Geothermics (1970) - SPECIAL ISSUE 2
U. N. Symposium on the Development and Utilization of Geothermal Resources, Pisa 1970. Vol. 2, Part 1

The Study of Underground Structure and Geophysical State in Geothermal Areas by Seismic Exploration

M. HAYAKAWA *

ABSTRACT

During the last several years, seismic prospectings have been conducted in some geothermal fields (Matsukawa, Otake and Onikobe) in Japan. In Japan, all of the geothermal fields are in volcanic areas, consequently mostly reflection techniques and partly refraction ones have been applied because of the complicated velocity distributions in such geothermal fields. From these field data, some interesting information has been obtained, however generally speaking, it is rather difficult to distinguish the feature of cap rock, hot fluid reservoir and fault structures and to get deeper infomation related to heat sources from these complicated data.

From such view points, recently, two techniques have been tried, the first one is to remove the undesirable noises and multiple reflections so that we will be able to make clear the deeper structure, by using digital data processing including the newly established software. The second one is to use not only the conventional arrival times, but also to utilize the absorption of wave energy caused by the fluid viscosity and high frequency, and to study the wavelength of a seismic wave to presume the geophysical state in such geothermal fields.

From the first one, in some geothermal fields, a very interesting deeper structure (about four kilometers' depth) which may indicate the structure related to the heat source, has been obtained, and from the latter, it has become clear that the areas where low frequency wave patterns predominate, correspond to the fluid reservoir. With regard to the absorption, it is under study. By comparing these seismic data with the related geological, geophysical and geochemical data, the application of a seismic method will be surely increased not only to find the suitable area for the utilization of natural steam from volcanic areas for electric power generation, but also to know the underground geothermal characters of those areas.

Introduction

During the last years, seismic prospectings have been conducted in some geothermal fields of Japan. In Japan, all of the geothermal fields are in the volcanic areas, consequently mostly reflection techniques and partly refraction ones have been applied because of the complicated velocity distributions in such geothermal fields. From these field data, some interesting information has been obtained. However, generally speaking it is rather difficult to distinguish the feature of cap rock, hot fluid reservoir and fault structures and to get better information related to heat source from these complicated data.

From such view-points, two newly developed techniques have been tried recently. The first one is to remove undesirable noises and multiple reflections so that we will be able to make the deeper structure clear, by using digital data processing including the newly established software. The second one is to use not only the conventional arrival times, but also to utilize the absorption of wave energy caused by the fluid viscosity and high frequency, and to study the wave-length of seismic waves to know the geophysical state of such geothermal fields.

From the first an interesting deeper structure which might indicate the structure related to the heat source has been obtained in some geothermal fields, and for the latter one, it has become clear that the areas where low frequency wave patterns predominate, correspond to the fluid reservoir. With regard to the absorption, this is at present being studied. By comparing these seismic data with the related geophysical, geological and geochemical data, the application of seismic methods will be certainly increased, not only to find a suitable area for the utilization in electric power generation of natural steam from volcanic areas, but also to know the underground geothermal characteristics in those areas.

The content of this paper is as follows.

— Historical review of seismic prospectings in the geothermal fields of Japan, including a study of the volcano Showa-Shinzan.

— Analysis of seismic reflection record at a geothermal field, Matsukawa in Japan, part one.

— Analysis of seismic reflection record at a geothermal field, Matsukawa in Japan, part two.

— Study of the wave-length of seismic waves and others to ascertain the geophysical state at Matsukawa geothermal field.

Historical review of seismic prospecting in the geothermal fields of Japan, including the study of the volcano Showa-Shinzan.

In New Zealand and Italy, some works related to seismic prospecting in geothermal fields have been conducted. In Japan, the first survey of this kind was made at the volcano Showa-Shinzan on Hokkaido about 15 years ago by the members of the Geological Survey of Japan including the present writer. After this, another seismic prospecting was conducted at the volcano Aso by MINAKAMI and the members of the Earthquake Research Institute of the University of Tokyo.

---

* College of Marine Sciences and Technology, Tokai University, Orido, Shimizu-shi, Shizuoka-ken, Japan. (Formerly Geological Survey of Japan).

Following these works, seismic surveys have been continuously performed at Matsukawa in 1959, 1966, 1967 and 1968, at Onikobe and Otake in 1967 and 1968 respectively by the members of the Geological Survey of Japan including the present writer and the members of the Ube Industrial Co., including KURIHARA, and H. TAKEUCHI of the Geophysical Institute of the University of Tokyo.

The major purpose of seismic prospectings at Showa-Shinzan and Asama was to make the underground structures at these volcanic areas clear, while the seismic ones at Matsukawa, Onikobe, and Otake have been conducted to find out not only the underground structure of these geothermal areas, but also to know the geophysical states, if circumstances permit. In the beginning, as an example for the former, a brief explanation is also tried. After these, two techniques recently applied will be shown in detail in the following sections.

SEISMIC PROSPECTING AT SHOWA-SHINZAN

Usu volcano being located at the north end of the Nasu volcanic zone, is situated at the southwestern part of Hokkaido, in Japan (Figure 1). The volcano was caused by the subsidence of the Toya caldera in the early alluvial age. At that time, the volcano had the shape of a truncated cone, being crowned with a comparatively large crater.

In this area, after the construction of the main body, the volcano had many eruptions of the belonite type and crypto-dome type. Mt. Ousu and Mt. Kousu, being the central cones of the Usu volcano, were described as pseudo-belonite type. Seven parasitic cones continuously developed around the volcanoes in historical times. As the latest activity, Showa-Shinzan in Hokkaido was formed as one of the parasitic cones of Usu volcano.

