An Application of Geostatistical Method to Estimation of Some Variables Distributed in a Geothermal Reservoir

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Abstract

In this study, the distributions of both the initial temperature and the peak intensity of diffracted X-ray of pyrophyllite in the Matsukawa geothermal reservoir, where is located in Northeast Japan, were estimated by using geostatistical method, the kriging. These are important to comprehend a hydrothermal convection system in a geothermal reservoir. As a result, it was showed that the high temperature zone extends in the direction of SW deeply and there is frequent occurrence of pyrophyllite along intrusive rocks. Moreover, it can be inferred that the temperature in this reservoir has decreased a few decades degrees C since pyrophyllite was made according to the mutual relationship between the initial temperature and the peak intensity of diffracted X-ray of pyrophyllite.

1 Introduction

Some estimation methods for geothermal reservoirs have been devised with their conceptual and numerical modeling techniques developed. These are for natural state simulation to understand construction process of hydrothermal system, history matching analysis of reservoir behavior and future prediction or life estimation of geothermal resources, for example.

In each geothermal development area, well logging data or well test data are accumulated and several values of physical properties for reservoir behavior from past to present are measured. Using these informations, future prediction of reservoir behavior or production of geothermal resources is now on trial.

In this paper, it is the purpose to estimate some variables distributed in a geothermal reservoir by using geostatistical method. In the first place, geostatistical method is described concisely. Secondly as a case study, the initial temperature distribution in the Matsukawa geothermal reservoir which is in natural state without development effect is estimated by the kriging. Consider the peak intensity of diffracted X-ray of pyrophyllite as semiquantitative occurrence strength of pyrophyllite, its distribution is also estimated. Moreover, the mutual relationship between the initial temperature and the peak intensity of pyrophyllite is discussed.

2 Geostatistical Method

2.1 Stationarity and Semivariogram

Stationarity is a property of the random function model (Deutsch and Journel, 1992). In order to consider a regionalized variable (abbr. Re.V.) as a randoni variable (abbr. R.V.), it is necessary of Re.V. to satisfy the following weak stationarity of order 2 (Delhomme, 1978).

If the Re.V. under study is such that the hypothesis can be reasonably made, then experimental semivariogram (abbr. exp.S.V.), $\gamma^*(h)$, is written as follows (e.g. Deutsch and Journel, 1992):

$$\gamma^*(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \{z(u_i) - z(u_i')\}^2 \qquad (1)$$

where $z(u_i)$ and $z(u_i')$ are sample values at two sample points, u_i,u_i', separated by the vector h and $N(h)$ is the number of pairs of them.

The exp.S.V. is discrete quantity. In order to express this as continuous function, fitting a model semivariogram (abbr. model S.V.), $\gamma(h)$, to a exp.S.V. is carried out. The spherical type model S.V. function which is the most typical one is expressed as follows (e.g. Delhomme, 1978):

$$\gamma(h) = \begin{cases} c\left(\frac{3}{2}\frac{h}{a} - \frac{1}{2}\frac{h^3}{a^3}\right) + c_0, & 0 \le h < a \\ c + c_0, & a \le h \end{cases} \qquad (2)$$

where a is range of influence, c_0 is value of nugget effect and c is sill value.

2.2 Kriging

In this paper, only the ordinary kriging (Deutsch and Journel, 1992, pp.63-64) is mentioned. The estimator Z_v^* of a block v is expressed as follows by a weighted average of n sample values:

$$Z_v^* = \sum_{i=1}^{n} \lambda_i z(S_i) \tag{3}$$

where λ_i is the kriging weight associated to ith sample, S_i represents ith sample and $z(S_i)$ is the value of the sample S_i.

