.000000	15.0000
12.500	17.500	2.500	1.400000	6.000000	15.0000
17.500	22.500	2.500	1.285714	8.000000	20.0000
21.500	26.500	2.500	1.232558	9.000000	24.0000
27.500	32.500	2.500	1.181818	12.000000	30.0000
37.500	42.500	2.500	1.130000	16.000000	40.0000
47.500	52.500	2.500	1.105263	20.000000	50.0000
40.000	60.000	10.000	1.500000	5.000000	50.0000
50.000	70.000	10.000	1.400000	6.000000	60.0000
60.000	80.000	10.000	1.333333	7.000000	70.0000
70.000	90.000	10.000	1.285714	8.000000	80.0000
80.000	100.000	10.000	1.250000	9.000000	90.0000
90.000	110.000	10.000	1.222222	10.000000	100.0000
110.000	130.000	10.000	1.181818	12.000000	120.0000
140.000	160.000	10.000	1.142857	15.000000	150.0000
190.000	210.000	10.000	1.105263	20.000000	200.0000
160.000	240.000	40.000	1.500000	5.000000	200.0000
200.000	280.000	40.000	1.400000	6.000000	240.0000
260.000	340.000	40.000	1.307692	7.500000	300.0000
360.000	440.000	40.000	1.222222	10.000000	400.0000
320.000	480.000	80.000	1.500000	5.000000	400.0000
420.000	580.000	80.000	1.380952	6.250000	500.0000
520.000	680.000	80.000	1.307692	7.500000	600.0000
620.000	780.000	80.000	1.258065	8.750000	700.0000
720.000	880.000	80.000	1.222222	10.000000	800.0000
820.000	980.000	80.000	1.195122	11.250000	900.0000
920.000	1080.000	80.000	1.173913	12.500000	1000.0000

rangement used at Otake. This system

	AB/MN	AO
00	5.000000	0.5000
00	6.000000	0.6000
33	7.000000	0.7000
14	8.000000	0.8000
00	9.000000	0.9000
22	10.000000	1.0000
18	12.000000	1.2000
57	15.000000	1.5000
00	6.000000	1.5000
28	6.800000	1.7000
14	8.000000	2.0000
58	9.600000	2.4000
18	12.000000	3.0000
30	13.600000	3.4000
13	16.000000	4.0000
3	20.000000	5.0000
0	5.000000	5.0000
0	6.000000	6.0000
3	7.000000	7.0000
4	8.000000	8.0000
0	9.000000	9.0000
2	10.000000	10.0000
8	12.000000	12.0000
7	15.000000	15.0000
0	6.000000	15.0000
4	8.000000	20.0000
8	9.000000	24.0000
8	12.000000	30.0000
0	16.000000	40.0000
3	20.000000	50.0000
	5.000000	50.0000
	6.000000	60.0000
	7.000000	70.0000
	8.000000	80.0000
	9.000000	90.0000
	10.000000	100.0000
	12.000000	120.0000
	15.000000	150.0000
	20.000000	200.0000
	5.000000	200.0000
	6.000000	240.0000
	7.500000	300.0000
	10.000000	400.0000
	5.000000	400.0000
	6.250000	500.0000
	7.500000	600.0000
	8.750000	700.0000
	10.000000	800.0000
	11.250000	900.0000
	12.500000	1000.0000

calculated will remain within the order of 0.014366 which is printed in the last line of *ERROR* column. Fig. 3 shows Wenner curve, which is the logarithmic plot of the relative resistivity in ordinate with reference to logarithmic electrode distance, a in abscissa, and shows Schlumberger curve plotted by the double logarithmic scales that the computed relative resistivity is taken as ordinate against a half distance between current electrodes, denoted by $L/2$, as abscissa.

If we now write II_1 for the group of resistivity sounding curves in two layer case when $\rho_1 < \rho_2$, and also II_2 for those when $\rho_1 > \rho_2$, then the characteristic feature of both curves is expressible as V_{11} (II_2, II_1, II_2, II_1). In other wards these involved consist of a series of II_2, II_1, II_2 and II_1.

Further, if the origin, (1, 1) of Schlumberger curve is slide to the left side along the axis of abscissa by 1.3 approximately, then we may roughly find the overlap one upon another. The shift of the origin is given by

$$\overline{m} = 1.256212 \tag{13}$$

which is the arithmetical mean of m showing a fixed value for a given electrode system available. As a result of this investigation, we may conclude that no essential difference exist between Wenner and Schlumberger curves.