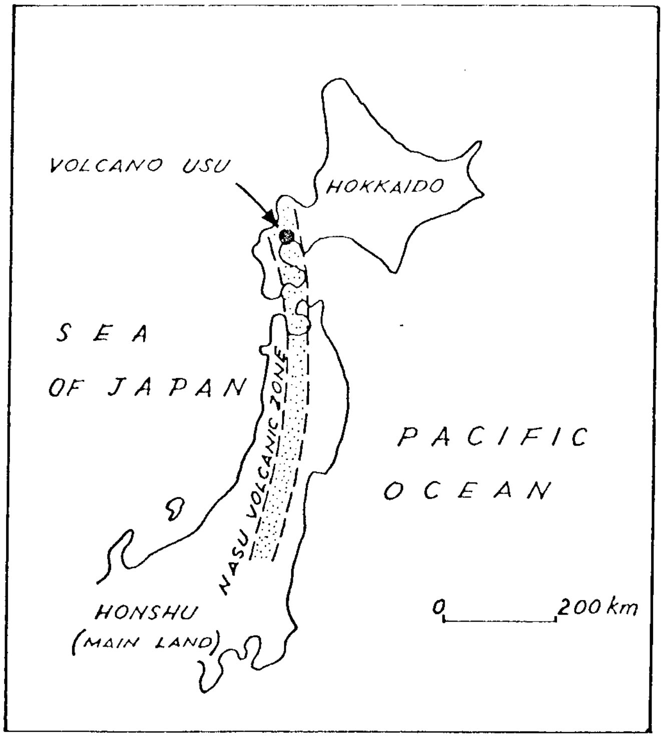


FIG. 1. — *Location map.*

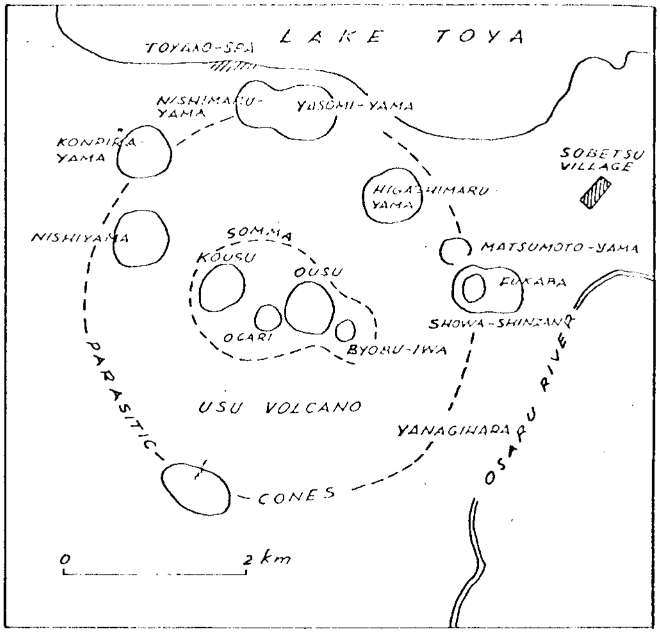


FIG. 2. — *Usu volcano area.*

Showa-Shinzan (the new mountain formed in « Showa period », in Japanese) which consists of a dome and a roof-mountain, had been formed by the uplift of solidified magma during the present volcanic activity. The present activity suddenly started at the same time as the severe local earthquakes on Dec. 28, 1943.

At that time, the volcanic activity continued for about two years. The activity may be divided into the following three stages:

1) earthquake stage Dec. 1943 - June 1944
2) explosion stage June 1944 - Oct. 1944
3) dome-building stage Nov. 1944 - Sept. 1945.

In the first stage, the frequency of shock reached 200 tremors per day at the maximum. In April and May, the epicenter of the earthquakes shifted gradually northward from Yanagihara to Fukaba (Figure 2). On June 23, 1944, the first explosion took place over the devasted area at the eastern foot of Mt. Matsumoto-yama. The tremendous explosions recorded over ten times until October of the same year had opened seven craters. In November, 1944, the peak of a pyramidal shape appeared on the top of the roof mountain. It was ascertained soon after that the solidified lava commenced to rise above the surface of the roof-mountain, and this continued for ten months. After a while, the lava mass developed gradually into a dome with a steep slope on the west side. M. MIMATSU, the postmaster of Sobetsu village, made excellent sketches of the morphological development of the newly forming dome throughout the period of growth. In September, 1945, as the final result of the present activity, a dome was formed whose maximum height was 406.9 m, and a roof-mountain whose elevation was about 250 m.

The dome was thickly covered with volcanic ashes. Therefore the rocks of the volcano and basement together with the new lava forming the dome, crop out only in several places at the foot of the steep slope on the south and west sides. The main products issued by the eruption are new lava and volcanic ash. The lava is hypersthene dacite containing plagioclase and hypersthene phenocrysts, and is similar to the Ousu and Kousu lava in mineral composition. These three domes (Ousu, Kousu and Showa-Shinzan) seem to have been formed by the same volcanic process. As already described, the dome lava is considered to be in a state of solid or solid like viscous mass. The upheaval of the land, by which the roof-mountain was constructed, suggests that the solidified magma was intruded into the rock layer underlying the uplifted area. Therefore it is assumed that solidified magma was injected repeatedly into the upper earth's crust from the lower magma reservoir, following the seismic movement during the present activity.

In order to obtain data that might clarify the general underground structure, a gravity survey was conducted at the eastern foot of volcano Usu including Showa-Shinzan. As great differences in gravity were observed over the dome (spine) and its southern zone, it may be evident that the observed gravity anomalies are not entirely due to the surface geological condition, but also largely depend on the regional underground magmatic effects.

The seismic method was used at the selected places for the purpose of confirming the gravity results, and also determining their underground geological and geothermal states. However, it was not so easy to perform such a survey, due to the presence of many unknown factors. Therefore, at first, we examined the velocity differences among several volcanic rocks, ashes and pumices, etc. and also made experiments on their changes caused by the physical properties of volcanic rocks pressure, temperature, viscosity, porosity and water content, etc.. Taking these elements into consideration, the seismic surveys were carried out. The seismic method usually employed for oil or coal problems is merely the reflection or refraction method. In our case, we used not only the reflection and refraction methods, but also other possible methods, using S-wave and amplitude attenuation due to the viscosity, laboratory experiments determining physical properties, etc..

As the results of these field survey and laboratory experiments, we obtained the velocity profiles as in Figure 3.

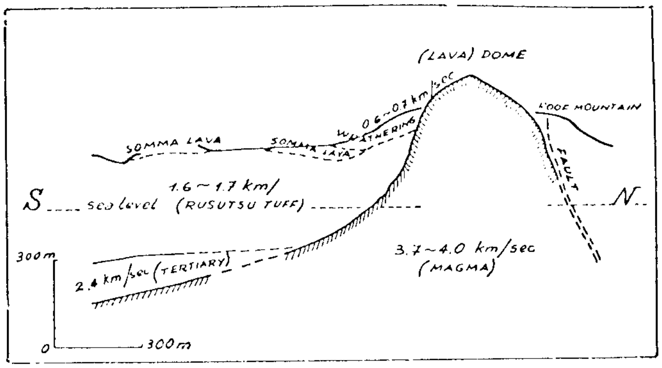


FIG. 3. — *Usu volcano cross section with seismic wave velocities.*

The top layer, which has a velocity of 0.6-0.7 km/sec and a thickness of about 50 m, corresponds to the weathering layer. The second layer has a velocity of approximately 1.7 km/sec and corresponds to the « Rusutsu » tuff and similar tuff sediments. The third layer has a velocity of 2.2-2.4 km/sec and perhaps corresponds to the Tertiary sandstone or shale. We find 3.7-4.0 km/sec velocity below these sediments. Judging from both time distance curves and their corresponding analysed section, we can see that there is a possibility of an underground extrusion of solid magmatic mass. Considering its velocity, we also imagine that this underground magmatic mass is still under high temperature conditions at present. If this assumption is true, this mass may correspond to the underground extension of the dome. By using the heat conduction theory, we calculated the temperature distribution inside the dome, and obtained the following result.

