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TASK I REPORT

Investigation of Water-Rock Interaction in Geothermal Systems of Japan and Taiwan.

I. The Onikobe Geothermal System, Japan

(Cooperative Agreement No. DE-FC07-80ID12148)

By

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INTRODUCTION

Japan and Taiwan provide excellent examples of active geothermal systems in geologic terrains which are well understood. Development of geothermal power has been greatly emphasized in these countries because it is potentially a major energy resource in active volcanic areas. Exploration for geothermal energy in Japan and Taiwan began in the early sixties, and many exploratory holes have been drilled up to 2000 m in depth. Drill hole cores have been sampled, thermal waters have been analyzed chemically and isotopically, and many other geological data (e.g., temperature gradient, flow rate, permeability) and geophysical data have been collected. A 25 MW geothermal power plant was successfully installed at Onikobe in 1975.

This project on low-temperature rock-water interaction in geothermal systems was initiated under a U.S.- Japan Project. Since April 1, 1978, the NSF and JSPS have sponsored a joint U.S.- Japan project on coordinated studies of rock-water interactions in geothermal systems utilizing experimental and field approaches. At Stanford, we have studied the interaction of andesitic-basaltic rocks with seawater and meteoric waters from 200°C to 400°C in order to determine the kinetic and equilibrium modes of interaction of rocks with solutions chemically, isotopically and mineralogically. In Japan and Taiwan, the properties of drill hole core samples and the field aspects of rock-water interactions in the Onikobe, Hakone and Tatun geothermal areas were investigated. The field studies include petrological-mineralogical-geochemical examinations of drill-hole core samples and their correlation with the chemical and isotopic properties of thermal waters. The collective specific aims were, and are: (1) to determine the mineralogical, chemical and isotopic characteristics of the hydrothermally altered rocks in these geothermal areas, (2) to deduce the sequence of chemical, mineralogical and geological events that have affected the mineral assemblages of the altered rocks, and (3) to determine the kinetics and equilibrium reactions attending the alteration. The conclusions and problems posed by the field data are to be correlated with and interpreted by the experimental data, to better our understanding of the genetic processes in geothermal systems.

Our common goal is to study rock-water interactions of Japanese geothermal systems in the hope that some general statements will be possible that apply to processes in this classic island arc. We hope that generalizations applicable to island arcs elsewhere will eventuate. There are many geothermal fields in Japan and some of them have already installed geothermal power plants. However, the project has focused only on a restricted number of areas, in view of time and personnel limitations. We have taken the Onikobe and Hakone areas in Japan and the Tatun area in Taiwan as on-going subjects. These geothermal areas were selected for detailed investigation because they are recognized as classic examples and because geological-geochemical-geophysical information and a nearly complete set of drill hole core samples are available. All three of these geothermal areas are in volcanic areas and are largely andesitic, but they differ from one another in the varieties of andesitic and other rocks present, and they differ somewhat in water types; hence, secondary mineral assemblages and mineral parageneses are different. The similarities and differences among the three geothermal areas could yield some principles relating to water-rock interactions in geothermal systems which might not be apparent from the investigation of a single system.

This report describes the results of our detailed investigations of drill-hole core and thermal water samples from the Onikobe geothermal area. Similar reports will be prepared for the Hakone and Tatun geothermal systems.

THE ONIKOBE GEOTHERMAL AREA

LOCATION AND BACKGROUND

The Onikobe geothermal area is located in the northwestern corner of Miyagi Prefecture, northern Honshu and lies within the Kurikoma - Quasi National Park. As shown in Fig. 1, the area is accessible by a 20 minute drive from Narugo station of the Rikuutosen National Railway through Highway 108. This area, which includes Onikobe geyser, Narugo-dam and Narugo-ravine, has been an excellent year around tourist resort.

Fig. 1

When the energy crisis became apparent in the early sixties, the Electric Power Developing Co., Inc. carried out exploratory surveys of many geothermal areas in Japan. It was concluded that all of the areas investigated, the Onikobe basin showed the greatest potential for geothermal power generation. In the period from 1962 to 1972, basic exploratory surveys were conducted and many pilot holes were drilled in order to collect samples, to measure subsurface temperatures and compositions of thermal waters and to investigate subsurface structures. As a result of the surveys, the company concluded that the geothermal steam was sufficiently abundant and of high enough temperature to generate electricity. Hence, the company started constructing a power plant in April of 1973 and it was completed in the spring of 1975. This 25 MW facility has been one of the proto-type geothermal power plants in Japan.

Moreover, the Onikobe geothermal steam is produced from as shallow as 300 meters in depth and this area is characterized by the surface manifestations of the geothermal field. The surrounding areas are covered by natural forest and the geothermal steam is re-injected into the deep portion of the basin. The installation of the geothermal power plant has preserved the natural beauty of the national park, and therefore the Onikobe geothermal system has been highly publicized.

It should be pointed out that the Senior author of the report (Y. Seki) has long been involved in geothermal energy exploration in the Onikobe area as he has been an Advisory Committee member of the Electric Company in Japan since 1962. He has participated in field geologic surveys, recommended the sites for drilling both exploratory and producing wells and systematically collected and examined all drill hole core materials. He and his colleagues have performed mineralogical and petrological investigations of the hydrothermally altered rocks and have outlined the effects of geothermal solutions on the enclosing rocks (e.g., Seki, _et_ _al_., 1969; Seki, 1970; Oki _et_ _al_., 1976).

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We thank the above mentioned institutions and their personnel and the individuals for their support, comments and advice. J.G. Liou is grateful to the John Simon Guggenheim Memorial Foundation for gracious and unencumbered support during 1978-1979.

PROCEDURES OF THE PROJECT AND METHODS OF INVESTIGATION

Many pilot, exploratory and producing wells ranging from 200 to 1300 meters in depth have been drilled in the Onikobe geothermal area since 1963 by the Electric Development Company Ltd. The drilling sites are plotted in Fig. 2; their columner stratigraphic sections and temperature distributions are shown in Figs. 5-8 (these features will be described in detail in later sections). The other drilling information is listed in Table 1.

As stated in the previous sections, many drill hole core samples from the Onikobe geothermal area have been studied by Seki and Oki. Some preliminary data for drill holes #GO-2, GO-5, GO-7 and GO-8 have been published (Seki _et_ _al_., 1969). Many other core samples were examined and these include core materials from P-5, P-7, P-8, P-10, GO-7, GO-8 and GO-11. These previously accumulated data together with our new observations on recently collected samples from new holes # 123, #123 and #127 will be described in this report. The general procedure of the project and method of investigation are described below.

I. Plan of the Project: Selection of the Onikobe and Hakone geothermal areas for the cooperative research targets was made in 1977, since their basic geology and the hydrologic-geochemical information about their thermal waters were available and both Seki and Oki had been working on these geothermal areas for a number of years. The Tatun geothermal system was added to our project for comparison with the Japanese systems because of its potential economic importance. The group (in part or as a whole) met several times during the 1976-78 period to discuss and define the basic role of each investigator. A set of interesting scientific questions was drawn up, and alternative target areas in Japan and Taiwan were proposed.