§ 4. SOME EXAMPLES OF THE INTERPRETATION FOR FIELD CURVES

We have observed resistivity sounding curves for a two-, three-, four- and five-layer earth at Otake geothermal area. In general better knowledge of the characteristics of such curves will enable us to determine the subsurface structure with better accuracy. Some results of the interpretation will be summarized briefly as follows:

Ex. 1. Two layer curve

Fig. 4 shows the result of the interpretation for a field curve obtained at the station S9 on the line L2, abbreviated to L2S9. The values of apparent resistivity are observed for the system of Schlumberger electrode arrangement as shown in Table 3. The observed values in ohm.m are plotted by circles and black circles. The theoretic-

wn in the lower part of Fig.
from this that observed val.
e. Therefore we may draw a
consists of a two layer earth
second layers in 800 and 44
f the first layer in 96 m. We
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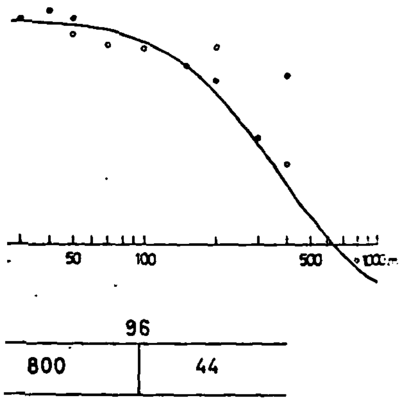

Field Curve obtained at L2S9.

own in Fig. 4 may be excluded
the experience that resistivity
when one or two electrodes of
hill, and on a road or into a

n between the observed values
3'S'8 and L/2 together with the
yer. This is one of the typical
eothermal area. Our presump-

tion is that the third layer corresponds to reservoirs of natural steams. Unfortunately we could not determined the thickness of the third layer from the field curve.

Fig. 6 shows the result of the interpretation for the field curve obtained at L1S21. As a whole, this curve gives a resistivity indication that altered zone exists in shallow depth.

Ex. 3. Four layer curves

As shown in Fig. 7, some points are apart from the calculated curve. By considering the relation between the positions of the electrode stakes and the topographies or geological conditions; we may easily find that these points show irregular values due to surface conditions. The third layer with the resistivity of 20 ohm-m and the thickness of 467 m corresponds to altered zone of andesite.

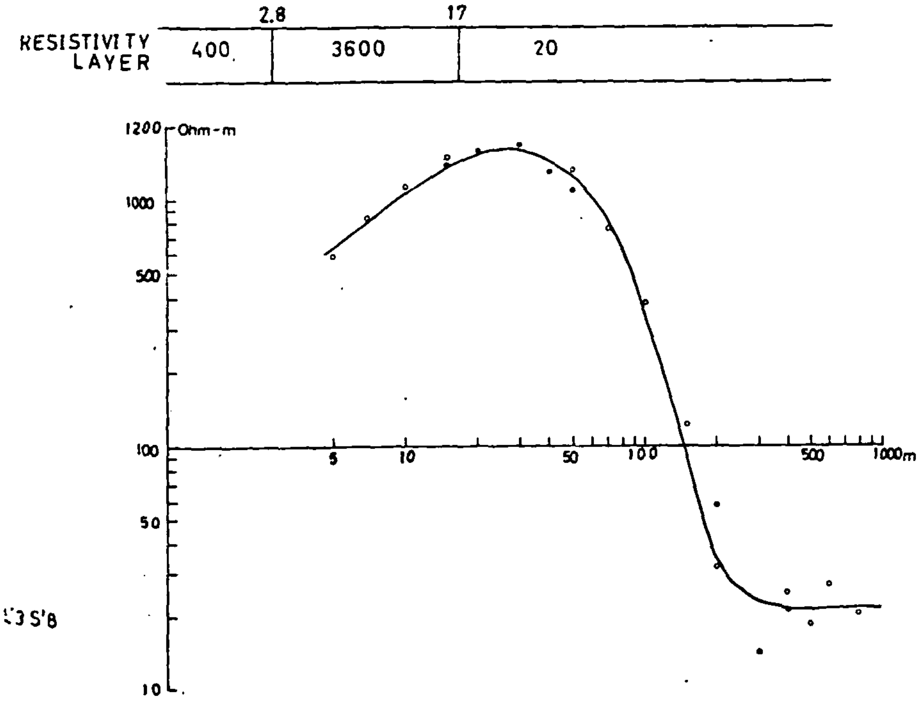

FIG. 5.