T (year)	Surface temperature	Temperature at one km deep
100	840°C	970°C
1000	675	780
10,000	75	85

Analysis of a seismic reflection record at a geothermal field, Matsukawa in Japan.

PART ONE

At the present stage, it is difficult to know the true picture of geothermal structure including the hydrothermal system and the behaviour of magma by a geophysical method alone, that means that a synthesized method of various kinds of geophysical prospecting and also geological and geochemical studies, will be most effective for our present purpose. Besides this, new techniques are necessary to establish reservoir engineering as in the case of oil prospecting.

In the following the writer will explain the seismic prospecting at Matsukawa in some detail. In this study, many of my friends have participated. They are K. BABA, S. TAKAKI, S. TANAKA, K. MORI, Y. ONO (Geological Survey of Japan), Members of Azumakako

Co., Members of Teikoku Oil Co.; also H. TAKEUCHI of the University of Tokyo helped the writer in considering the heat problem and utilizing new techniques. S. KURIHARA and his colleagues in Ube Industrial Co. have made seismic profiles with the writer. The writer wishes to express his cordial thanks to them.

During the nine years since 1959, the writers have conducted seismic and electrical prospectings and geophysical logging by using some test wells. Besides these, the writer has also calculated the underground temperature distribution assuming some geophysical states. Parallel to the geological studies described in a separate paper, they started with laboratory experiments including density, porosity and ultrasonic wave velocity measurements by using the specimens of outcrops at and adjacent to the area of this geothermal field.

From these results they tentatively made the following assumptions by combining geological data. Matsukawa andesite might correspond to the first cover-rock because of the high velocity and low porosity, while the subsequent dacite tuff formation might probably be the first reservoir of hot water because of low velocity with high porosity. Likewise the dacite lava beneath the dacite tuff might correspond to the second cover-rock, and the underlaid marine sediments to the second reservoir.

Consequently, they preferred the reflection seismic method instead of the refraction method because of the existence of low velocity layers. For the seismic prospecting, the magnetic tape recording system was utilized, and after several trials of playback, some interesting reflection records were obtained.

As the result of these seismic records, depths of reflection interfaces from the surface were obtained.

They are 160, 550, 980, 1300 and 2000 meters. By taking geological events into consideration, these reflection phases should correspond to the boundaries between different formations. As explained above, the first layer consists of a hard andesite which is a cover rock and has a high ultrasonic wave velocity and low porosity. Below this, from 160 meters to 550 meters in depth, there is a possible reservoir for hot water as it shows low ultrasonic wave velocity and high porosity. This layer consists of dacite tuff and partly dacite lava. This was named the *first reservoir.* The layer between 550 meters and 980 meters corresponds to the dacite lava formation. This formation was named the second cover. But this is not such a complete cover-rock as the first one, as according to the seismogram it includes some cracks. Below this layer to 1300 meters, there should be a sedimentary formation, considering the pattern of seismic records and presumed geological information. From this information we can presume a suitable hot water or steam reservoir, by considering the physical properties of the rocks and the records of the seismogram. So it was named *second reservoir.* Below this to 2000 meters there should be a green tuff formation. From seismic records, it is easy to predict vertical fissures in it, which might provide steam or gas paths. Deeper than 2000 meters the material should correspond to chert or slate of Paleozoic formation. The ultrasonic wave velocity in a horizontal direction has generally a higher value than that of the vertical direction. From this fact, we can consider the existence of horizontal fissures in the dacite lava.

Besides these, electrical prospecting and temperature calculation were applied. With regard to the electrical prospecting, BABA will explain it in a separate paper for this Symposium.

The sites for drilling were selected by taking these data into consideration, and after drilling, it became clear that the results of geological and geophysical prospecting were fairly accurate.

Besides these, as explained above, during the process of drilling, self potential, resistivity and temperature measurements were made in the borehole. These data were not only very useful to decide the lengths of liner pipes, but also effective in indicating the existence of fissures and cracks in the formation. Let us here remember some experiments in test wells. By using the data from these test wells we can say the surface cold water might flow seasonally into the so called first reservoir. On the other hand, the resistivity logs show small value in shallow part, say until about 550 meters, while deeper than that, depth resistivity values are high especially in well No. 1. Synthesizing the above phenomena, we decided to set the casing pipes to a depth of 550 meters to avoid the surface cold waters flow into the well. Later, this arrangement proved to be effective. Deeper than this, we set slotted pipes.

From these exploitation boreholes, many core specimens were collected. By using these specimens, density, porosity, permeability, longitudinal wave velocity and transverse wave velocity with pressure and temperature were determined in the laboratory. Some of the results are shown in Figure 4 and in Figure 5. For example, the ultrasonic wave velocity increases with pressure, while it decreases with temperature, and at a certain depth these effects compensate for each other. These data are also instructive for the analysis of seismic results. B. OZCICEK and B. JANAKIRAMAIAH joined this experiment.

Here the writer would like briefly to explain the recovery curves. Taking the example of No. 1 borehole, during the process of drilling, usually circulating mud was used and just after completion of this borehole, this mud was replaced by cold pure water, and so just after this replacement, temperature was very low as is seen in Figure 6.