II. Field Study and Sample Collection: The group met in Japan during the summer of 1978 and visited many geothermal areas there. At the Onikobe caldera, the power plant was visited and rock types, geologic structures and flowing springs were examined. Two drill hole cores with depths down to 350 m (Nos. 123 and 124) and one down to 1300 m (GO-11) were selected for detailed petrologic-geothermal studies (see Fig. 2 for location). Their stratigraphic relations and temperature gradients have been constructed by Seki. Core samples were collected at every 10 to 20 m and were separated into three portions: one to Seki and Oki for petrographic and clay mineral identification, one to Sakai for isotopic study, and one to Stanford for petrographic, microprobe and SEM investigations.

In September 1980, Ray Guillemette visited the Onikobe geothermal area and collected core samples from a newly drilled hole No. 127 (see Fig. 2 for location). This hole was drilled on the recommendation of Seki and Oki based on our petrological-geochemical data, and this has been the best producing well in the area.

III. Petrographic Study: During September 1978 to December 1980, we studied thin sections of the drill-hole core samples. Minerals identified include Ca-zeolites (mordenite, stilbite, epistilbite, heulandite, yugawaralite, laumontite and wairakite), analcime, prehnite, epidote, albite, K-feldspar, gypsum, anhydrite, alunite, carbonate, kaolinite, illite, smectite-chlorite clay minerals, pyrite, magnetite, hematite and others. Their paragenetic sequence and depth zonal distribution were delineated.

IV. X-ray Diffraction and SEM Study: By using X-ray diffraction together with Differential Thermal Analyses (DTA), we have identified 4 types of smectite-chlorite clays in these geothermal areas. Systematic study of these clay minerals by Scanning Electron Microscopy (SEM) was undertaken at Stanford in order to determine (1) morphology and crystallinity of the 4 types of clay minerals; (2) textural relationships and paragenesis among the clay minerals and other silicates and (3) compositions of these fine-grained clay minerals. These data are significant for our interpretation of rock-water interactions in geothermal systems, as these clay minerals are ubiquitous and abundant in most drill-hole core samples.

V. Microprobe Analyses: Microprobe analyses of silicates, clay and carbonate minerals were done at Stanford. It is well known that most Ca-zeolites have extensive compositional variations. For example, wairakite ($CaAl_2Si_4O_{12} \cdot 2H_2O$) and analcime ($Na_2AL_2Si_4O_{12} \cdot 2H_2O$) form a nearly complete solid solution (e.g., Seki and Oki, 1969), yet only the end-member stabilities have been determined (Liou, 1970, 1971c). Therefore, depending on the Ca-Na substitution, wairakite minerals may form at temperatures much lower than those experimentally determined. Both epidote and prehnite from geothermal areas may contain substantial amounts of ferric iron; a previous experimental study by Liou (1973) and studies on natural paragenesis by Seki (1971) and Liou (1979) suggest that Fe-rich epidote may form at very low temperatures in a very oxidized environment. Therefore, compositions of those Ca-Al silicates are important in deciphering the physico-chemical conditions of their formation.

Polished thin sections were prepared for most drill hole core smaples and each section was carefully examined. Individual mineral grains selected for probe analysis were sketched and photographed before being coated with carbon in preparation for microprobe analysis. Microprobe analyses of carbonate and clay minerals require highly polished carbon-coated surfaces. Slight imperfections caused by cleavage, fracture and impurities can significantly affect the analytical results. Moreover, carbonate, clay and zeolite minerals are readily damaged by high electron-beam currents of the small beam diameters used during the microprobe analysis (e.g., Macqueen and Ghent, 1970; Bickle and Powell, 1977;

Matsumoto, 1978; Liou, 1979). Therefore, special precautions were necessary to ensure that the data were reliable.

VI. Isotope Studies: Concurrent with the mineralogical-petrological and compositional investigations, stable isotope studies were made on selected drill hole core samples and their mineral separates including carbonates, sulfates, sulfides and silicates by Sakai in his laboratory. The isotopic compositions (C, O, H, S) were carefully defined and the data utilized to establish the source and nature of the hydrothermal fluids and to estimate the temperatures of equilibration of the mineral species.

Isotopic fractionation factors between co-precipitated mineral pairs such as quartz-carbonate, or sulfate-sulfide are functions of temperature. The fractionation of oxygen isotopes among carbonates and silicates has been commonly used for geothermometry. The fractionation factors of sulfur isotopes have been experimentally determined by Sakai and Dickson (1978) and by Sakai et al. (1980) as part of the U.S. - Japan Cooperative project. During the 1980-82, water samples from rain, rivers, and shallow and deep wells in the Onikobe geothermal area will be collected periodically and analyzed for deuterium and O^{18} contents. These data, together with the isotopic analyses of many Japanese geothermal waters and meteoric waters (e.g., Matsubaya and Sakai, 1973) will be used to determine the origin of the present-day geothermal fluids in the Onikobe caldera. The carbon and sulfur isotopic ratios of carbonates and sulfur minerals from the drill-hole core samples indicate whether the geothermal fluids are magmatic, meteoric or brines or mixtures of these. Furthermore, once the temperature of a fossil fluid is determined, the oxygen and hydrogen isotope ratios of the fluids will be estimated. Hence, the source and origin of the fossil geothermal area will be evaluated and compared with the present active geothermal system and the evolution of a geothermal system will be better understood.

VII. Interpretation: After the mineralogical-petrological-isotopic data had been accumulated, the interaction modes between andesitic rocks and hydrothermal solutions were addressed. The experimental data on andesite-water (+CO_2) undertaken at Stanford was utilized to explain the genetic conditions and processes causing chemical and mineralogical changes during the rock-water interactions in the geothermal system.

VIII. Specific Goals and Anticipated Results: In conclusion, this report intends to address the following questions which are necessary for our better understanding of the evolution of a geothermal system. This, in turn, will aid in the future exploration and assessment of geothermal potential for other areas.

1. The paragenetic sequence of formation of secondary minerals in the geothermal area and the metamorphic reactions related to their formation.
2. The physico-chemical conditions of their genesis deduced from phase equilibria and their comparison with recorded temperatures, depths, pH values and analyzed solution compositions.
3. The spatial patterns of hydrothermal alterations and their relation to the flow of hydrothermal solutions.
4. The source of the hydrothermal fluids responsible for the alteration.
5. The effective water-rock ratio in the geothermal system.
6. The attainment of chemical and isotopic equilibrium in the coexisting minerals.
7. The change of isotopic and fluid compositions and temperature of geothermal fluids as a function of time as recorded in the changes of mineral assemblages in these geothermal areas.

PREVIOUS STUDIES OF HYDROTHERMAL ALTERATION

Solid Materials

The hydrothermal alteration of volcanogenic rocks at the surface of fumarolic areas within the Onikobe caldera basin has been briefly described (e.g., Nakmura, 1959a,b; Nakamura et al., 1961; Hitosugi, 1969; Yamada, 1975; Yamada et al., 1978). Three intensely altered areas around many thermal springs have been located: (1) Arayu-Katayama area; (2) Ogama-Megama area; and (3) Miyazawa-Fukiage area (e.g., see Fig.3). The areal distribution of secondary minerals including cristobalite, opaline silica, sulfur, limonite, Fe-sulfide, kaolinite, halloysite, alunite and montmorillonite has been delineated by Yamada et al. (1978). Minor zeolites such as mordenite and heulandite have been identified in some of these surface altered volcanic rocks. However, whether these zeolites are the products of the recent hydrothermal alteration or the earlier burial metamorphism is not certain.