Another example similar to above is shown in Fig. 8. After close al curve for the resistivity layer as shown in the lower part of Fig. 4 is drawn by a solid curve. We can see from this that observed values lie roughly on the theoretical curve. Therefore we may draw a conclusion that the subsurface structure consists of a two layer earth with the resistivity of the first and the second layers in 800 and 44 ohm-m respectively and the thickness of the first layer in 96 m. We should note that observed values and some of them for 4 fixed values

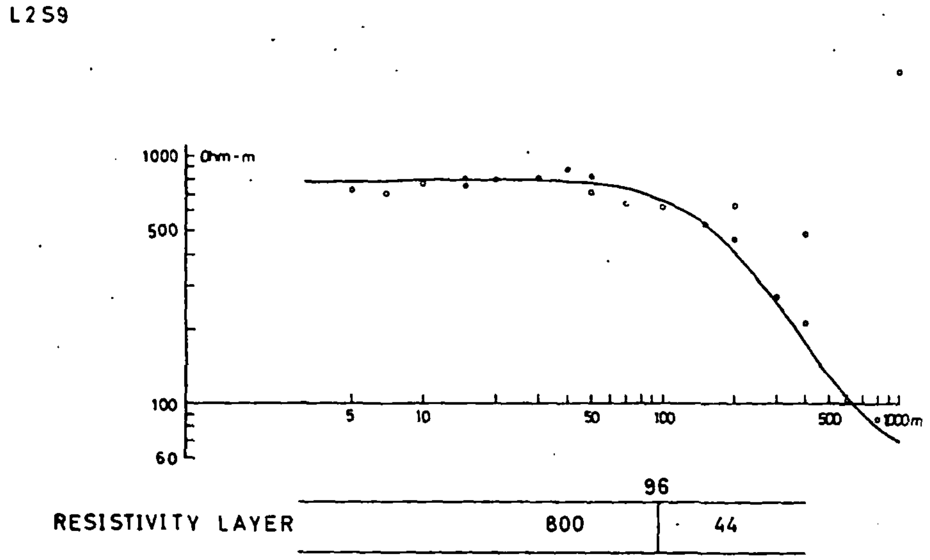

FIG. 4 - The Result of Interpreting the Field Curve obtained at L2S9.

of L/2 *i.e.* 200, 400, 500 and 1000 m shown in Fig. 4 may be excluded from resistivity data on the basis of the experience that resistivity measurements show the erratic values when one or two electrodes of the system are grounded at a ridge of hill, and on a road or into a river.

Ex. 2. Three layer curves

Fig. 5 shows the plot of the relation between the observed values in apparent resistivity at the station L3'S'8 and L/2 together with the calculated curve for the resistivity layer. This is one of the typical resistivity sounding curves at Otake geothermal area. Our presump-

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Ex. 3. Four

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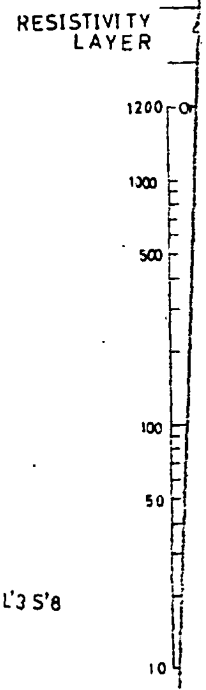

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examination of this field curve, we get the resistivity layer, in which the third layer corresponds to steam reservoirs. The limit of drilling depth is given by the interface between the third and the fourth resistivity layers.

Finally an interesting phenomenon is presented in measurements of apparent resistivity by introducing the commutated current of the rectangular wave, 15 cps and the direct current into the ground. The measurement was made with Schlumberger electrode arrangement on the same station LOS14 near production wells and yielded a result as shown in Fig. 9. In this figure circles show the plot of the values in apparent resistivity observed by Gish-Rooney apparatus for the electrode system available. In this case there is no need to take into consideration the effect of polarization of the ground. While black circles show the plot of the same relation when the direct current is supplied into the earth. In this case it will be natural to consider the polarization phenomenon of any materials in the earth due to high density of current sources. In Fig. 9, both curves have the same indication as long as L/2 is smaller than 50 m approximately, but they show different shapes when 50 < L/2 < 1000 m. This difference probably seems to be derived from the conduction of ion in the subsurface formation containing heated water. Although the investigation of this interest-