The estimation variance, $\sigma_E^2 (= Var\{Z_v - Z_v^*\})$, is the variance of the estimation error (Olea (Ed), 1991) and is written as follows:

$$\sigma_E^2 = 2\sum_{i=1}^{n} \lambda_i \bar{\gamma}(S_i, v) - \bar{\gamma}(v, v) - \sum_{i=1}^{n}\sum_{j=1}^{n} \lambda_i \lambda_j \bar{\gamma}(S_i, S_j) \tag{4}$$

where the expression $\bar{\gamma}(\alpha, \beta)$ represents the average semivariogram between all pairs of points, where one point is inside α and the other is inside β.

The nonbias condition that the estimation error should be 0 on average is expressed as follows:

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{5}$$

The kriging weights should be determined to minimize the estimation error.

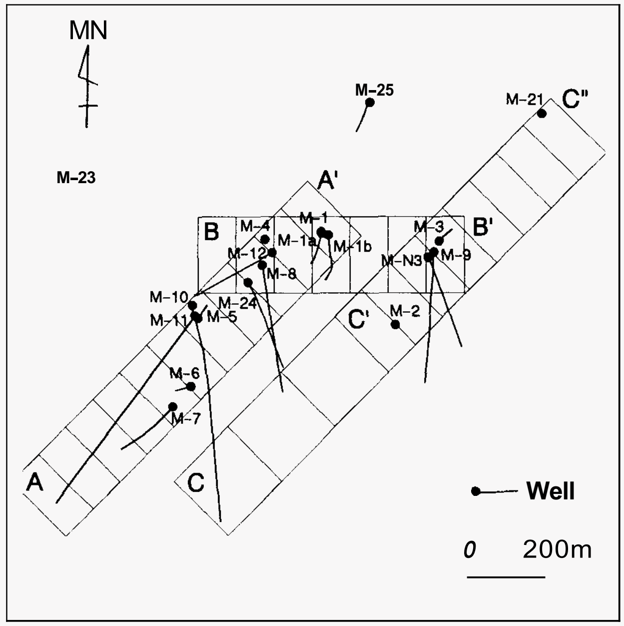


Figure 1. Location map of wells with cross sections to be estimated at the Matsukawa geothermal field.

3 Case Study : Matsukawa Geothermal Reservoir

3.1 Geology

According to the data obtained from drillings in the Matsukawa geothermal field, the geological succession in this field can be described as follows (JMC, 1991): Quaternary Matsukawa andesite, Pliocene-Pleistocene Tamagawa welded tuff formation, Miocene Takinoue-onsen and Kunimitoge formations, in descending order.

This field is covered with Quaternary Matsukawa andesite. It is confirmed that Pliocene-Pleistocene Tamagawa welded tuff and Miocene series are distributed under this formation and intrusive rock of porphyrite and quartz diorite are locally emplaced in this horizon. Geological cross sections in this field, which these locations are shown in location map of wells (figure 1), are shown in figures 2(a)-(c).

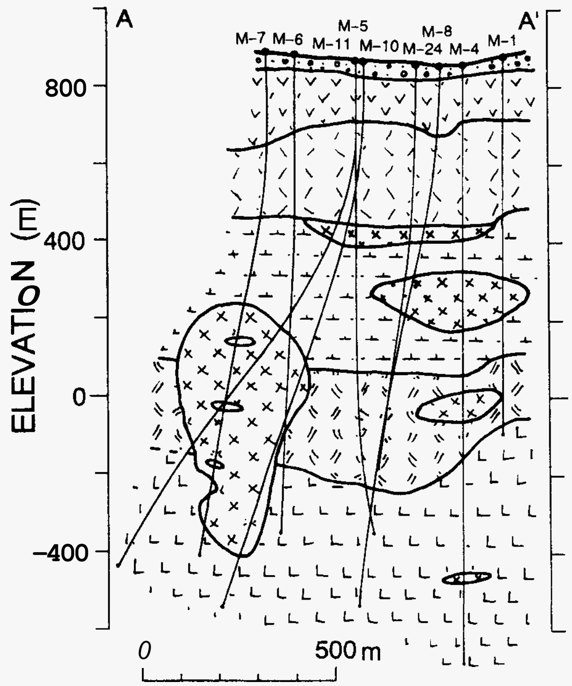
3.2 Initial Temperature Distribution

A initial temperature denotes a true formation temperature in natural state just before development of geothermal resources. The initial temperature distribution is important to estimate a hydrothermal convection system in a geothermal reservoir. Whereas in the area many wells were drilled and geothermal fluid was produced or (re)injected for a long time, the distribution of the temperature in the reservoir may differ from that before development. Especially variability of the temperature nearby production and (re)injection wells should be remarkable.