Fig. 3

The Arayu-Katayama area occupies about 6 Km^2 and the original rocks are mainly andesitic-dacitic lavas and their pyroclastic deposits. Hydrothermally altered rocks are colorless and consist of an inner silicified zone and an outer argillized zone around some thermal springs. Some of the zonal distributions are obscure. The silicified rocks contain α-cristobalite, quartz and tridymite as main secondary phases whereas the argillized rocks contain kaolinite, montmorillonite and alunite in addition to the silica phases. Siliceous sinter, sulfur and limonite are actively precipitating from some thermal springs and sulfur crystals are sublimating from fumaroles. Buth sulfur and silica veins are abundant.

The Ogama-Megama area covers about 0.5 km^2 and consists of altered massive siltstone with amorphous silica as the major secondary mineral. Surrounding the silica deposit occurs an alunite-kaolinite-opal zone. Around the Miyazawa-Fukiage area, the original white tuffs have been silicified and argillized and a small amount of siliceous sinter is presently precipitating from thermal springs.

The hydrothermal alteration of the deep bore-hole cores of the Katayama geothermal area has been studied by Seki et al. (1969). One hundred and forty core samples from drill holes No. GO-2, 5, 7, and 8 have been examined by petrographic microscope and by X-ray diffractometer. The zonal distribution of zeolite and clay minerals from the surface to 701.5 m in depth has been determined based on <u>reconnaissance</u> petrographic examination of deep bore hole materials. With increasing depth and temperature, a non-zeolite zone, mordenite zone, laumontite zone and wairakite zone and a variation of clay minerals from smectite to chlorite through chlorite/smectite interstratified clay minerals occur. Yugawaralite has also been found between the laumontite and wairakite zones (Seki & Okumura, 1968). The core materials from bore hore GO-8 at depths of 552.5 and 598.1 m contain wairakite, quartz and pyrite, according to Seki et al. (1969). However, the core materials from GO-10 at depths of 1200 m and 1243 m contain quartz, chlorite and mixed-layer clay minerals, together with quartz and kaolinite respectively, but no zeolite. The detailed study of the core samples has not yet been done and it will be carried out in the present study. Nevertheless, the zonal variation of alteration minerals with depth roughly corresponds to the changes of chemical composition of thermal waters in this area.

It is apparent from the above review that except for the reconnaissance study of some drill hole cores by Seki et al. (1969), detailed mineral parageneses with respect to depth and their correlation with chemical compositions of the geothermal fluids have not been investigated. Compositions of the secondary phases have not been characterized. Moreover, many geochemical and petrological data of the Onikobe geothermal area have been collected by Seki and his colleagues, but only limited data have been published to date. These data together with our new observations on recently recovered core materials are described in detail in this report.

Thermal Waters

Chemical compositions of fumarolic gases, and hot-spring and high-temperature geothermal waters from the Onikobe geothermal area have been collected and investigated by a number of investigators. Their results will be compared with our data in later section. The fumarolic gases (at T = 100°C , according to Nakamura et al. 1959) consist of 99.8 vol % H_2O and 0.2 % gas whereas H_2O (about 32-59 %) and CO_2 (35-60 %) are dominant gas components. The high-temperature waters, according to recent studies by Ozawa and Nagashima (1975), Nakamura *et al.* (1977) and Ozawa *et al.*, (1980), are primarily originated from acid HCL - rich fluid formed by volcanic emanation and these acidic waters become neutral or alkaline by interaction with volcanic rocks during their ascent to the surface.

GEOLOGY AND GEOLOGIC SETTING OF THE ONIKOBE CALDERA

The Japanese island arc has experienced repeated volcanism, both terrestrial and submarine. Intensive volcanism that has continued since the early Miocene is believed to be intimately connected with the generation of fumaroles and hot springs, development of high geothermal gradients, evolution of the Green Tuff tectonic belt, and intensive alteration of rocks at the surface and at depth in numerous existing geothermal areas, including Onikobe and the surrounding region.

The zonal distribution of Quaternary volcanic rocks has been revealed by the classic studies of Kuno (1966, 1968), Katsui _et al_. (1974), Ishihara (1974), and Miyashiro (1974). They are (successively from the Pacific ocean side of Japan toward the west) (a) an outer volcanic zone with tholeiite and calc-alkaline rocks containing relatively low K_2O and Na_2O, (b) an inner zone of tholeiitic and calc-alkaline rocks with higher K_2O and Na_2O contents, (c) and a westernmost zone characterized by tholeiitic, calc-alkaline and alkali rocks.

The Miocene Green Tuff basin of Japan extends from Hokkaido through Honshu to pass under the sea just east of Mt. Fuji and Izu-Bonion Island and to northern Kyushu. The basin has been the site of steady volcanism since the Miocene, and the accompanying thermal and hydrothermal effects are recorded in diverse altered and metamorphosed rocks. The basin contains mainly thick volcaniclastic marine rocks, mostly coarse breccias, and tuff ejected from undersea volcanoes. Intrusive activity during sedimentation emplaced dikes and plugs; some rhyolite masses reached the sea floor, with widespread alteration and mineralization. On burial, the suite of materials was metamorphosed and hydrothermally altered to propyllite assemblages. Quaternary volcanism has injected heat, which is being dissipated in part by circulating water systems. In places in the basin the rocks have been subjected to multiple alteration processes.

Stratigraphy

The Onikobe caldera, the site of a geothermal power station, is on the east edge of the Green Tuff basin in north central Honshu. Physiographically, the caldera is characterized by an oval-shaped depression about 10 Km in mean diameter and the geologic units are concentrated around the caldera fills of various lithology. The stratigraphy, structure, and geologic history of this caldera basin have been described by Katayama and Umezawa (1938), Kuno (1952, 1953), Katsui (1955), Nakamura (1959, a, b), Matsuno and Nishimura (1965), Hitosugi and Yoneya (1972), Yamada (1972 a, b, 1973, 1975), and Yamada et al. (1978). The distribution of the lithologic units is shown in Fig. 4 and their stratigraphic relations are schematically presented in Table 2. Brief descriptions of these units are as follow:

A. Paleozoic Pelitic Schists and Cretaceous Granodiorite:

Pelitic schist and granodiorite constitute the basement complex of the Onikobe caldera and they unconformably underlie the Miocene Green Tuffs and younger formations. The schistose pelitic rocks crop out only along the exposures of National Highway 108 and at the mouth of Suginomori Creek. The schists consist of muscovite + albite, quartz, chlorite; some of them contain graphite. The pelitic rocks were locally intruded by the biotite-hornblende granodiorite of probable late Cretaceous age. The granodiorite is extensively exposed in the western and southern borders of the Onikobe caldera and also sporadically outcrops within uplifted blocks of the Green Tuff formation in the caldera basin. Dikes of rhyolite, dacite, and andesite are intruded into the granodiorite masses and these dikes are probably related to Miocene volcanic activity. The granodiorite was found at the bottom of a deep (1300 m) bore hole (GO-11) drilled by the Japan Electric Development Corporation (Hitosugi, 1970).

B. Miocene Volcanogenic Formation (Green Tuffs):

The Miocene volcanogenic sediments in this area unconformably cover the above noted basement rocks. The Miocene formation consists of lava, agglomerate, tuff breccia and tuff of andesitic and dacitic compositions, intercalated with thin bedded sandstone and shale. The volcanogenic sediments have suffered intense burial and hydrothermal alteration and the rocks have been replaced by a propylitic assemblage of sodic plagioclase, chlorite clay, illite, quartz, calcite and leucoxene with or without epidote.