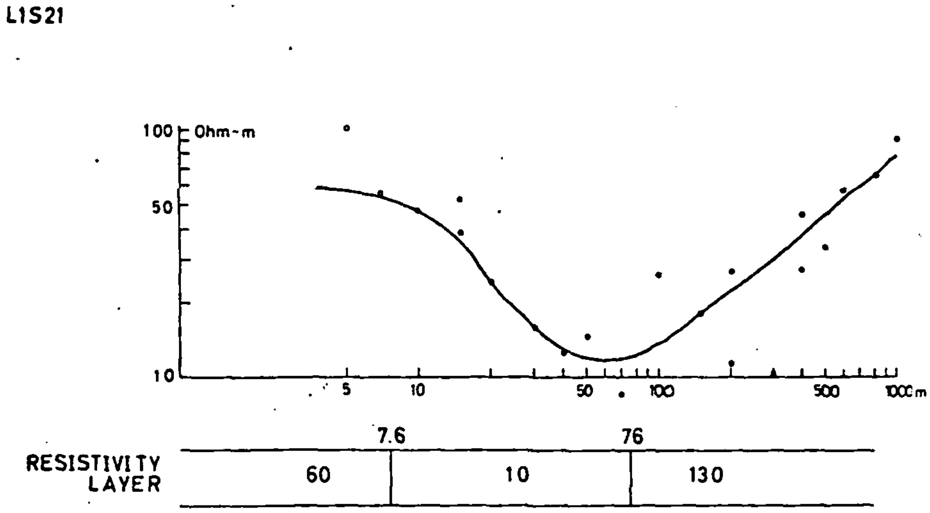

Fig. 6.

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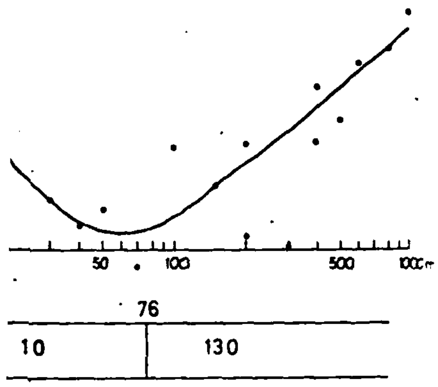

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ing phenomenon leads to another key of detecting geothermal resources, the problem will be left in future.

The result of the interpretation in the former case is given by the resistivity layer as shown in the lower part of Fig. 9. In comparing this result with the drilling loggs at the production wells, Nos. 7-10, we may conclude that the result agrees with the subsurface stracture producing natural steam.

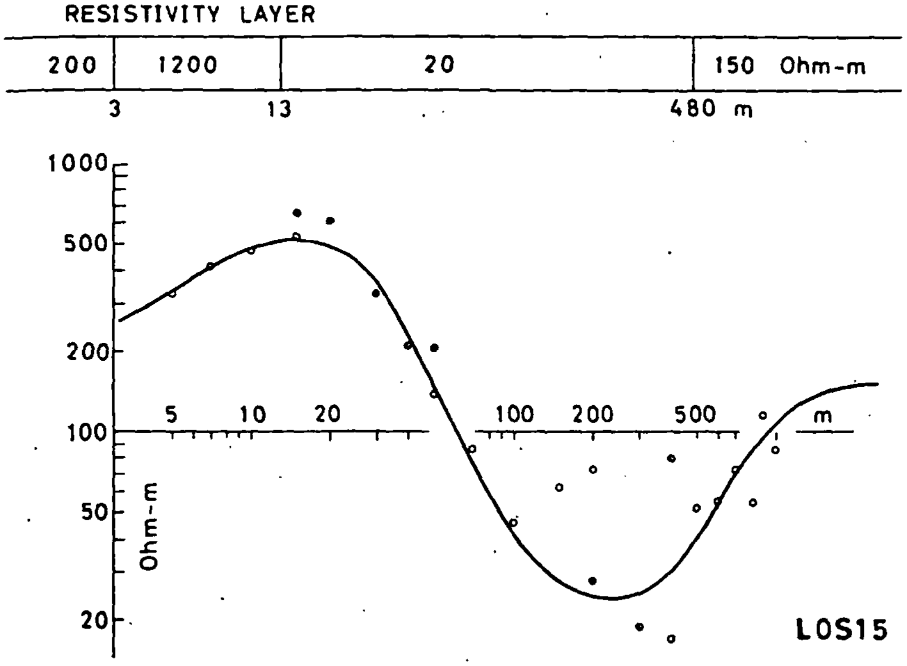

Fig. 7.

