Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Three-Dimensional Modeling and Inversion of the Mise-a-la-masse Data Using a Steel-Casing Borehole

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Keywords: mise-a-la-masse method, 3-D inversion

ABSTRACT

An advanced geoelectrical technique for imaging potential fractures has been developed by Engineering Geophysics Laboratory in Kyushu University. The method, Fluid Flow Tomography (FFT), has been applied to monitor fluid flow behaviors during water injection and steam production operations in geothermal areas in Japan. Distribution and extension of potential fractures can be evaluated by 3-D inversion of the mise-a-la-masse data using a steel casing pipe as a charged current electrode in a surveyed area. It is concluded that potential fractures in geothermal reservoirs could be traced and visualized as a function of time by the charged potential method.

1. INTRODUCTION

In order to monitor the transient phenomena of dynamic fluid flow behaviors during injection and production operations, we have developed a 4-D geoelectical system with a three-dimensional (3-D) inversion program for the mise-a-la-masse data using a casing pipe as a line source of current electrode. This program can be used for interpretation of the mise-a-la-masse data using an arbitrarily shaped casing pipe such as directional and horizontal wells. Fluid flow distribution can be visualized from the residual potentials obtained by subtracting the preinjection data from the postinjection data. The amount of fluid flow and asymmetric anomaly due to anisotropic permeability of the formation, can be estimated from the 3-D inversion of the mise-a-la-masse data during massive production and or reinjection operations.

2. AUTOMATIC RECORDING SYSTEM

An advanced geoelectrical technique for imaging potential fractures has been developed by Engineering Geophysics Laboratory of Kyushu University (Ushijima, et al., 1999). The method, Fluid Flow Tomography (FFT), has been applied to monitor fluid flow behaviors during and after massive water/steam injection and production operations through a cased borehole.

Figure 1 shows photographs of automatic recording system of the mise-a-la-masse field survey. A charged current electrode (C1) is connected to the conductor casing of the charged well. The earthing electrode (C2) is fixed at 3 - 5 km away from the charged well. The base potential electrode (P2) is also fixed 3 km away from the charged well and on the side opposite of the other current electrode (C2 cable line) to minimize electromagnetic coupling effects. A potential electrode (P1) is moved along a traverse line for the conventional mise-a-la-masse survey, while multiple potential electrodes are used for the present automatic measuring system of 4-D geoelectrical survey. An electric current of 1 - 5 A and a frequency of 0.1 Hz are introduced into the earth by a conventional transmitter used for a conventional electrical resistivity surveys. Potential distributions on the ground surface are continuously measured at multiple stations by a digital recording system controlled by a personal computer on the survey site.



Figure 1: FFT recording system; data recorder (PC) and remote scanner (120ch).

3. DATA PROCESSING OF MAM SURVEY

The charged potentials are converted to apparent resistivity values multiplying by a geometric factor of the mise-a-la-masse method. Self potentials due to streaming potentials are also simultaneously measured and interpreted according to the flowchart of data processing as shown in Figure 2.

In this system, data acquisitions are automatically conducted and time series data are stored on memories of a personal computer with a sampling rate of 1,800 runs/hour. The time series data can be visualized on the CRT of the computer in real time. Therefore, fluid-flow fronts and the distribution of fluid flow can be continuously imaged as a function of time on the survey site. Practical images of fluid-flow behaviors may be obtained by making contour maps and bird's-eye views (3-D) with a comparison of two datasets between an arbitrary time lag and an initial time (a base time). These contour maps could be continuously obtained before, during and after man-made stimulations of reservoirs such as hydraulic fracturing, production and reinjection operations.

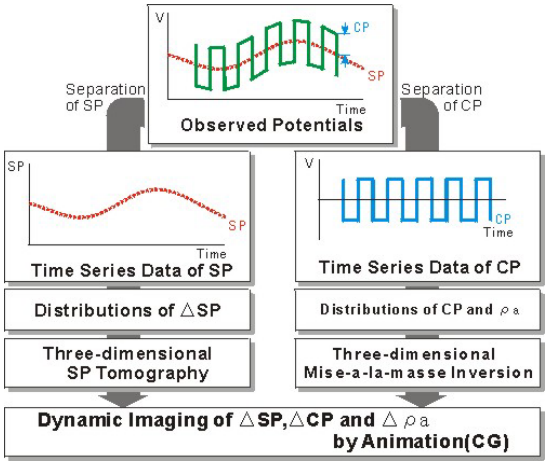

Figure 2: Data processing of the mise-a-la-masse measurements with a personal computer.