The Green Tuff formation is widely distributed in the areas surrounding the Onikobe caldera basin and it also occurs as an uplifted block within the basin. This fact indicates that the Green Tuff formation must form, at least partly, the basement above which Plio-Pleistocene volcanic rocks were accumulated. Hitosugi and Yoneya (1972) concluded that the depth interval between 760 m and 1300 m of bore hole No. GO-11 drilled at the Katayama geothermal area is composed of the Miocene Green Tuff formation. However, careful examination of many drill hole core samples from this and other bore holes in the present study can not conclusively confirm the occurrence of the Green Tuffs at the depths noted above. This is because almost all cores from this and other bore holes have suffered severe alteration due to the present geothermal activity and it is difficult to clearly differentiate the Miocene Green Tuff from the Plio-Pleistocene volcanic rocks.

C. Pliocene-Pleistocene volcanic and sedimentary rocks

The Pliocene-Pleistocene rocks were deposited subaerially or in lacustrine envrionments. Geologically they can be divided into six formations, as follows:

(1) Kitagawa dacitic welded tuff formation: This welded tuff formation of about 100 m thickness unconformably overlies the Green Tuff formation and is exposed only outside of the Onikobe caldera basin. The petrographic and

chemical characteristics of this welded tuff, the product of nuee ardente type volcanic activity, are quite similar to those of a pumice flow and welded tuff formation widely distributed in the surrounding area of the Towada volcano caldera which is located to the north of the Onikobe area (Katsui, 1955). Fission track ages of this welded tuff formation are 2.2, 2.3 and 2.4 my BP (Yamada *et al*., 1978).

(2) Akazawa Formation: This is the lowest portion of the non-marine basin deposits of the Onikobe caldera and has a thickness of about 500 m. Probably the circular caldera, the diameter of which is about 10 km, was formed before the deposition of this Akazawa formation.

This formation is chiefly composed of conglomerate, andesitic and dacitic tuff breccia, and lava flow intercalated with thin beds of siltstone. Pebbles which are considered to have been derived from the above-noted Kitagawa dacitic welded tuff formation were found at the basal part of the Akazawa formation. The fission track age of the andesitic agglomerate of this formation is 1.8 my BP (Yamada *et al*., 1978).

(3) Miyazawa Formation: This non-marine volcanogenic formation is composed of hornblende dacitic lava flow, tuff breccia and pumice flow breccia with some thin siltstone and conglomerate beds. The thickness of this formation is estimated to be about 300 m. The fission track age of dacitic lava of this formation is 1.5 my BP (Yamada *et al*., 1978).

(4) Kawakurazawa Formation: This non-marine formation of 100 m thickness unconformably covers the Miyazawa formation. Rocks composing this formation are andesitic lava, tuff breccia and tuff with some insertions of mud-flow deposits. During the deposition of the Kawakurazawa formation a 3 by 4 km basement block was uplifted in the northwestern part of the Onikobe caldera basin.

(5) Takahinata dacite dome: This lava dome forms the oval shaped mountain of Takahinata-yama at the eastern part of the Onikobe caldera basin. Matsuno and Nishimura (1965) and Yamada (1972a, 1972b, 1973, 1975) have considered the lava dome to have been formed after the deposition of the Onikobe formation which is described below. However, absolute age determinations by the fission track method indicate that the Takahinata dacite lava dome was erupted about 0.35 my BP (Yamada et al., 1978), making it much older than the C^{14} dated Onikobe formation. The Takahinata dacite must be unconformably covered by the Onikobe formation as has been noted by Tani et al., (1968).

The Arayu fumarolic area is located within this dacite dome. Other active geothermal areas such as Katayama, Okuno-in and Megama are distributed near the western boundary of the Takahinata dacite dome (for localities, see Fig. 2 and 3). The volcanic activity related to the formation of this dome is believed to be the major heat source for the present day geothermal activity and associated hydrothermal manifestations in the Onikobe caldera basin area. Geomorphological evidence clearly indicate that many fumarolic explosive craters in the Katayama-Arayu area occur at the western and north western flanks of dome-shaped Takahinata volcano (Nakamura, 1959b; Matsuno and Nishimura, 1965).

(6) Onikobe formation: This non-marine formation of about 100 m thickness is composed of conglomerate and siltstone. No volcanic strata such as lava flows and agglomerates are intercalated, but clastic materials derived from surrounding Miocene and Pliocene-Pleistocene volcanic rocks are common. The accumulation of this formation occurred about 14000 years ago based on the C^{14} method (Yamada et al., 1978).

Development of the Onikobe basin

The geologic development of the Onikobe basin has been considered to be a Krakatau type caldera (Kuno, 1953), a volcano-tectonic depression (Katayama and Umezawa, 1958; Matsuno and Nishimura, 1965) or a resurgent cauldron (Yamada, 1972). Such differences in opinions appear to be due to the abrupt facies changes and the structural complexity of the lacustrine and volcanogenic deposits (basin deposits) and the lack of concrete correlation data among various lithologic units within the basin and those strata elsewhere. These problems are due partly to the heavy vegetation covering the entire area and partly to the intense hydrothermal alteration of many lithologic units. Nevertheless, the model proposed by Yamada, (1972) is modified and described below.

The Onikobe basin may have formed after the deposition of the Kitagawa welded tuff which occurs both in and outside the basin. The basin deposits, unconformably overlying the welded tuff, are divided into the Akazawa, Miyazawa, Kawakurazawa and Onikobe formations in ascending order. Prior to the deposition of the Onikobe non-marine deposits, the Takahinata dacite dome was extruded in the southern part of the basin. A nearly rhomb-shaped block (the Zanno-Mori block) 3 x 4 Km in dimension, which consists of the Green Tuff and granodiorite, is exposed in the northwestern part of the caldera. The block is primarily bounded by normal faults and the basin Miyazawa deposits are steeply dipping away from the block. Such relations suggest the block was uplifted after the deposition of the Miyazawa formation. The geological constraints described above suggest that the sequence for the formation of the Onikobe basin can be summarized as follows:

(1) Pre-caldera deposition of the Kitagawa dacitic welded tuff, which unconformably overlies the Green Tuff and grandiorite, 2.3 -2.4 M.Y.B.P.

(2) Regional block faulting and formation of a caldera by collapse or subsidence.

(3) Deposition of the non-marine Akazawa (1.8 M.Y.) and Miyazawa formations within the caldera basin.

(4) Uplift of the Zanno-Mori basement block and deposition of the Kawakurazawa formation.

(5) Extrusion of the Takahinata dacite lava (0.35 m.y.) and intense hydrothermal alteration.

(6) Deposition of the non-marine Onikobe formation about 0.14 m.y. ago.

Geologic Structure and Fracture Systems

Because of difficulties in traversing the area, the dense vegetation cover, and the intense hydrothermal alteration, the detailed geologic structures of the Onikobe basin have not been worked out. Based on aerial photography, ground surveys and subsurface drilling, some regional structures have been suggested (e.g., Matsuno and Nishimura, 1965; Yamada, 1972).

The Onikobe basin is characterized by a circular depression bounded by a series of ring faults and by a structural dome whose axis is NW-SE inside the basin. Many high-angle normal faults have been suggested to have formed during the development of the Onikobe basin. Some of these faults were active again later and the Zanno-Mori block of basement rocks was uplifted in the northwestern part of the caldera. Around the Zanno-Mori block where the strata dip steeply, many minor faults are observed.

