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STATISTICAL AND GEOSTATISTICAL ANALYSIS OF TEMPERATURE PROFILES IN THE YANAIZU-NISHIYAMA GEOTHERMAL FIELDS, NORTHEASTERN JAPAN

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ABSTRACT

In order to reveal characteristics of temperature distribution, temperature profiles in the Yanaizu-Nishiyama geothermal field has been analyzed statistically and geostatistically. Most of the temperature profiles are approximated by the equation, $T = a + b \cdot \sqrt{d} + c \cdot d$. The equation can give a good temperature estimate at deep levels, when all data shallower than 1000m are used. Temperature deviation, which is defined difference between the temperatures measured and estimated by Equation (1) gives a typical variogram in most cases. Only when the variance of temperature deviation is large, a variogram has a local maximum. These statistical and geostatistical characters suggest that kriging should be available for estimating a 3-D temperature distribution.

1. INTRODUCTION

Temperature data are the most important information for not only exploration but also development of geothermal resources. It is possible to obtain temperature data continuously in a well, but is impossible in a 3-D space, because the data are measured in wells. Accordingly, temperature distribution in a 3-D space must be estimated on the basis of discrete data. Geostatistics suggests that the accuracy of the estimation in such case depends largely on the special continuity of the data. In this paper temperature profiles in a geothermal field has been analyzed statistically and geostatistically as a preliminary work for the estimation. The treated data were given from 41 wells in the Yanaizu-Nishiyama geothermal field, Fukushima, northeastern Japan. The standing times for measuring temperatures were 120 h at least, and 1 months at longest.

2. REGRESSION

Fig. 1 shows the temperature profiles of all wells. Profiles of most wells are hardly recognized because many data are plotted in the diagram. It is obvious, however, that temperatures increase gradually with increasing depth in most of the profiles. It is also obvious that the temperature gradients generally become gentle with depth. In order to approximate the profiles, some of functions were examined. The finally selected function is as follows:

$$T = a + b \cdot \sqrt{d} + c \cdot d \qquad (1)$$

where T and d are temperature (°C) and depth (m), respectively, and a, b and c are constants. The constants are determined for each temperature profile by the least-square method.

Let us define temperature deviation, ΔT, as follows:

$$\Delta T = T_{\mathrm{meas}} - T_{\mathrm{regr}} \qquad (2)$$

where T_{meas} is measured temperature, and T_{regr} is the temperature calculated by Equation (1). The variance of temperature deviation, σ^2, is given by the following equation:

$$\sigma^2 = \sum \Delta T_i^2 / n \qquad (3)$$

where T_i is temperature deviation at point i, and n is the number of data,. The variance varies from 0.2 to 700 °C^2 in this study. Fig. 2 shows the temperature profiles and the regression curves of the wells which are selected because of deeper holes (> 1500 m), and small variances (< 20 °C^2). On the other hand, Fig. 3 shows the temperature profiles and the regression curves of the wells whose variance is larger than 300 °C^2, except Well 92N-27P whose variance is 111 °C^2.

Figs. 2 and 3 indicate that Equation (1) sufficiently approximates each temperature profile, especially when the profile is gentle. The shapes of the profiles shown in Fig. 2 seem to be controlled by the heat conduction (Wells 86N-11T and 90N-25P) or the vapor pressure curve of water (Well 84N-5t). The result suggests that the approximation is independent of these characters. Well 90N-24P is large in variance, because temperature is locally high. However, Equation (1) sufficiently approximate the temperature profile. The equation is also available for the oscillating pattern like Well 92N-27P. The equation, however, cannot follow the profile where temperature increases rapidly as the case of Well 87N-15T. Finally, it is notable that Equation (1) is available for Well 84N-2t, where the profile curves downwards.

3. TREND ESTIMATION

It is important to estimate temperatures at deep levels based on a temperature profile at show levels in an exploration process. The fact that Equation (1) fairly approximates a temperature profile indicates that the equation can be used for estimating temperatures at deeper levels.