4. 3-D INVERSION OF MAM DATA

Least squares method has generally been used for the interpretation of geophysical data. In a non-linear least squares method, unknown parameters can be obtained by a repeated calculation using Marquardt equation as follows:

$$\left(\mathbf{A}^{\mathrm{T}}\mathbf{A}+\lambda\mathbf{C}^{\mathrm{T}}\mathbf{C}\right)\Delta\mathbf{P}=\mathbf{A}^{\mathrm{T}}\Delta\mathbf{g} \tag{1}$$

where $\mathbf{A}$ is Jacobian matrix, λ is the damping factor, $\mathbf{C}$ is the smoothing factor, $\Delta\mathbf{P}$ is parameter adjustment vector and $\Delta\mathbf{g}$ is the residual vector.

The following procedures have been used for the inversion analysis of geophysical data: (1) forward calculation, (2) calculation of Jacobian matrix, (3) least squares method, (4) iterative numerical calculations, and (5) statistical evaluation of solutions. Because a large CPU time is necessary for calculating Jacobian matrixes especially in a three-dimensional inversion, Jacobian matrix proposed by Loke and Baker(1995) has been used for minimizing a processing time in our computer program. That is, each element $\mathbf{A}_{ij}$ of Jacobian matrix for a homogeneous earth is expressed as

$$\mathbf{A}_{ij}=\frac{\partial\log\rho_{aj}}{\partial\log p_i}=\frac{p_i}{\rho_{ai}}\cdot\frac{\partial\rho_{aj}}{\partial p_i}=\frac{p_i}{\rho_{ij}}\cdot G\cdot\frac{\partial V}{\partial\rho}\cdot\frac{1}{I} \tag{2}$$

where p_i , ρ_{aj} are parameter and apparent resistivity corresponding to each block, respectively, G is the geometric factor, V is then electric potential and I is the intensity of electric current. Using Single Scattering theory for a homogeneous earth (Park and Van, 1991), potential sensitivity against resistivity is given by

$$\frac{\partial V}{\partial\rho}\cong\rho^{-2}\int_v\nabla V\cdot\nabla V'\,d\tau \tag{3}$$

where V is the electric potential due to current source $(+I_c)$, V' is the electric potential due to a fictious current source (+1) at potential electrode P and v denotes volumetric element due to a change of electrical resistivity.

Considering a theory of scattering field, equation (3) can be expressed as

$$\frac{\partial V}{\partial\rho}\cong\rho^{-2}\int_v\nabla V\cdot\nabla V'\,d\tau$$
$$\cong\frac{I_c}{8\pi}\int_v\left(\frac{\mathbf{r}_c\cdot\mathbf{r}_p}{|\mathbf{r}_c|^3|\mathbf{r}_p|^3}+\frac{\mathbf{r}_c^*\cdot\mathbf{r}_p}{|\mathbf{r}_c^*|^3|\mathbf{r}_p|^3}\right)d\tau \tag{4}$$

where, C and P denote the current and potential electrode respectively, $\mathbf{r}$ is the distance vector from volumetric element to each electrode and * denotes the mirror image of current electrode. Line source equation can be derived by integrating a point source equation. If we assume C moves at points from $C1$ to $C2$ on a line source of current, point $C(x_c,y_c,z_c)$ is expressed using a parameter $t(-1\le t\le 1)$ as

$$\begin{cases}x_c=\{(x_{C2}-x_{C1})t+x_{C2}+x_{C1}\}/2\\ y_c=\{(y_{C2}-y_{C1})t+y_{C2}+y_{C1}\}/2\\ z_c=\{(z_{C2}-z_{C1})t+z_{C2}+z_{C1}\}/2\end{cases} \tag{5}$$

Assuming current density of a line source be constant, current dI for a small element dt is

$$dI=\frac{I}{l}\cdot d|\mathbf{r}_c|=\frac{I}{l}\cdot\sqrt{dx_c^2+dy_c^2+dz_c^2}=\frac{1}{2}dt \tag{6}$$