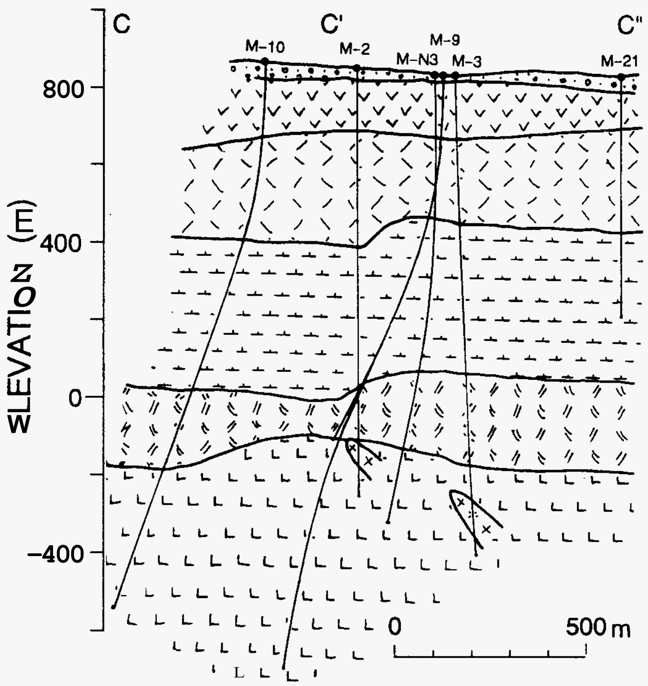
Hanano (1992) showed that the initial temperature distribution was reasonably estimated by a natural state simulation based on measured temperature data at a cross section along southwest to northeast of the Matsukawa geothermal reservoir, but there still remains minor disagreement. On the other hand, despite lacking of underground temperature data in natural state in this reservoir (Hanano and Matsuo, 1990), Kato et al.(1994) roughly illustrated the initial temperature distribution at a NE-SW cross section as geometrically isotropic distribution by using the kriging.

In this study, the temperature data which were used in calculation were logging data or estimated one of six wells on investigation or in initial step of development from 1964 to 1983 (Hanano, 1992) for the same reason as Kato et al. (1991). These data are regarded as the initial temperatures which are nearly equal to true formation ones (JMC, 1991). Locations of wells which include these six wells in this field are shown in figure 1. In due consideration of the number and locations of wells, estimation of the initial temperature distribution was carried out using four wells data contained just in the C-C'-C" cross-section area with 200 m wide shown in figure 1.

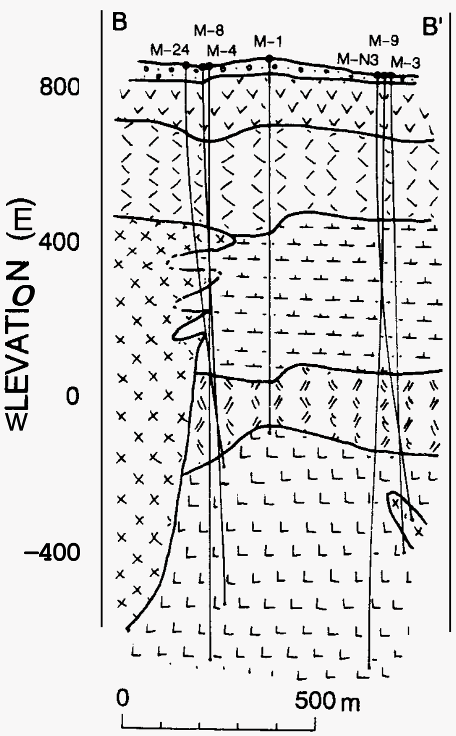
The exp.S.V.s calculated with these temperature data in two directions (vertical and horizontal) are shown as dots in figure 3. The solid and the broken line in the same figure express the spherical type model S.V. curves fitted to the directional exp.S.V.s. Similarly, histogram which have two kinds of lines express the frequency of pairs of two sample points. When curve fitting is made, it is necessary to regard the exp.S.V. as important which are near the origin and have many pairs of two sample points.