In general, within the Onikobe basin, minor faults, clastic dikes and joints are well developed and they sporadically occur in the uncomformably overlying younger basin deposits. Minor faults of northwest-southeast direction are cut by those of northeast-southwest direction. Many conjugate systems of fractures and clastic dikes in the southeastern area of the Onikobe basin have been studied in detail by Yamada (1972); in this region the exposure is better and the rocks are less altered. The results of his study indicate that the southeastern part of the caldera has undergone lateral extension. Some fractures and clastic dikes are concentrated along a narrow shear zone extending probably to the foundation of the caldera. The hydrothermal system of the Onikobe caldera is controlled mainly by such fracture systems.

In the Katayama geothermal area, which is located in the southeastern part of the caldera, no fault could clearly be identified by geomorphological or air-photo geological data. The occurrence of subsurface faults has been inferred from seismological and electric survey data by Hitosugi (1976). Matsuno and Nishimura (1965) and Nakano (1981) have recently suggested a series of NW-SE trending major faults occurring at depth. These faults may provide channels for high-temperature geothermal water to flow in this area. However, these faults have not been confirmed by geologic surveys and deep drilling. Our studies of many deep drill hole core samples from the Katayama area revealed no lithological or structural features such as slickensides, fault striations or brecciations to substantiate the occurrence of such large faults at depth.

Within the Katayama geothermal area, three strong geothermal belts were delineated from drilling of over fifty production and pilot bore holes. These belts may be closely related to those subsurface faults inferred from the geophysical data mentioned above. These belts are shown in Fig 2 and are respectively called K-line, Y-line and Z-line by the Japanese Electric Development Company. The production wells #101, 102, 103 and 112 are on the K-line, # 108, 109, and 117 are on the Y-line and # 104, 105 and 127 are on the

Z-line. Future production wells will be drilled along these three belts which apparently have enough fracture spaces for large flows of high-temperature thermal waters at depth.

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Table 2. The lithostratigraphic Units of the Onikobe Caldera, Japan

Geologic Unit		Thickness (in meters)	Age (in Years before the present)
BASIN DEPOSITS	Onikobe Formation	100	23,380 ± 890* 24,970 ± 1210* 732,500
	Takahinata Dacite Dome	Unknown	0.3 million**
	Kawakurazawa Formation	100	
	Miyazawa Formation	300	1.5 million**
	Akazawa Formation	500	1.8 Million**
	Kitagawa Dacite Welded Tuff Formation	100	2.2-2.4 Million**
BASEMENT	Green Tuff Formation	7500	Early-late Miocene
	Granodiorite and Schist	Unknown	Palaeozoic

*C^{14} dating; ** Fission track dating (both from Yamada *et al.*, 1978.

FIGURE CAPTIONS

Fig. 1. Location of the Onikobe area, Japan.

Fig. 2. Distribution of bore holes in the Katayama geothermal area, Onikobe, Japan. Open circles: Bore-holes described in this report. Black dots within Open circle: Production wells (e.g., #123 and #127).

Fig. 3. Skematic map showing the localities and fumarolic and hot-spring areas in the Onikobe Caldera, Japan. KY: Kayayama; AR: Arayu; ME: Megama; KS: Kanisawa; MT: Mitaki; FA: Fukiage; MZ: Miyazawa; TR: Todoroki.

Fig. 4. Geologic map and cross section of the Onikobe Caldera, Japan (modified after Yamada et al., 1978). KA: Katayama fumarolic area; OK: Okuno - in fumarolic area; AR: Arayu fumarolic area; ME: Megama fumarolic area; MI: MitaKi Spa; K: Kanisawa Spa; T: Todoroki Spa; F: Fukiage Spa; M: Miyazawa Spa.

Fig. 5. Geologic cross sections along A-B, A-C, and C-D of Fig. 2 for the Katayama geothermal area, Onikobe, Japan. A: Volcanic rocks of andesitic compositions. D: Volcanic rocks of dacitic compositions.

Fig. 6. Geothermal gradients for bore-holes, P-5, P-7, P-8, P-10, No. 123, and No. 124, the Katayama geothermal area, Onikobe, Japan.

Fig. 7. Geothermal gradients for bore-holes GO-7, GO-8, GO-10 and GO-11, the Katayama geothermal area, Onikobe, Japan.

Fig. 8 Geothermal gradients for bore holes #127, the Katayama geothermal area, Onikobe, Japan.

A: 51 hours after the stop of cooling water supply.

B: 99 hours after the stop of cooling water supply.

C: 596 hours after the stop of cooling water supply.

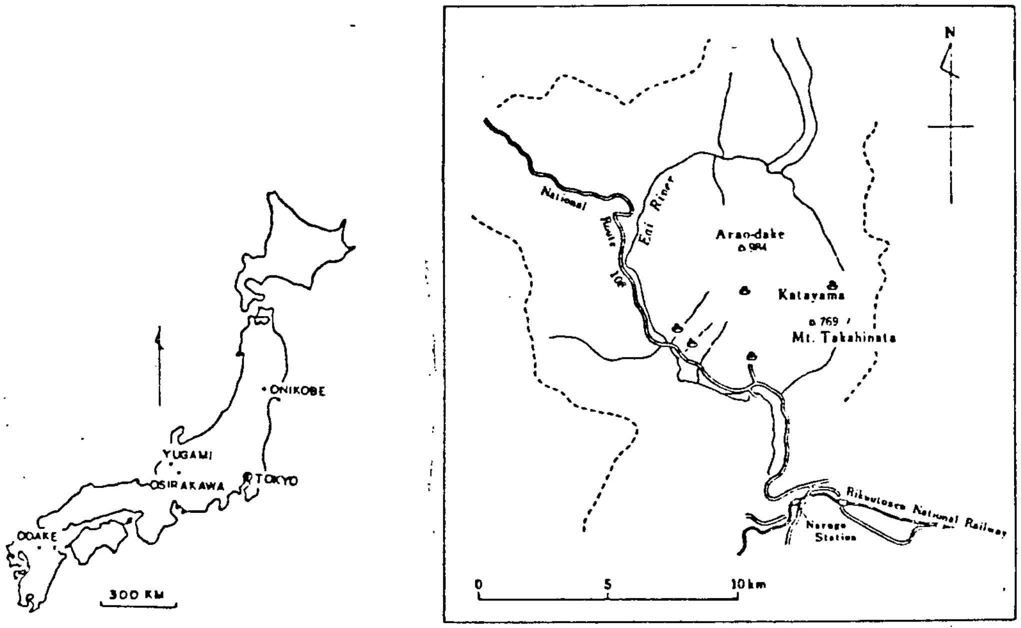

ONIKOBE
YUGAMI
OSIRAKAWA
TOKYO
OOAKE
300 KM
N
National Route 108
Eni River
Arao-dake
984
Katayama
769
Mt. Takahinata
Rikuutosen National Railway
Naruge Station
0
5
10 km