Scattering field for a line source of current can be derived by replacing dI into I_c in eq.(4) and integrating from –1 to +1 on t as

$$\frac{\partial V}{\partial\rho}=\frac{I}{16\pi^2}\int_{-1}^{1}\int_v\left(\frac{\mathbf{r}_c\cdot\mathbf{r}_p}{|\mathbf{r}_c|^3|\mathbf{r}_p|^3}+\frac{\mathbf{r}_c^*\cdot\mathbf{r}_p}{|\mathbf{r}_c^*|^3|\mathbf{r}_p|^3}\right)d\tau dt \tag{7}$$

Finally, potential sensitivity in eq.(3) is defined as

$$\frac{\partial V}{\partial\rho}=\frac{I}{16\pi^2}\int_{-1}^{1}\int_{z1}^{z2}\int_{y1}^{y2}\int_{z1}^{z2}F(x,y,z,t)\,dxdydzdt \tag{8}$$

This integral value can be calculated by Gauss-Legendre integral equation formula. General equation of Jacobian matrix for a directional well can be also derived by integrating a small element of a line source based on a superposition of potential.

5. NUMERICAL MODELING AND INVERSION

It is sometimes difficult to determine the anomalous body from the observed data of the mise-a-la-masse survey. Therefore, the numerical modeling is very important for the various types of conducting bodies and geological environments of the surveyed area. However, numerical solutions should be carefully checked with an exact solution. In oreder to compute potentials and apparent resistivities, the finite element method and finite difference methods are used for simulating the 3-D anomalous bodies in the subsurface. Three-dimensional mesh design used in the numerical calculation is shown in Figure 3.

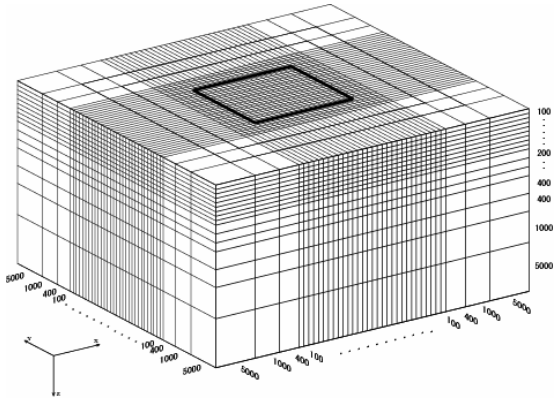

Figure 3: Three-dimensional mesh design for a numerical modeling and inversion.

Results of 3-D numerical modeling for anomalous bodies are shown in Figures 4 and 5. The resistivity contrast between the target bodies and the surrounding formations is 0.1 or 10 , with the target body being conductive or resistive. Modeling results with a vertical line source and an inclined line source of a directional borehole are presented as contour plots of apparent resistivities.

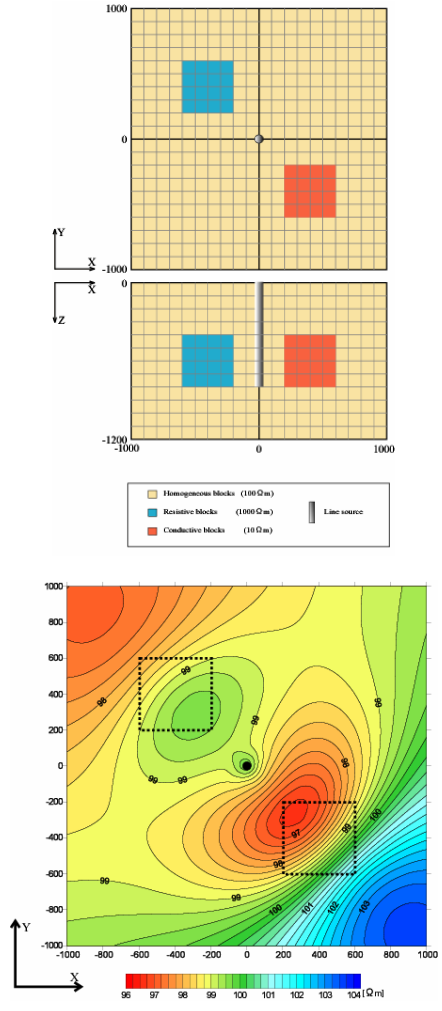

Figure 4: Three-dimensional model with resistive and conductive anomalous targets.