Part II - Results of Resistivity Exploration

It is the aim of resistivity exploration to determine the shape and the distribution of altered zone in close relation to heat sources.

The resistivity survey with the apparatus devised by Noguchi (1942) covers the central area of 12 km^2 approximately, and the total length of surveying lines is 32 km approximately. In August 1965, 35 resistivity sounding curves were observed on the L1, L2 and L3' lines.

In July 1966, 36 curves on the L3 and L4 lines and in July 1967, 36 curves on the L5 and L0 lines (Fig. 10).

The interpreting process of resistivity data was carried out in the following two steps: the first step deals with the interpretation of resistivity mapping curves, which were prepared from a series of resistivity sounding curves on the same line. Discussing the tendency of these curves accompanied with the increase of L/2, we get such the knowledge of information as the part of the area showing the stratified earth, which is indicated by horizontal forms of these curves, the existence of faults, which is indicated by step forms, and of high or low resistivity zone. The second step is to apply the curve matching method of interpretation to the resistivity sounding curves showing the layered earth.

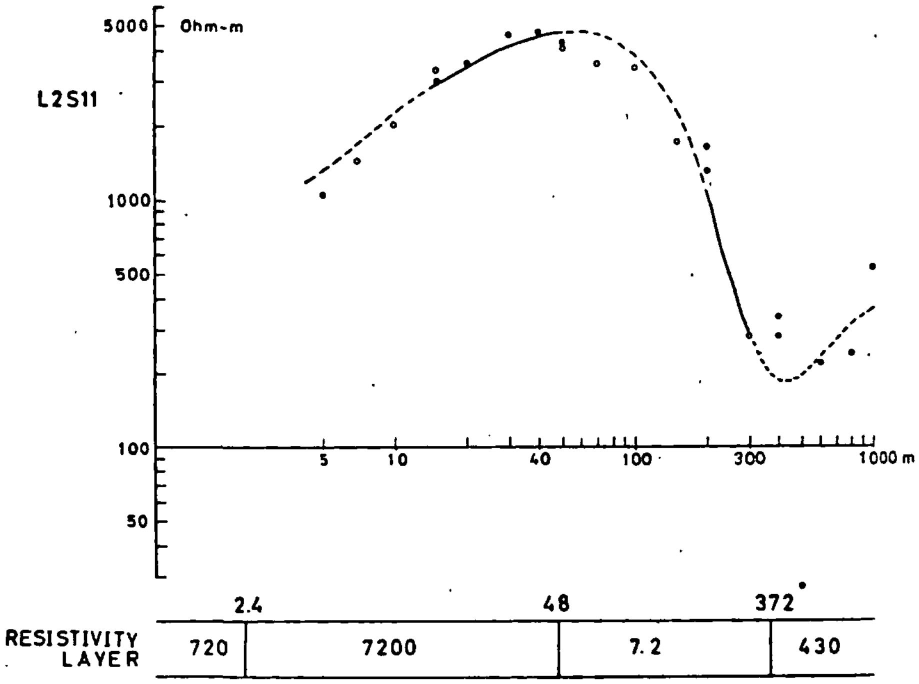

FIG. 8.

Owing to the effect of topography, the existence of faults, complex geological conditions characterized by volcanic area, groundwater and so on, the observed curves in many cases deviated from

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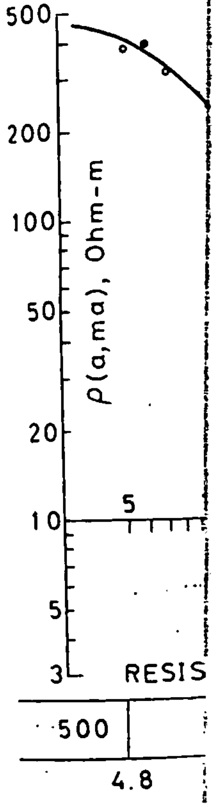