(a) At the A-A' cross section.



(c) At the C-C'-C" cross section.



(b) At the B-B' cross section.

Figure 2. Schematic geological cross sections of the Matsukawa geothermal field. (These are internal data of JMC.) Locations of the cross sections are shown in figure 1.

The distribution of the estimated initial temperature and the kriging variance calculated by the kriging are shown in figures 4 and 5 respectively.

3.3 Pyrophyllite Distribution

According to Sumi (1968) and Sumi and Maeda (1970), the altered rock zone extends along the Matsukawa river in a direction from ENE to WSW, compris-

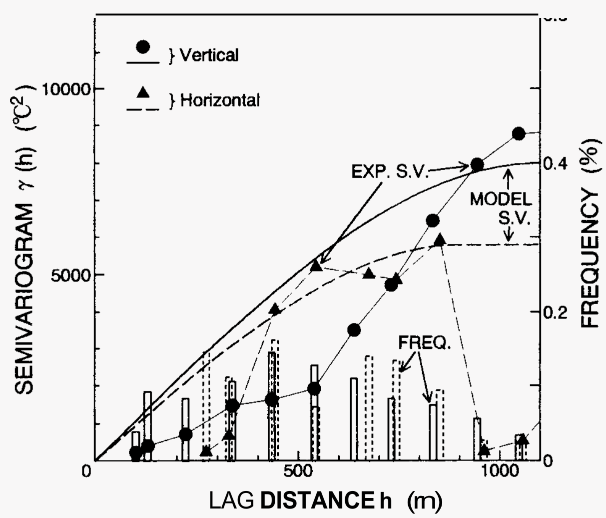


Figure 3. Experimental and model semivariograms of the initial temperature with the frequency of the pairs of two sample points at the C-C'-C" cross-section area.

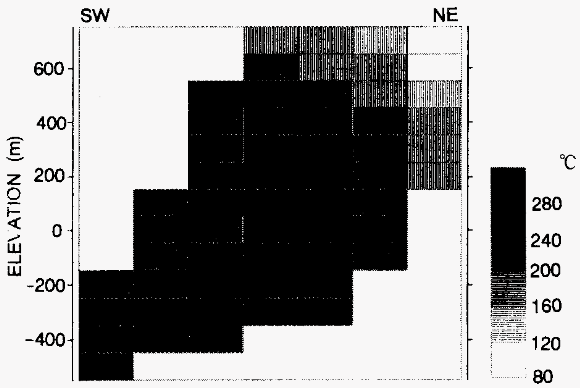


Figure 4. Distribution of the estimated initial temperature at the C-C'-C" cross-section area.