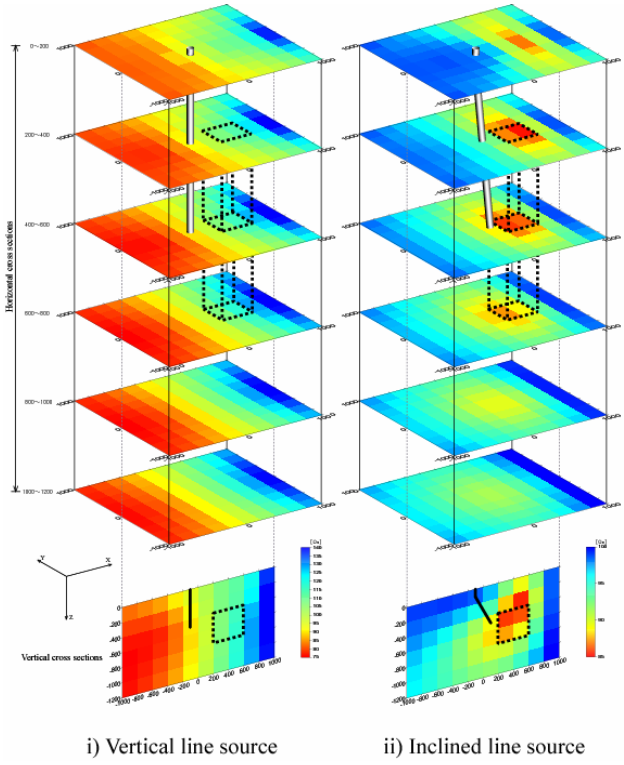

Figure 5: Calculated apparent resistivity distribution.

6. THE MAM SURVEY IN SUMIKAWA GEOTHERMAL AREA

The Sumikawa geothermal field is located in the Hachimantai volcanic region of north eastern Japan, where there are active volcanoes, hot springs and fumaroles, as well as Ohnuma, Matsukawa and Kakkonda geothermal power plants. The Sumikawa geothermal power station has been jointly developed by Mitsubishi Materials Corporation (MMC) with Tohoku Electric Power Inc., and operated since 1995. The mise-ala-masse field survey using the casing pipe of the S-3 well has been conducted in conjunction with a periodical inspection of the geothermal power plant. Charged potentials using a casing pipe of the S-3 well as a current electrode were automatically measured at multiple potential electrodes on the ground surface surrounding the well. Subsurface resistivity structure of the area could be determined using apparent resistivity data derived from the mise-a-la-masse data using a line current source as a function of time. The stratigraphy of the Sumikawa field consists of Quaternary volcanic rocks, lacustrine sediments, and Tertiary formations intruded by granitic rocks. The pre-Tertiary basement has not been reached by geothermal drillings (Ariki, et. al., 2000). The hydrothermal system occurs under lacustrine sediments and a shallow zone of hydrothermal alteration, which act as the cap rock of geothermal reservoirs.

Resistivity structures are obtained by two-dimensional (2-D) inversion of MT and CSAMT data (Uchida et al., 1995). The resistivity structure is characterized by a very low resistivity (from 1 to 3 Ωm) cap rock beneath a resistive layer and rather high resistivity layer of reservoirs (on an order of 100 ohm-m). The very low resistivity of the cap rock is due to clay minerals such as montmorillonite.

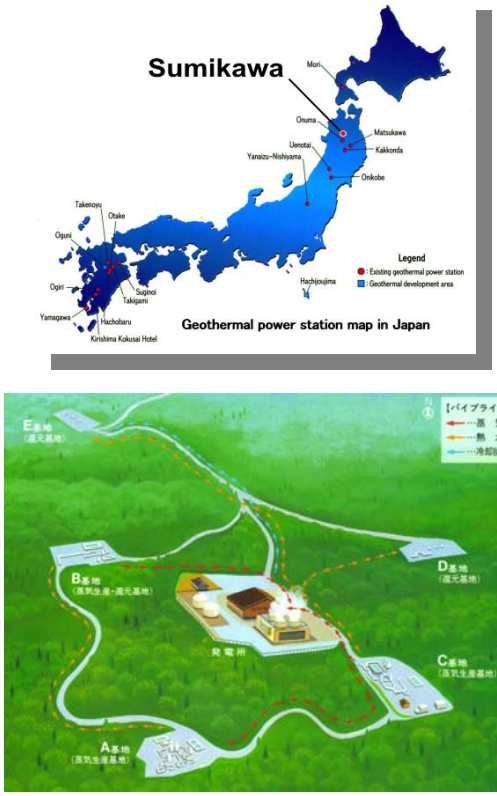

Figure 6: Location map of Sumikawa geothermal field.