Fig. 1

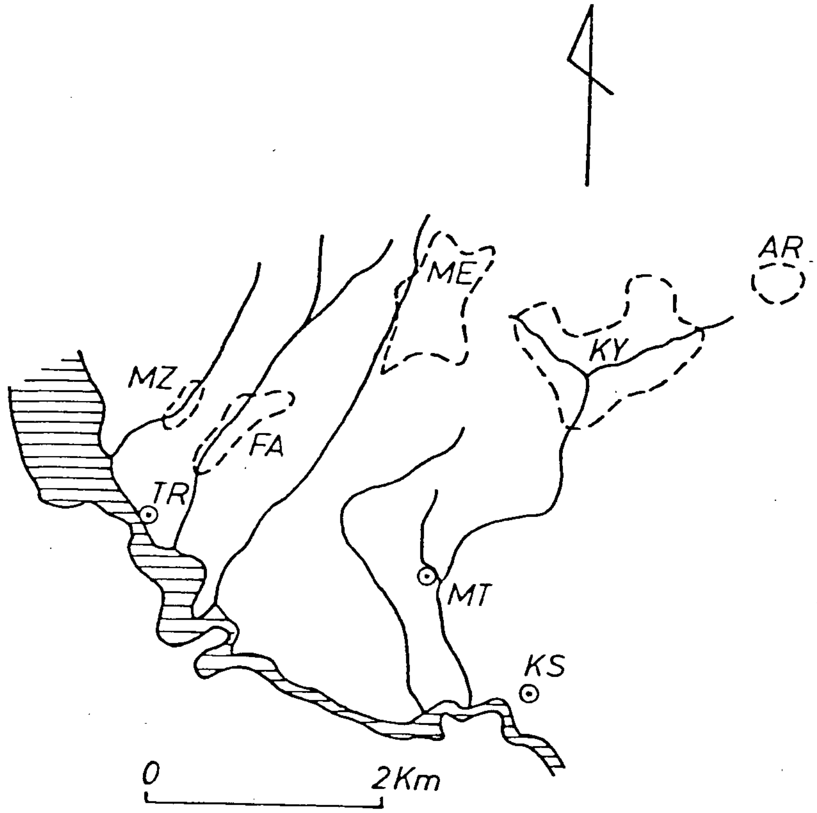
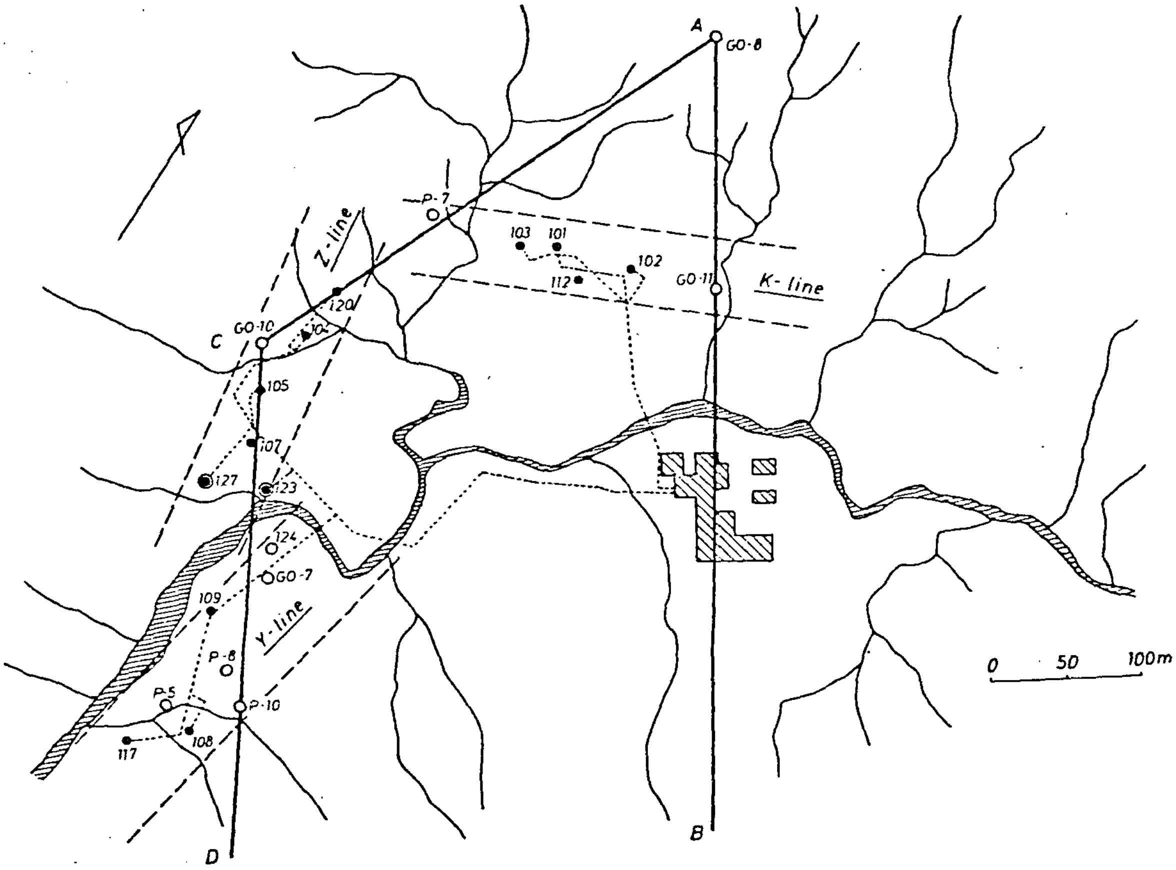
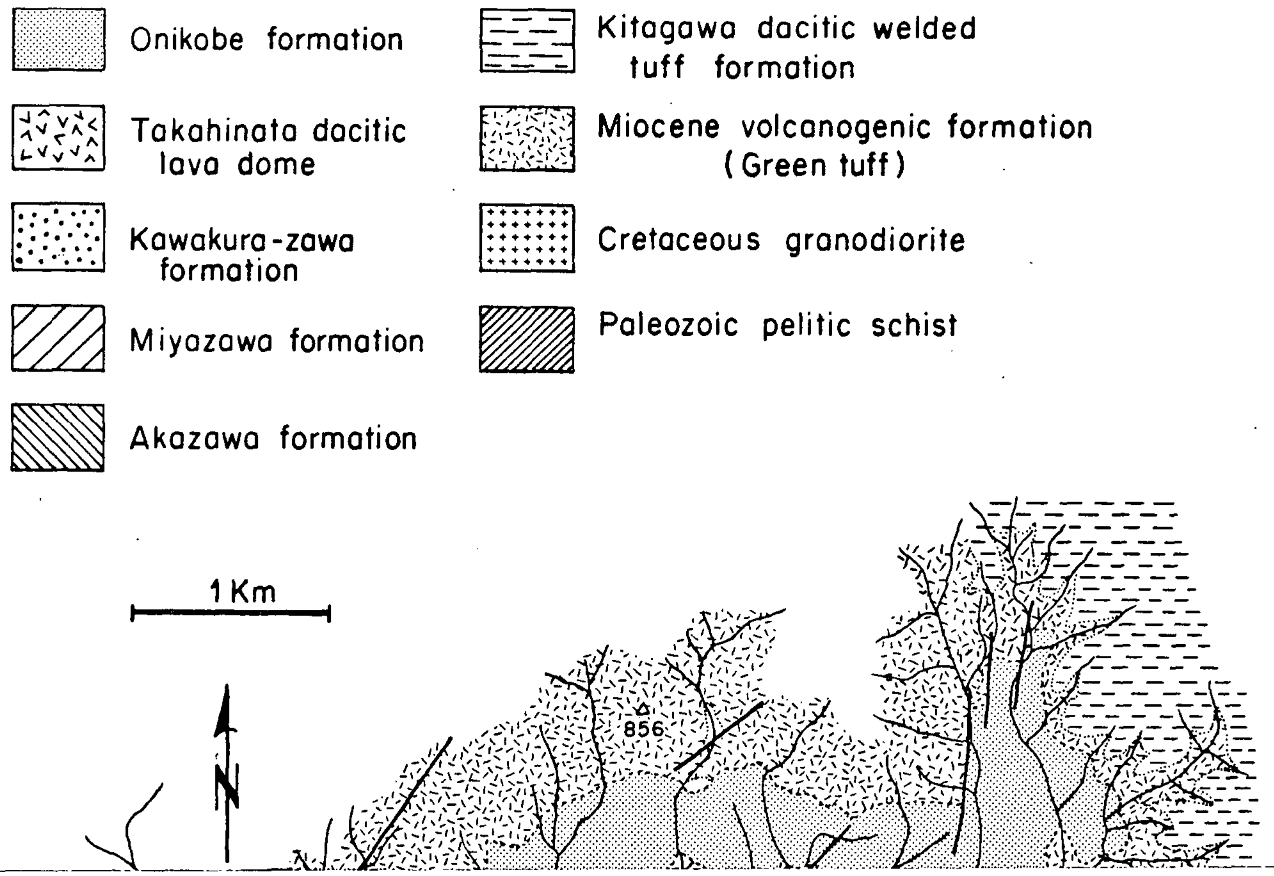