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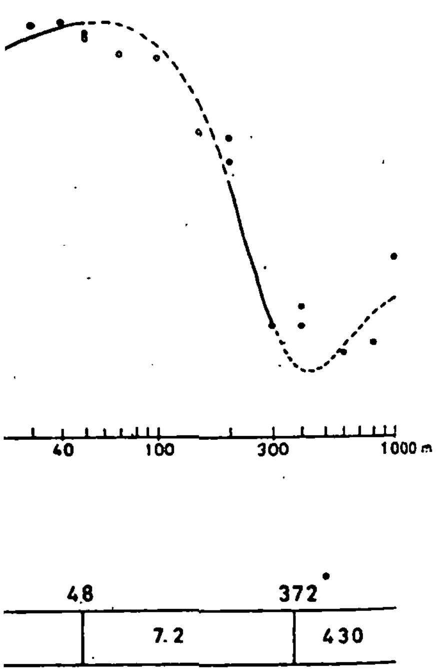

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' horizontal forms of these curves.
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step is to apply the curve match-
resistivity sounding curves show-

ɔhy, the existence of faults, com-
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ves in many cases deviated from

the theoretical curve. However resistivity measurements indicated clearly low resistivity layer corresponding to altered zone because of very high resistivity contrast between altered zone and formations above or below it. The effect of resistivity contrast of geologic body on the field curve is shown at the upper left hand corner of Fig. 11 togheter with the theoretical curve of four layer case.

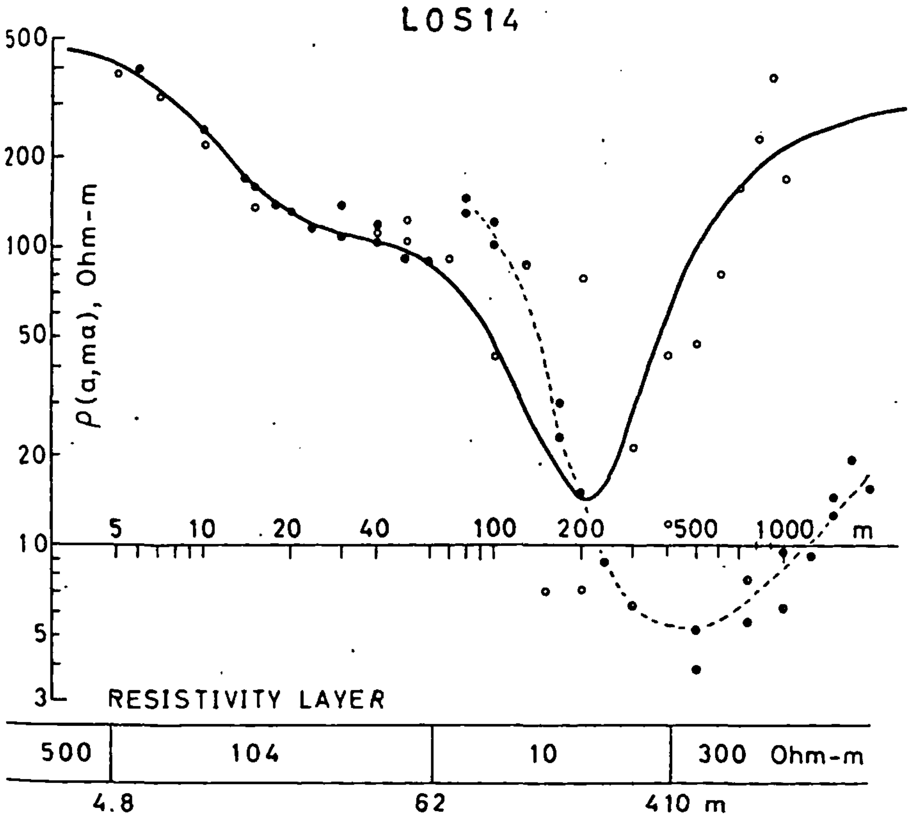

FIG. 9.

Fig. 11 shows the resistivity block diagram drawn from the result of interpreting the field curves. The break in the resistivity continuity is a good evidence for different geological conditions such as altered zone in existence.

On the section of resistivity layer for L2 line the subsurface in the north part of S9-10 consists of two layer earth and that of the south part of the same station shows a series of multiple structures.

Low resistivity layer is divided into three blocks, say S10-16, S19-22 and S23-24, where resistivity values are 7-21, 2-6 and 6-14 ohm·m respectively. We may assume that a fault exists between S11 and S12.