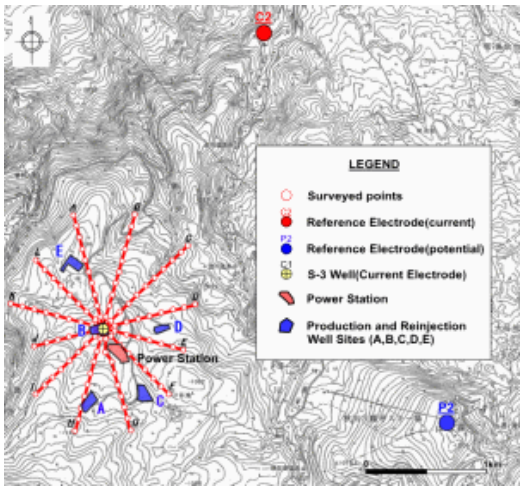

Figure 7: Electrode array of the mise-a-la-masse survey in the Sumikawa geothermal area, Akita Prefecture in Japan.

7. RESULTS OF MAM SURVEY

The mise-a-la-masse survey using the casing pipe of the S-3 well has been conducted at reinjection well site B in the Sumikawa geothermal field. The current electrode C1 was connected to the wellhead part of a casing pipe (800 m length) and 101 of multiple potential electrodes are radially set along the survey lines from A-direction to L-direction with a station interval of 100 m as shown in Figure 7. The MAM measurements have been conducted for about 4 weeks from 14th September to 7th October during the periodical inspection of the Sumuikawa geothermal power plant in the year of 2000. Data acquisition is automatically conducted, and time-series data are stored on diskettes with a sampling rate of 2 seconds.

Charged potential data can be obtained by the running average method from observed data. Therefore, the apparent resistivity can be calculated from the charged potential data multiplied by a geometric factor (Ushijima, 1989):

$$\rho_a = K(V / I) \tag{9}$$

Apparent resistivity distribution observed on 1st October in 2000 is illustrated in Figure 8.

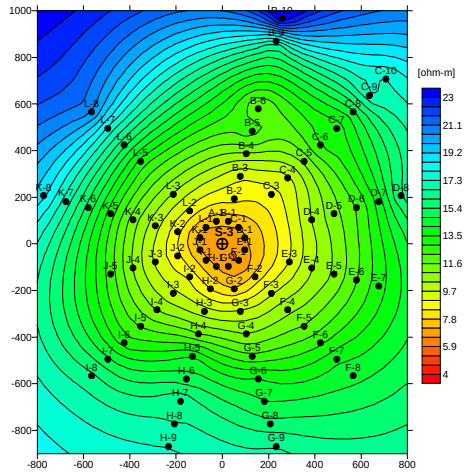

Figure 8: Distribution of apparent resistivity.

The subsurface resistivity distribution is not homogeneous. It is because resistivity changes laterally and vertically as a function of the distance from the well. Therefore, resistivity inversion was applied based on a layered earth model in order to remove the vertical resistivity change. The results of inversion of the mise-a-la-masse data are as follows: the first layer resistivity and thickness are 2.5 Ωm and 800m respectively, and the second layer resistivity is 620 Ωm. Thus, residual apparent resistivity values are calculated using the two-layer earth model. The residual apparent resistivity distribution is shown in Figure 9.