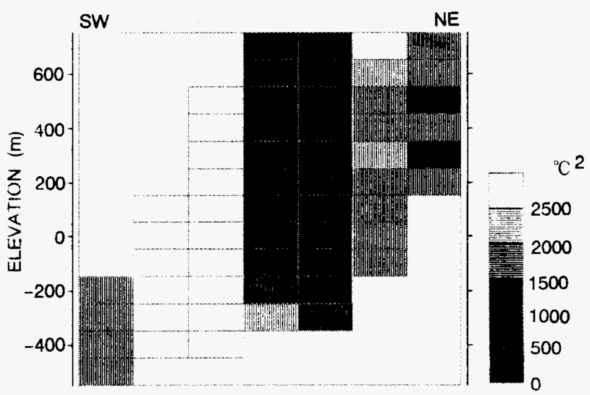


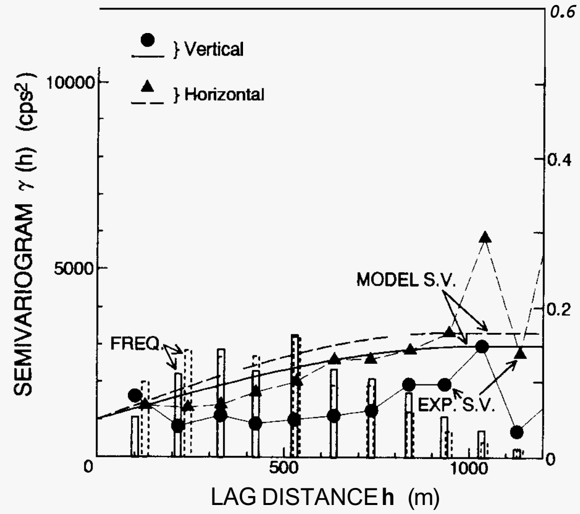
Figure 5. Distribution of the kriging variance when the initial temperature was estimated at the C-C'-C" cross-section area.

ing an area of 7 km long and 0.5-1 km wide. The altered rock zone is classified into silicification and argillization subzones. As for the alteration minerals, laumontite, eight types of clay minerals, and nine other minerals have been identified by X-ray analysis.

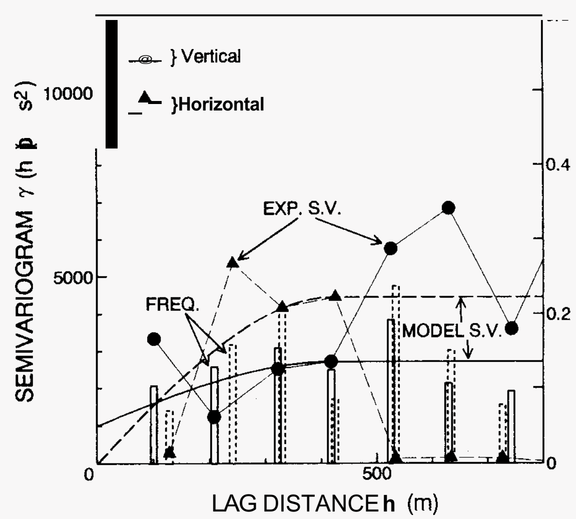
The argillization subzone is usually distributed around the silicification subzone and is characterized by zonal distribution from the outer to the center. Apart from the mineral sequence mentioned above, a pyrophyllite zone has developed, overlapping the zonal arrangement of the argillization subzone. This pyrophyllite zone is considered to have been formed at a higher temperature condition than the other mineral zones.

From the investigation of the production wells, it has become apparent that the pyrophyllite zone corresponds to the locality of circulation loss during drilling and to that of high temperature and low resistivity. These facts suggest that geothermal fluid is stored in the fissures and cracks developed in the pyrophyllite zone in this field.

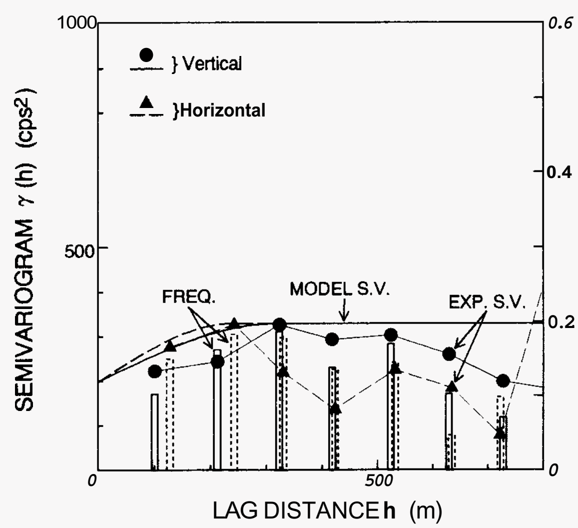
About twenty wells were drilled and then their cores or cuttings were taken from 1963 to 1990 in the Matsukawa geothermal field (Hanano et al., 1993). Most of these cores or cuttings were analyzed using X-ray pow-



(a) At the A-A' cross-section area.