AR
ME
KY
MZ
FA
TR
MT
KS
0
2Km

Fig. 3



A
GO-8
B
C
GO-10
D
P-7
Z-line
120
105
107
127
123
124
GO-7
109
Y-line
P-8
P-5
P-10
117
108
103
101
102
112
GO-11
K-line
0
50
100m

Fig. 2


Onikobe formation
Takahinata dacitic lava dome
Kawakura-zawa formation
Miyazawa formation
Akazawa formation
Kitagawa dacitic welded tuff formation
Miocene volcanogenic formation (Green tuff)
Cretaceous granodiorite
Paleozoic pelitic schist
1 Km
N
856

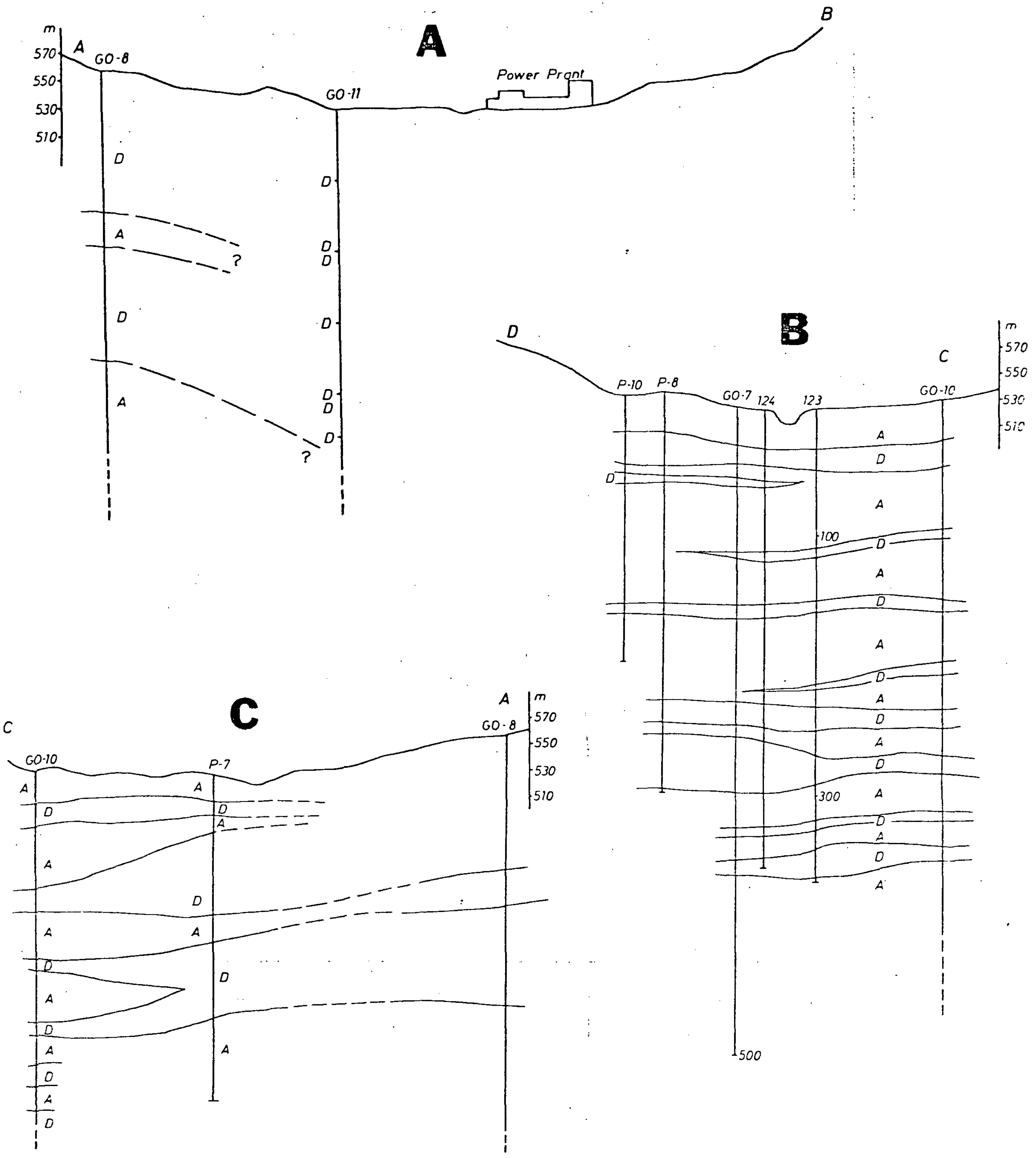

A
m
570
550
530
510
A
GO-8
GO-11
Power Plant
B
D
A
?
D
A
?
D
D
D
D
D
D
D
B
D
C
m
570
550
530
510
P-10
P-8
GO-7
124
123
GO-10
A
D
D
A
100
D
A
D
A
D
A
D
A
D
300
A
D
A
D
A
500
C
C
GO-10
P-7
A
GO-8
m
570
550
530
510
A
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Fig. 5