Due to this time elapse, temperature in the borehole increased as is seen in this figure. During the increase of temperature with time, the pattern of temperature increase is not uniform, for example, at a depth of

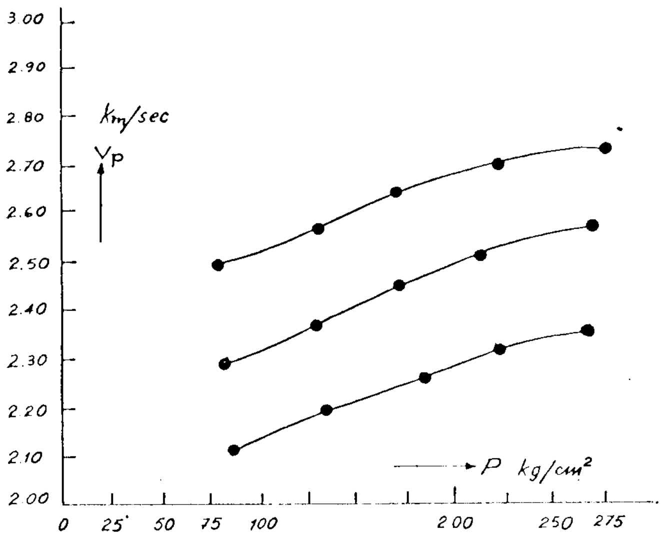


Fig. 4. — *Ultrasonic wave velocity versus pressure, Matsukawa geothermal field.*

600 m, at the beginning, the temperature increased very much, but in the later part of this period the temperature did not increase so much. This must depend upon the heat conductivity at this depth. On the contrary, at the depths of 700 m and 850 m, at the beginning, the temperature did not increase so much, but 4 days after there was a rise in temperature at these depths, because of the existence of so many fissures and hot water might have been transported from the surrounding formation into the borehole through these fissures. The final temperature distribution curve resembles very much the result of the calculation made before this drilling.

Three days after the completion of all temperature measurements, water in this borehole was lifted up so that the last temperature curve approaches and crosses the boiling point/depth curve, and as a result, lots of steam suddenly gushed from the outlet of this borehole. The writer presumes that if this borehole was kept without using swabbing, the temperature would reach boiling temperature. By the temperature calculation, we can expect to obtain the temperature of 374°C (critical temperature) at the corresponding depth of 3 km, assuming the existence of saturated steam.

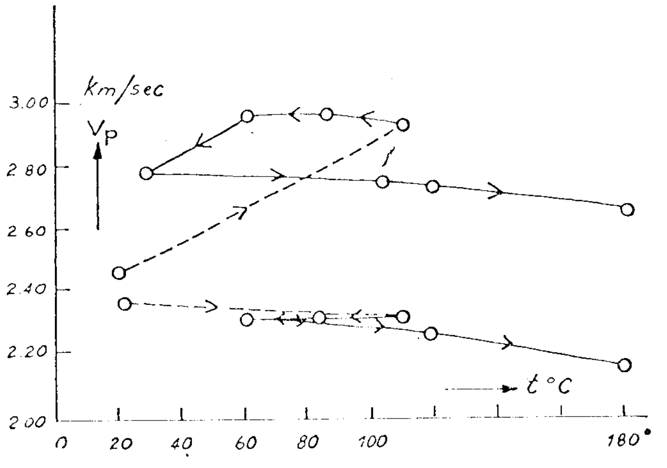


Fig. 5. — *Ultrasonic wave velocity versus temperature, Matsukawa geothermal field.*

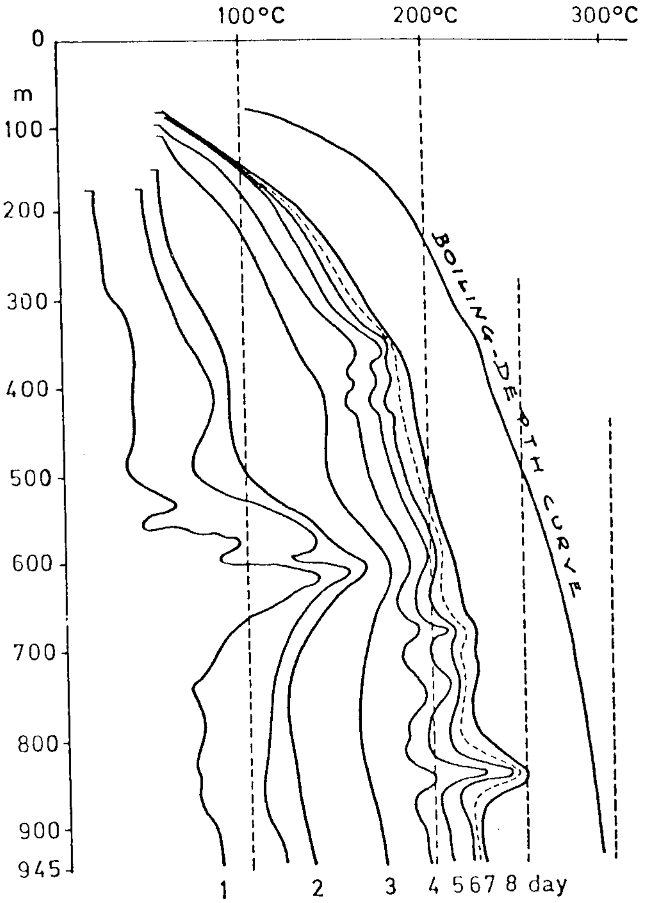


Fig. 6. — *Matsukawa geothermal field, borehole No. 1 temperature-depth curves versus time.*

The average velocity obtained in the field was 2.6 km/sec, but the value of velocity determined by the rock specimens in the laboratory is higher than 2.6 km/sec. The low value obtained in the field may be due to the presence of fissures.

In some part of the field seismogram there are poor reflection phases and in the remain there are clear reflection phases. This might depend upon the existence of hot water or steam.

By using the result of laboratory ultrasonic wave velocity measurements, the writer made an artificial seismogram using the following equation,

$$\text{reflection coefficient} = \frac{\rho_2\nu_2 - \rho_1\nu_1}{\rho_2\nu_2 + \rho_1\nu_1}$$

where ρ and ν are density and wave velocity respectively, and suffixes 1 and 2 indicate the successive layer numbers.

The depth to the reflection phases in the field seismogram and the artificial seismogram are given in the following table.

Field seismogram (meters)	Artificial seismogram (meters)
180	120
240 to 280	260
390	410
500	485
520	505
580	565
680	650
720	710
780	760
810	800
1000	1000

Thus there is generally a good agreement between the depths of the artificial seismogram and the depths of the reflection phases in the field seismogram. It is also found from this table that except for a few points the depths obtained from the field seismogram are always greater than the depths obtained in the artificial seismogram.

The high value obtained from the field seismogram for the boundary surface may be interpreted as follows.

From the laboratory experiments, it is found that the longitudinal wave velocity decreases with the increase of temperature. Inside the borehole, the temperature increases with depth. The temperature at the depth of 1000 meters must be higher than 265°C. Therefore the actual longitudinal wave velocity at great depth must be lower than the value of 2.6 km/sec which is assumed for the calculation of depths in the field seismogram. Thus the depths obtained are slightly greater than the actual depths (the artificial seismogram is made by laboratory experiment under atmospheric pressure).