On the L1 line resistivity layer is classified by three parts, that is from S13 to S16, from S19 to S21 and from S22 to S24, and each value of resistivity is in the range of 4-22, 10-52 and 9.5-17 ohm·m

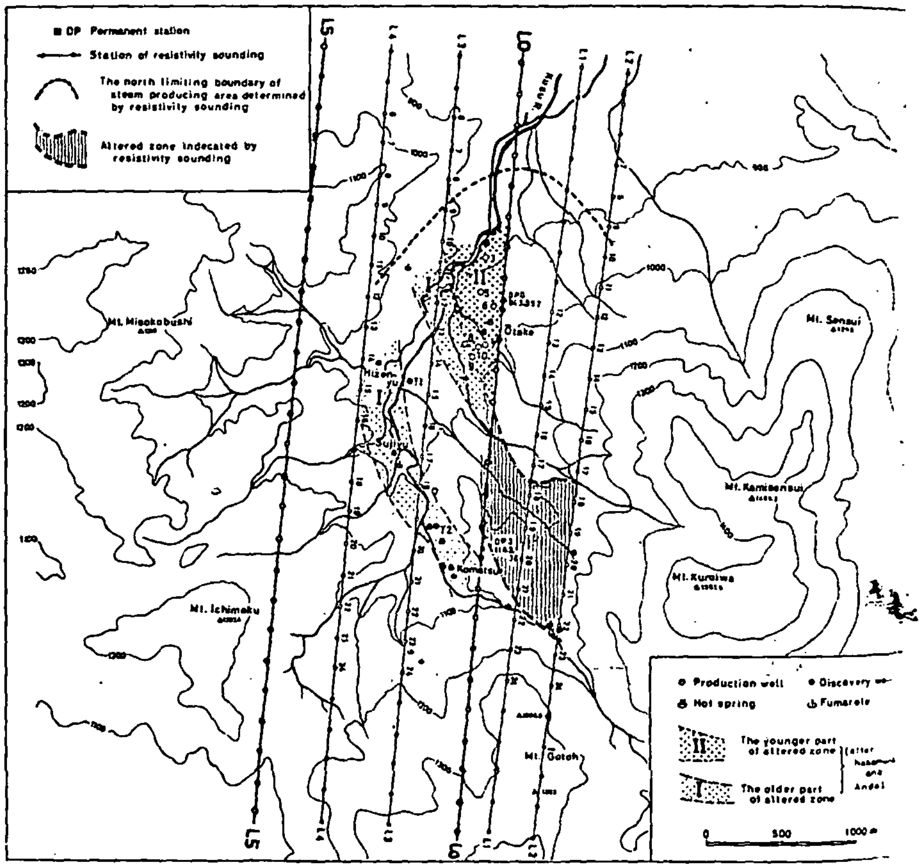

FIG. 10 - Resistivity Stations and the Distribution of Altered Zone after NAKAMURA and ANDO.

respectively. We may find that low resistivity zone at and near surface corresponds to the remarkable altered zone, of which the distribution is distinguished by double chain lines as shown in Fig. 10. This altered zone is situated on the extension of the south-east of the NAKAMURA's Altered Zone (1954).

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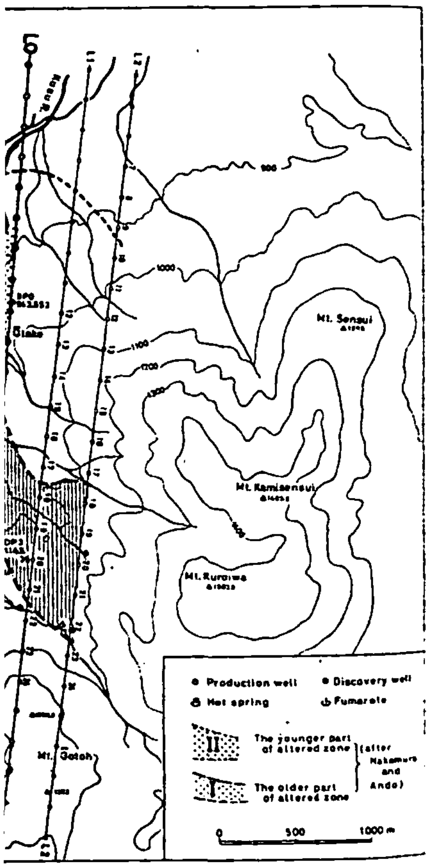

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Low resistivity layer for L3 line lies below S8, S12-17, S20 and S22-24. It will be seen that low resistivity layer of S11-16 for L13 is correlated to that of S13-17 for L4, and that it runs toward the west.