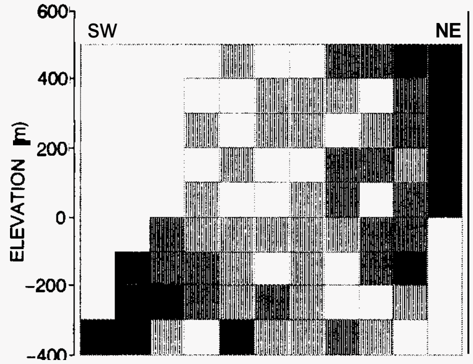


(b) At the B-B' cross-section area.

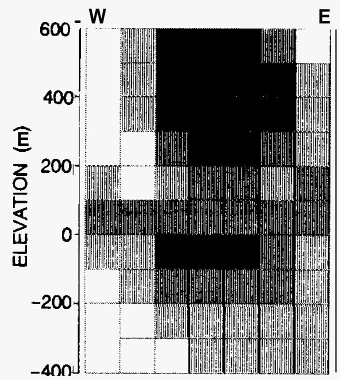


(c) At the C'-C" cross-section area.

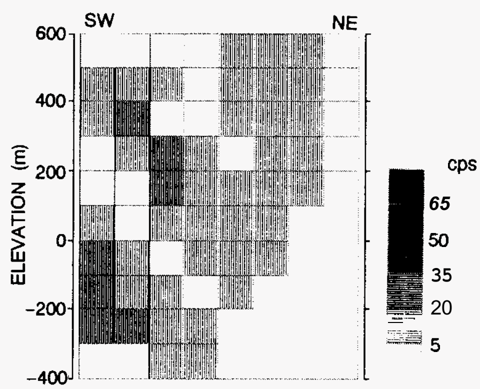
Figure 6. Experimental and model semivariograms of the peak intensity of diffracted X-ray of pyrophyllite with the frequency of the pairs of two sample points.



(a) At the A-A' cross-section area.



(b) At the B-B' cross-section area.



(c) At the C'-C" cross-section area.

Figure 7. Distribution of the estimated peak intensity of diffracted X-ray of pyrophyllite.

der diffraction data by JMC. It is available for semi-quantity to use a peak intensity of diffracted X-ray of pyrophyllite (Shirozu, 1988).

Before calculation of the exp.S.V., the peak intensity data of diffracted X-ray of pyrophyllite were regularized for three cross-section areas (A-A', B-B' and C'-C") with 200 m wide shown in figure 1 because of plenty of its data. After this work, computing was done in the same way as the initial temperature. The exp.S.V.s and the model S.V.s at three cross-section areas are shown in figures 6(a)-(c) and the distributions of the estimated peak intensity of pyrophyllite are shown in figures 7(a)-(c) respectively.

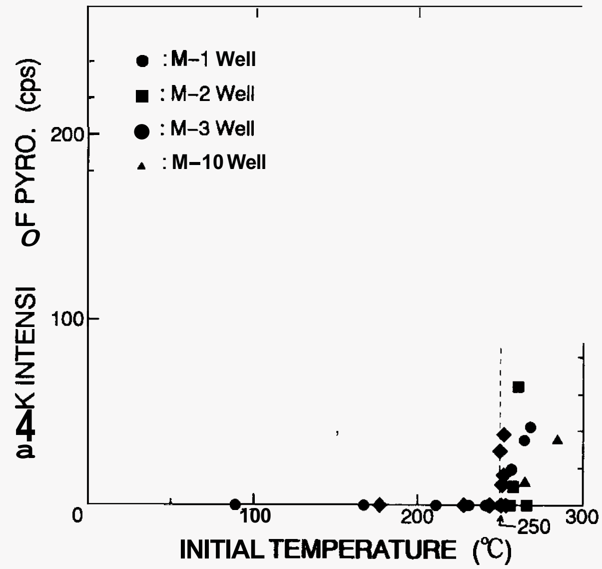


Figure 8. Relationship between the initial temperature and the peak intensity of pyrophyllite.