For 1000 meters depth, the depth calculated from the field seismogram and the depth obtained from the artificial seismogram are the same. This can be interpreted as follows: at great depth, the pressure increases, the velocity increases with pressure as in Figure 4. Therefore the reduction of velocity with increase of temperature is annulled by increase of velocity with increase of pressure. Thus the depth calculated from the field seismogram will be the same as that obtained from the artificial seismogram at 1000 meters depth.

Finally by taking these facts, we have arrived at the following conclusion regarding the existing state of hot water or steam.

In the first stage of the study, we thought that the second cover rock formation could not supply a lot of steam and hot water to the well which penetrated it. But finally it became clear from the evidence that hot water or consequently steam might come from the deep heat source through the faults, fissures or cracks into the narrow pockets in the lava of the so called second cover. The rocks which form the first reservoir are more porous than the second cover rocks, of course, but the reservoir does not contain enough hot water and steam to supply productive wells because it does not possess many cracks and fissures, and furthermore the surface cold water may flow into it. Consequently we are now tapping the hot water and steam from the hard formation first named as the second cover and from the second reservoir, because the hard formation has plenty of cracks and/or fissures, and it also acts as the cover-rocks against the surface cold water.

PART TWO

In 1967 and 1968, seismic reflection surveys were conducted at Matsukawa geothermal field mostly by KURIHARA and the members of the Ube Industrial Co. with the help of the members of JAPEX (Japan Petroleum Exploration Co.), the members of GSJ (Geological Survey of Japan) including the writer, sponsored by Azumakako Co..

In these surveys, a quadruple stacking method was applied, based upon the CDP (Common Depth Point) principle. The results were represented by the wiggle and variable density method, after the data processing including static and dynamic corrections, stacking and filtering low cut 16 cps/1 section, high cut 47 cps/2 section, Figure 7.

In these processes, the static correction was made by using the weathering corrections and the calculation of the altitude corrections, from the datum plane; and considering the vertical wave velocity distributions, the idea of velocity increase with depth, (which was slightly different from the previous one at this place) was utilized after discusion.

For this purpose, ultrasonic wave velocities were utilized, using the same core samples as for the previous case, and velocity relations were obtained as follows by using the least square method.

$V_z = 1.955 + 1.36\,Z$ (1) obtained by using the velocity values in a vertical direction

$V_z = 2.160 + 1.13\,Z$ (2) obtained by using the mean values velocities with three directions

where V_z velocity at the depth Z

The increments 1.13-1.36 seemed to be higher than the true value, because of the use of compact core specimens. As already explained above, in general, there are the facts that the ultrasonic wave velocity increases with pressure, while it decreases with temperature, and at a certain depth (about 1000 meters at Matsukawa) these effects compensate each other. Besides these, the velocity decreases due to the existence of fault or fissure (fractured) zone and also the existence of the porous and permeable formations of reservoir structure are not overlooked. The rate of these velocity decreases cannot

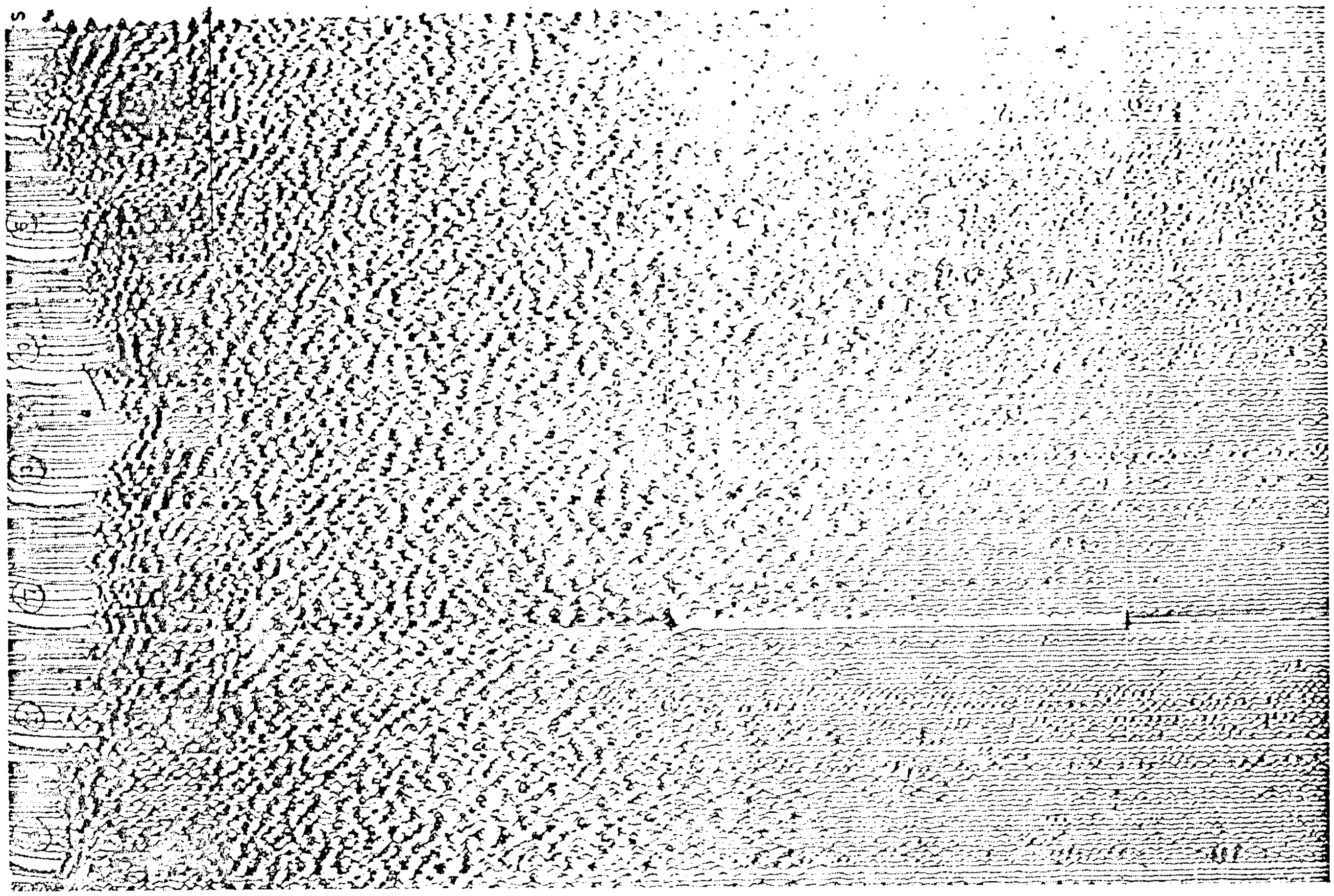


FIG. 7. — *Matsukawa geothermal field, seismic record.*

be estimated absolutely. Here, a method is tried that is obtained by combining the borehole data and the corresponding phase data in seismogram. (Recently, besides this, another method to obtain velocity value directly from the reflection data is under study).