By the correlation between resistivity layer and the geolocical section of the steam production wells, Nos. 7, 8, 9 and 10, we may suggest that steam reservoirs should correspond to the third resistivity layer with thickness in the range of 180-400 m below L1S13-16 or with thickness in the range of 650-800 m below L2S12-16. This layer is in an increasing state from L1 to L2.

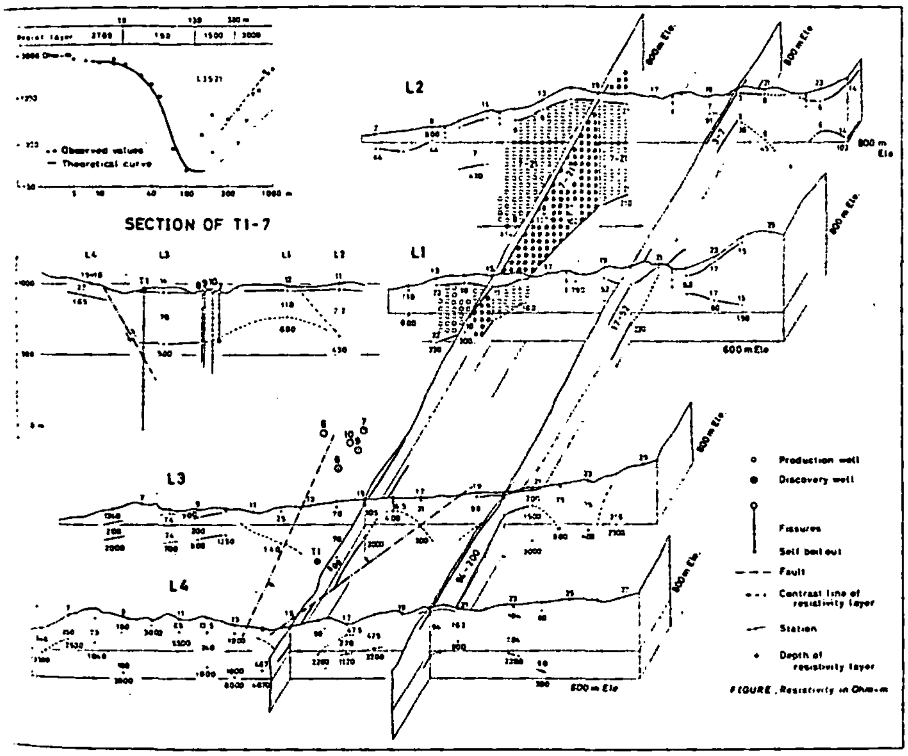

FIG. 11 - The Resistivity Block Diagram for Otake Geothermal Area.

On the other hand, the form of altered zone below the lines L3 and L4 is turned into a horn type which shows a section of typical altered zone.

The section of bores T1-7 is drawn to show additional informations on the development of natural steams (see the middle part at the left hand side of Fig. 11). This is also proved by the resistivity layer shown in Fig. 9.

From the resistivity indications the north limiting boundary of steam producing area is drawn by the large dotted line on the Fig. 10.

Probable faults were based on the resistivity discontinuity, and they were also drawn by the characterized deviation of a field curve from computed resistivity one.

In general it is seen from the result of resistivity survey that geology at and near L2 and L1 consists of stratified structure over the wide area, while the subsurface structure of L3 and L4 is almost complicated.

Concluding Remarks

A method of calculating the standard resistivity curve was presented and its computer calculation was developed. On the basis of the computer output described in the preceding section, the acadimic conclusion is that both Wenner and Schlumberger curves showed similar figures, and the shift of the origin of Schlumberger curve in abscissa was indicated by $\bar{m}$. Therefore no advantages and disadvantages exist between both curves. In part II results of computer calculations were applied to the interpretation of field curves at Otake.

In general the application of resistivity method to the detection of natural steams is to determine the distribution of formations storing supper heated waters. In this geoelectrical case history it should be noted that resistivity measurements indicated low resistivity layer which corresponds to altered zone, but it is not always reservoirs. Further resistivity data offered such many important informations as new areas to be developed, the existence of faults, the depth, shape and distribution of reservoirs and the limit of drilling depth for the development of geothermal resources at Otake.

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Kyushu Electric Power Co. Lt
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