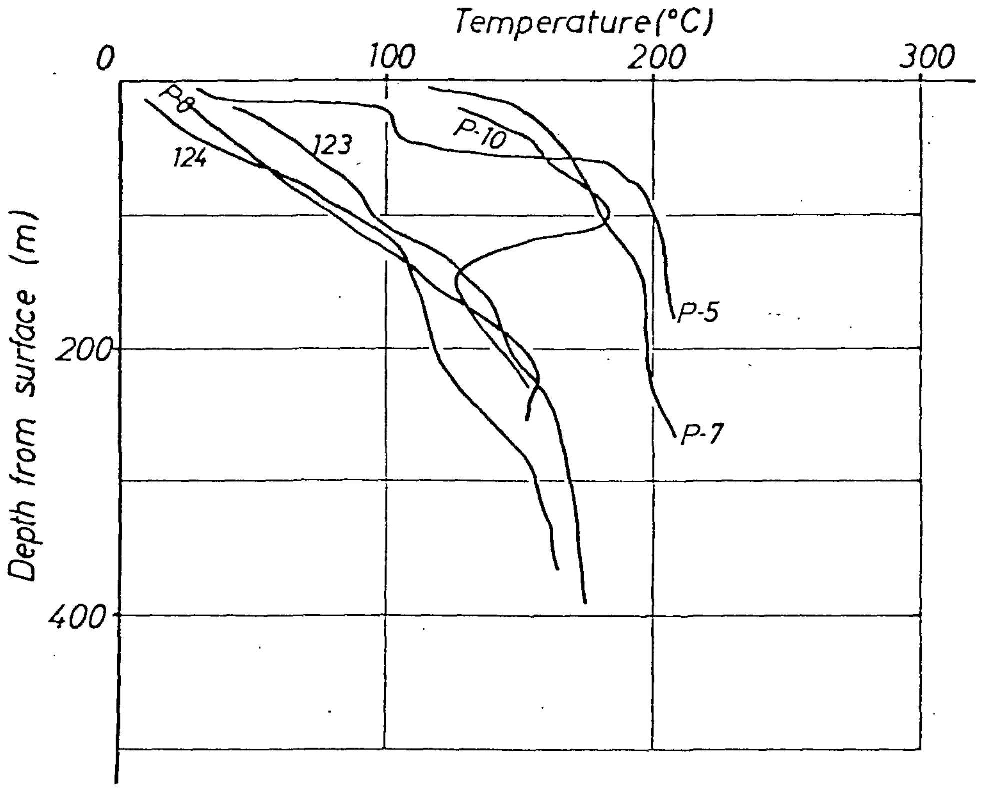
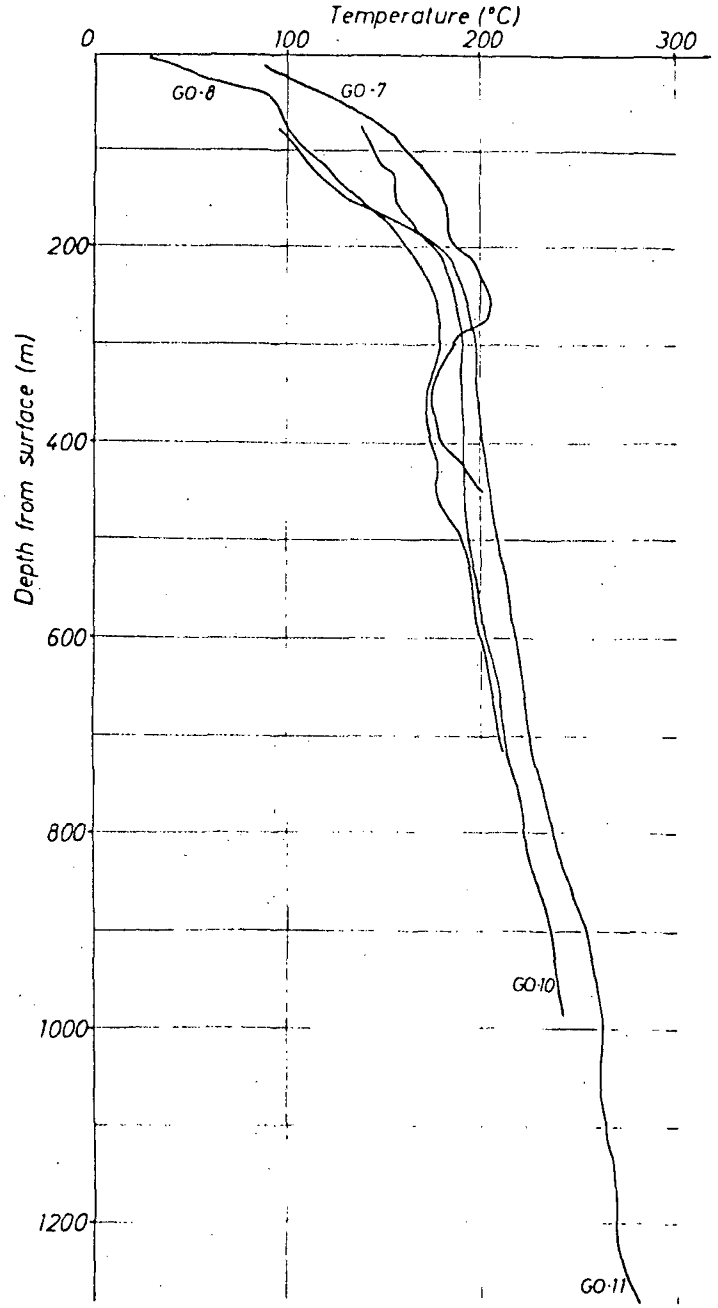
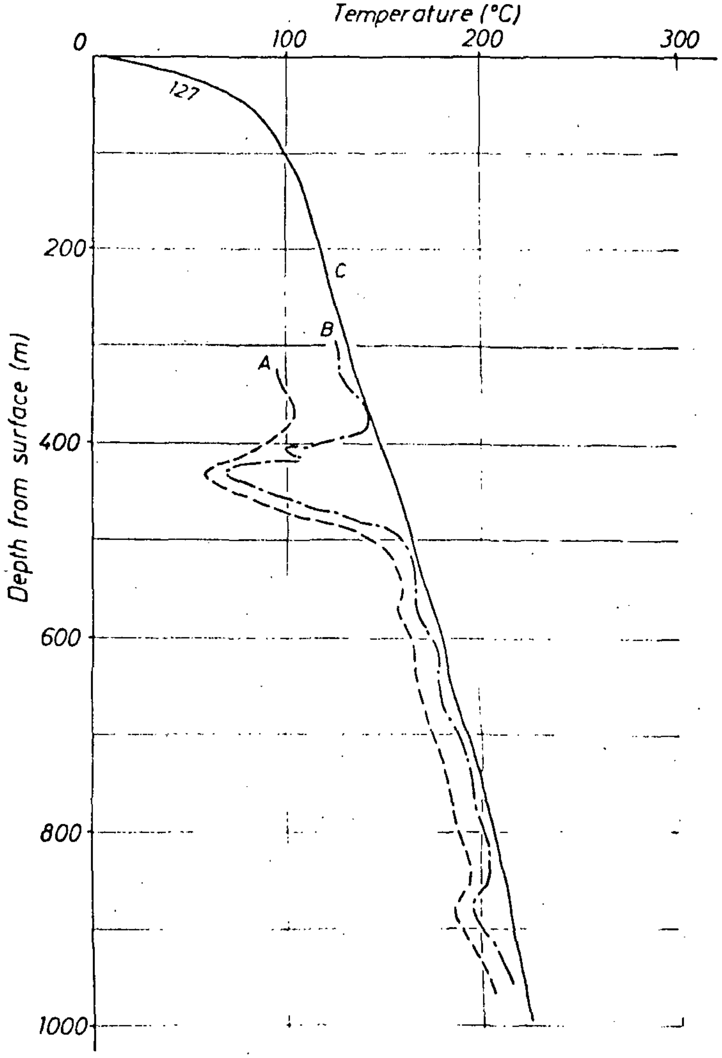

Temperature(°C)
0
100
200
300
Depth from surface (m)
200
400
P-8
124
123
P-10
P-5
P-7

Fig. 6



Temperature (°C)
0
100
200
300
Depth from surface (m)
200
400
600
800
1000
1200
GO·8
GO·7
GO·10
GO·11

Fig. 7



Temperature (°C)
0
100
200
300
Depth from surface (m)
200
400
600
800
1000
127
C
B
A

Fig. 8