In applying this idea, by assuming the synthesized velocity decreases as follows

depth Z (m)	temperature in borehole (°C, presumed)	rate of velocity decrease (%)
2000	400	÷ 20
1000	300	÷ 14
500		÷ 9
250	200	÷ 5

equations (1) and (2) become

$$V_z = 1.955 + 0.89\ Z \qquad (3)$$

$$V_z = 2.160 + 0.68\ Z \qquad (4)$$

In the present case, Eq. (3) is utilised for the practical calculation because of its better relation to the borehole data.

The basic mathematical formulas needed to construct the wave front chart are as follows (Figure 8)

FIG. 8. — *Construction of the wave front.*

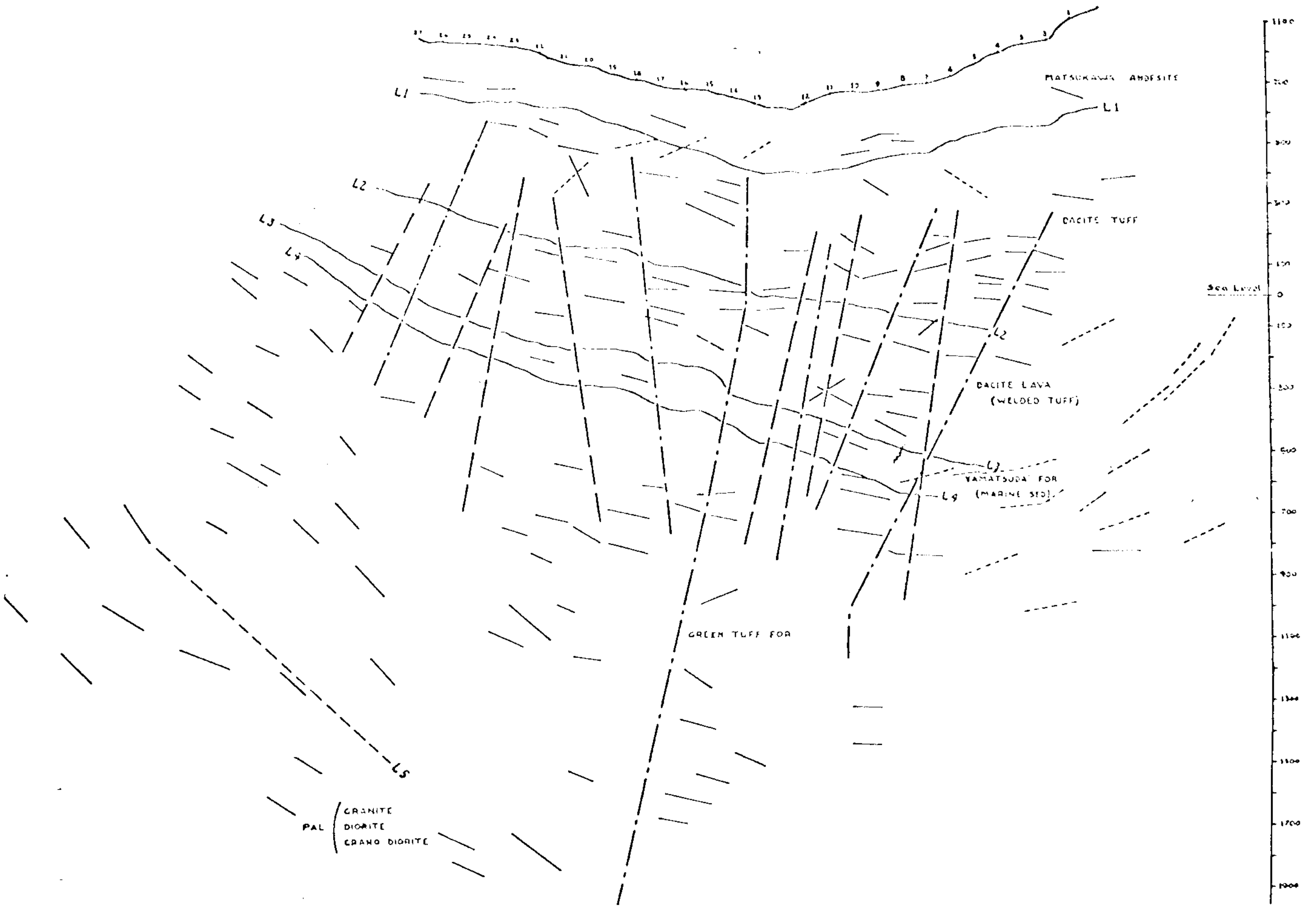


FIG. 9. — *Geological section obtained from seismic data, Matsukawa geothermal field.*

$$H = \frac{V_o}{k}\left(\cosh(kt) - 1\right)$$

$$R = \frac{V_o}{k}\sinh(kt) \qquad x = \frac{V_o}{k}\sinh(kt)\sin\alpha$$

One of the results is seen in Figure 9.

From these underground reflection interfaces, some conclusions will be drawn as follows.

1) By comparing borehole data with their corresponding reflection phases in seismogram, L_1, L_2, L_3, L_4, and L_5 will correspond to the boundaries between Matsukawa andesite and dacite tuff, dacite tuff and dacite lava, dacite lava and marine sediment, marine sediment and green tuff, green tuff and Paleozoic formations, respectively.

2) Fault structure and fissure zone can be located by the quick decrease of wave energy in a narrow band and also by the change of wave phases.

3) Steam or hot water reservoir can also be located by the quick decrease of wave energy.

4) Better reflection records can be obtained by means of stacking rather than using the conventional reflection techniques, when we consider oil fields and geothermal fields of this type.

In 1968, some traverses were added by similar methods, and consequently a three dimentional underground model is now under construction.

To make the reflection data still more clear and also to increase the detectable depth, it is necessary to eliminate undesirable noises and multiple reflections from these reflection data. For this purpose, it is necessary to utilize the recently developed techniques by using an electronic computer so that we will be able not only to economize on time, but also to increase the accuracy of the data qualitatively and quantitatively.