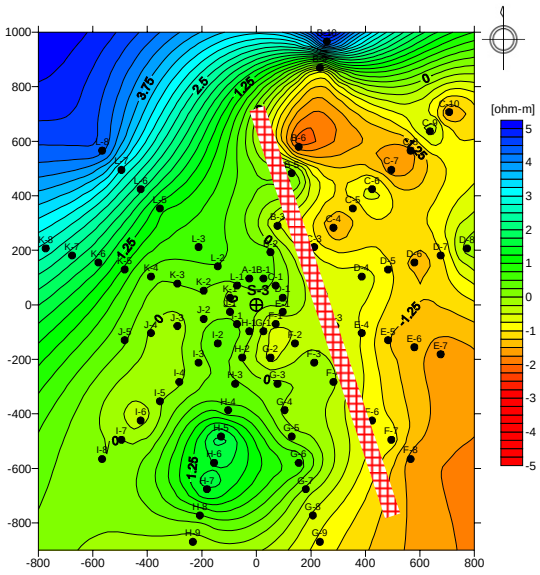

Figure 9: Distribution of residual apparent resistivity.

It is clearly detected that low resistivity zones are distributed in the eastern area and faults with the strike of north-south direction are delineated in the eastern area from the well.

Finally, 3-D inversion of the mise-a-la-masse data was conducted using a 3-D block model based on the least squares method. The resultant depth sliced contour maps are illustrated in Figure 10.

Low resistivity zones less than 10 Ωm are widely distributed in a shallow depth down to 600 m, while high resistivity zones are distributed deeper than 600 m. It is concluded that geothermal reservoir exists beneath the low resistivity zone at the north-eastern part of the S-3 well in the Sumikawa geothermal field.

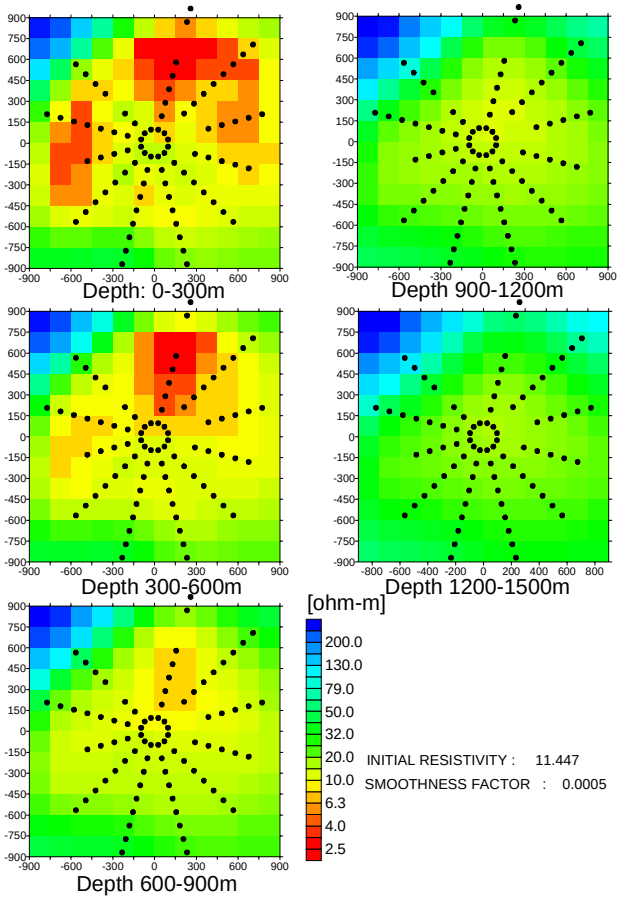

Figure 10: Depth sliced resistivity distribution from 3-D inversion of the mise-a-la-masse data.

8. CONCLUSIONS

A multichannel geoelectrical system and various programs for data acquisition, processing, and interpretation techniques had been developed. The FFT method had been applied to image potential fractures in the Sumikawa geothermal field. The fluid-flow behavior in the subsurface could be monitored and visualized by the present 4-D geoelectrical technique such that: (1) time-series data of charged potentials (apparent resistivities) and self potentials (streaming potentials) could be obtained in real time; (2) fluid flow boundaries can be visualized from the residual potentials obtained by subtracting preinjection data from postinjection data; (3) the anisotropic permeability of the formation can be evaluated from the percent difference of apparent resistivity data based on Archie's law; (4) 3-D distribution of fractures could be imaged by the joint interpritation with the other geophysical data such as magnetotelluric and vertical electrical soundings.

ACKNOWLEDGEMENTS

We thank to MMC and MMRC corporations for applying the FFT method to reservoir monitoring in the Sumikawa Geothermal Field, Japan.

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