4 Discussion

Judging from exp.S.V.s at the origin in figure **3**, it can be found that the initial temperature is continuous because of the property of quantity of state. The distribution of the estimated initial temperature in figure **4** roughly shows that high temperature zone extends in the direction of SW deeply in the Matsukawa geothermal reservoir. The locality of high values of the kriging variance in figure **5** correspond to that of sample points.

For pyrophyllite, it is found that the value of some exp.S.V. near the origin in figures 6(a) and (b) are bigger than those at a short distance from it further. It can be considered that these are because of hole effect (Olea (Ed), 1991) at the short distance. The values of the S.V. in figure 6(c) are smaller than those in figures 6(a) and (b) (it is necessary to pay attention to smaller scale than the other) because the number of occurrence of pyrophyllite is few. So the values of the estimated peak intensity of pyrophyllite in figure 7(c) is also small on the whole.

Figure 7(a) shows parts of not less than 50 cps value of peak intensity of pyrophyllite located at both edge in the direction of NE-SW while a part of small value of that located widely at the center in the area. As seen in figure 2(a), porphyrite or quartz diorite intruded into the formation in the direction of NW in this field. Pyrophyllite occurred along these intrusive rocks because fissures and cracks which geothermal fluid flowed and was stored were formed due to these intrusions. On the contrary, in the center of the A-A' cross-section area, 0 value of the peak intensity of pyrophyllite is located widely in only shallow part. Because of plenty of 0 value, regularized data have small value.

There are two parts of not less than 50 cps value at the B-B' cross-section area in figure 7(b). Similarly to the A-A' cross-section area, it can be considered that the B-B' cross-section area was intersected by the zone of fissures and cracks along intrusive rocks (figure 2(b)) which geothermal fluid flowed and was stored.

Figure 8 shows the relationship between the initial temperature and the peak intensity of diffracted X-ray of pyrophyllite in this reservoir. According to this figure, some occurrence of pyrophyllite appear in places where the initial temperature are higher than 250 "C. Sumi and Maeda (1970) described transformation from sericite to pyrophyllite requires a high temperature. As Sumi (1968) and Sumi and Maeda (1970) described, considering that the pyrophyllite is made at not less than about 300 °C, it can be inferred that the temperature in the Matsukawa geothermal reservoir has decreased a few decades degrees C since it was made.

5 Conclusions

By using the kriging, the distributions of both the initial temperature and the peak intensity of diffracted X-ray of pyrophyllite in the Matsukawa geothermal reservoir were estimated; the former at one cross-section area, the latter at three cross-section areas.

As a result, the followings were substantiated, which were estimated by Sumi (1968), Sumi and Maeda (1970) and Akazawa and Muramatsu (1988) so far.

(1) The distribution of the estimated initial temperature roughly shows that the high temperature zone extends in the direction of SW deeply in this reservoir.

(2) There is frequent occurrence of pyrophyllite at the zone of fissures and cracks along intrusive rocks which geothermal fluid flowed and was stored in this field.

(3) Some occurrences of pyrophyllite in this reservoir appear in places where the initial temperature are higher than 250 "C in figure 8. Considering that the pyrophyllite is made at not less than about 300 "C, it can be inferred that the temperature in this reservoir has decreased a few decades degrees C since it was made.

It is necessary to keep on estimating the distribution of the peak intensity of pyrophyllite while sample data are increased. Since it is not yet quantitatively clear that there is mutual relationship between the distribution of the initial temperature and that of the peak intensity of pyrophyllite, making clear its relationship should be required for better understanding of the Matsukawa geothermal reservoir. Further estimation of variable, e.g. pressure or permeability, also will be carried out with application of other kriging or geostatistical simulation in the future.

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