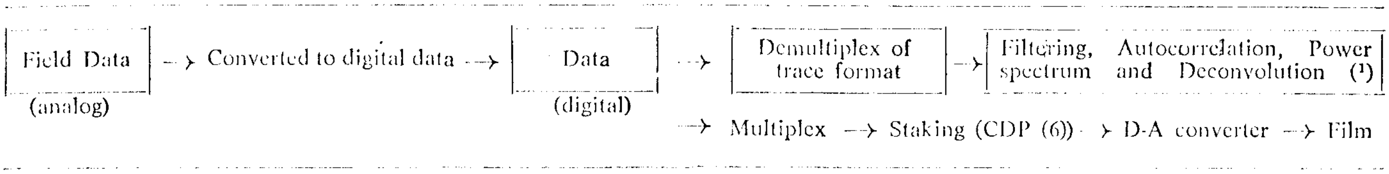
During the last few years, the processing of seismic reflection data from oil fields using electronic computers has successfully been done in many parts of the world. H. TAKEUCHI, University of Tokyo, Y. ISHI of the JAPEX, and the writer have obtained new seismic reflection records of the Matsukawa geothermal field, after treating the original data by using special soft-ware and hard-ware prepared by TAKEUCHI, with electronic computer processes.

These are based upon the deconvolution method attributed originally to E. A. Robinson. By this method, each impulse response is contracted to an impulse, and the original seismogram, which is assumed to be composed of a series of impulse responses, is converted to succession of impulses.

The original seismic data was obtained by S. Kurihara of the Ube Industries Co., applying the stacking CDP tecnique utilizing the SIE reflection seismograph. The detailed process of data treatment is omitted here. However, a brief outline of the calculation process is given below:

Nos. 1, 2, and 3 will correspond to those chosen in the previous case (Figure 9) which are the boundaries between:

1 Matsukawa andesite → first cover rock
Dacite tuff → first reservoir
2 Dacite tuff
Dacite lava → second cover rock
3 Dacite lava
Marine sediments → second reservoir



After such processes, the undesirable noises and multiple reflecitons were removed. A result of the seismic reflection record obtained after carrying out the above mentioned process is seen in Figure 10.

It is interesting to compare this record with the one as it looked before such a process. The original one is seen in Figure 7. It is possible to see that the deeper structures, easily seen in the new record, are absent in the original one.

The result of analyzing the original one is seen in Figure 9. During the process of this analysis it was assumed that the velocity increases linearly with depth. Taking into account the various field and laboratory data, the numerical values are as follows (as for the previous case)

$$V_z = V_o + kZ$$

where

$$V_o = 1.955 \text{ km/sec}, \qquad k = 0.89$$

For the present case, after discussions, the same process for the numerical calculation was utilized, with the difference that in the present, the graph for the calculation of reflection interfaces, was made for greater depths than those of the previous case.

Using this graph for deeper depth calculation and the revised seismic record (Figure 10), the underground reflection interfaces have been calculated as seen in Figure 11. These practical calculations were made with the help of M. Ramirez and J. Rubin de Cellis.

In Figure 11, one can see various interfaces each of which has a geophysical significance; however, if we choose some of them, we can pick up continuous phases, namely in sequence from top bottom, Nos. 1, 2, 3, 4. However, No. 4 in Figure 11 does not seem to be greatly justified because it is not so clear. The same can be said of interface No. 5.

No. 8 seems to be much clearer and might correspond to the boundary between

8 Marine sediments → second reservoir
Green tuff formation,

Nos. 9 and 10, also clear, will probably correspond to the boundary between

9, 10 Green tuff formation
Paleozoic formation (basement)

Nos. 6 and 7 will be some reflection planes inside the dacite formation.
Nos. 11 and 12 will correspond to some fault structures or fractured zone.

In addition to these, there is other information in deeper parts, for example, No. 13; energy is concentrated in this part and it can be related to the heat source. Generally speaking as seen in Figure 11, at depths greater than four kilometers, it is difficult for us to pick up any signal information (at present) because the seismogram shows noise patterns at these depths.

Anyway, it is very interesting to have been able to get such remarkable information as seen in No. 13 by using this new technique.

Synthesizing the temperature data (to 1500 m deep, we have the temperature data in boreholes, Figure 12 and hydrothermal alteration data and others, it is quite possible to assume No. 13 represents materials of the same kind as those which make up the heat source.

(¹) After filtering, filter coefficient was obtained by autocorrelation and power spectrum, then by using this filter data were deconvolved.

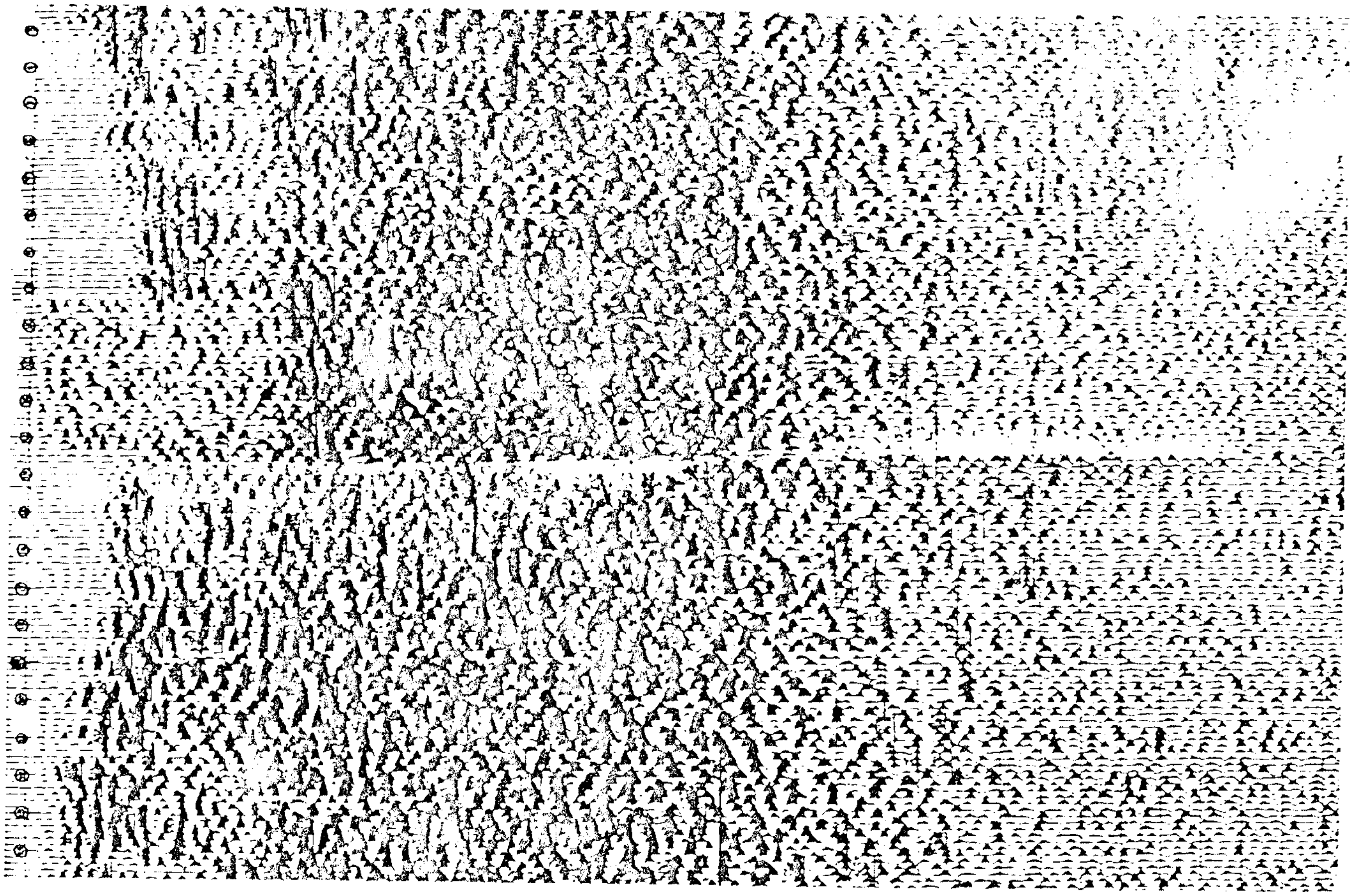


FIG. 10. — *Matsukawa geothermal field, revised seismic record.*

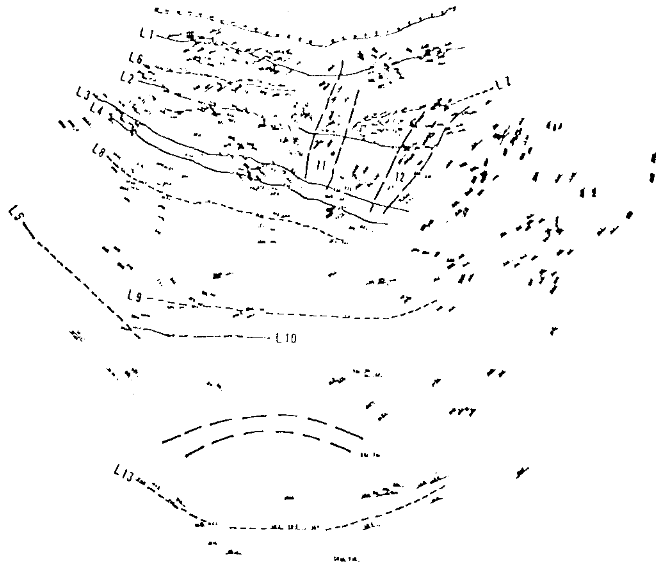


FIG. 11. — *Underground reflection phases and a geological interpretation, Matsukawa geothermal field.*

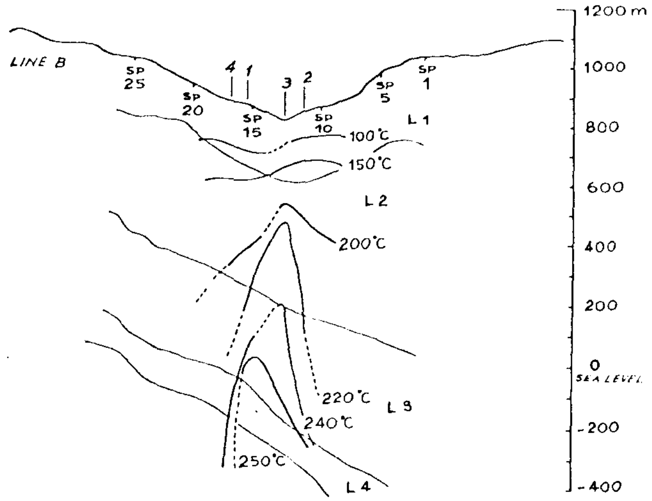


FIG. 12. — *Matsukawa geothermal field, temperature data in boreholes.*

Study of the wave-length of seismic wave and others to ascertain the geophysical state at Matsukawa geothermal field.

As already explained in the above parts, from the data obtained at Matsukawa geothermal field, the writer noticed the following: namely, that the low frequency wave patterns are predominant in the hydrothermal area which corresponds to the place of hot water, and as a consequence of the hot water and steam reservoir, the attenuation of the wave energy is very rapid.

KURIHARA also suggested the following similar ideas in same detail, using the various seismograms by the seismic reflection method not only at Matsukawa, but also at Onikobe (in the northern part of the Japanese islands) and at Otake (in Kyushu) geothermal fields.

These are:

— By comparing the seismograms in a geothermal area with those in a sedimentary area, there are some differences in the patterns. For the sedimentary area, continuous horizontal reflection phases can usually be seen, while in geothermal areas partly continuous horizontal reflection phases and the patterns related to the existence of fault structures can be seen.

— In the compact rock formation area, high frequencies with small wave amplitudes predominate, while in the reservoir area (hydrothermal area) low frequencies with large wave amplitudes are predominant. For the latter, usually the signal to noise ratios are comparatively good. However, the attenuation of wave energy is fairly rapid.

Usually, the attenuation of low frequency wave is rather slow, based upon the following relation,

$$I = I_o \frac{e^{-qr}}{r}$$

where I is the amplitude at a distance r from the source, I_0 the initial amplitude, and q a constant dependent on the material and, according to BIRCH, proportional to the frequency.

However, in the hydrothermally altered geothermal areas even with high temperature, there is the possibility of quick attenuation, because of the viscosity, based upon the following equation

$$u = \Lambda e^{if(x-v_1 t)} e^{-w_1 f^2 t}$$

where u is the displacement at a distance x, with time t, Λ the constant, f the wave function, and v_1, the longitudinal wave velocity while w_1, is the function of viscosity.

The writer hopes and believes that such a kind of seismic exploration research will develop, thus clarifying the underground structure and also the geophysical state of the geothermal fields.