Fig. 4 shows the estimation of temperature profiles at deeper levels in the cases that the variances defined by Equation (3) are small. Three estimated profiles and a regression curve are drawn for each well. The dotted, dashed and thin solid lines correspond to the estimations based on the data shallower than 500, 1000 and 1500 m, respectively. The thick solid lines show the regression curves. The estimation based on the data shallower than 500 m does not sufficiently predict temperatures at deeper levels. If the data by 1000 m are used, the estimation seems to be accurate.

Fig. 5 shows the estimation in the case that the variances are large. If a temperature profile is oscillated in the case of Well 92N-27P, the estimate based on the data by 1000 m is enough acceptable as the cases of the small variances. In case that temperature increases rapidly at a narrow range as the case of Well 87N-15T, however, a good estimate is not obtained.

Fig. 6 shows an example of the case that the variance is small, but the estimation is not sufficient. The variance of Well 52-NY-1 is 30 °C². Consequently, it seems to belong to the group characterized by small variances. However, the regression curve calculated using all data decreases with increasing depth at levels deeper than 500 m, and reaches 0 °C around 1500 m in depth. This trend is abnormal, and hence is not acceptable. It is concluded, therefor, that the estimation is suggestive only when all data at levels shallower than 1000 m at least are used.

4. VARIOGRAM

Generally, temperature increases with increasing depth as shown in Fig. 1. It is expected, therefore, that a variogram calculated using raw temperature data diverges. On the other hand, temperature deviation given by Equation (2) is expected to be controlled by a random function, and hence to give a common variogram. Fig. 7 shows temperature deviation of seven wells, whose temperature profiles and trends are shown in Figs. 2 and 3.

Variogram, $\gamma(h)$, is defined by the following equation:

$$\gamma(h) = \sum \{w_i - w_{i+h}\}^2 / n \qquad (4)$$

where w_i and w_{i+h} are values at points i and $(i+h)$, respectively, and n is the number of point pairs whose distances are approximately h.

A variogram of temperature deviation was calculated for every well. The variogram patterns are divided into two types: 1) the typical type, and 2) the local maximum type. In the former type, the variogram value increases with increasing lag (h), and the range is clearly recognized. On the other hand, in the latter type, the variogram increases with increasing lag, but decreases when the lag is over a value. For this reason, a local maximum appears, and hence the range is not clear. Two types of the variogram patterns largely depend on the variance. If the variance is less than 200 °C², all variograms belong to the typical type. In contrast, if the variance is more than 300 °C², a half of the variograms belong to the local maximum type.

Fig. 8 shows the variograms in the case of extremely small variances: the values are less than 5° C². When lag is over 700 m, the variogram values increase rapidly. This is not meaningful, however, because the number of pairs is small. The variogram of Well N-57-OA-5 seems to belong to the local maximum type. Probably this is also not meaningful, because the variance is very small, and the number of pairs decreases with increasing lag. This inference is confirmed again in the next paragraph.

Fig. 9 shows the variograms in the case of small variances: the values are between 5 and 50 °C². All variograms belong to the typical type. In any variogram, the range and the sill are clearly defined. The range values vary from 100 to 500 m. If the points shown in Fig. 8 are plotted in this diagram, they are localized near the horizontal axis. Accordingly, the inference stated in the previous paragraph is right.

Fig. 10 shows the variograms in the case of middle variances: the values are between 50 and 300 °C². All patterns, except that of Well 89N-21T whose variance is the largest (227 °C²) in this category, belong to the typical type. The pattern of each variogram is similar to any of the variograms shown in Fig. 9, but the sill value is always higher than any of the variograms of the previous category. This is due to the fact that the variances of the data shown in Fig. 10 are larger than those in Fig. 9. The range values vary from 100 to 500 m. This is also same in the case of the small variances.

Fig. 11 shows the variograms of large variances: the values are more than 300 °C². The variograms of Wells 84N-2t and 90N-24P belong to the typical type, while those of Wells 87N-15T and 87N-17T to the local maximum type. The temperature profile of Well 87N-17T is very similar to that of Well 87N-15T, though it is not shown. The temperature in these wells rapidly increases near 900 m in depth. Accordingly, the regression curves cross the temperature profiles at this depth, and hence the temperature deviation changes from positive to negative. In contrast, the temperature profile of Well 89N-21T, which belongs to the local maximum type as shown in Fig. 10, shows a different pattern. In this well, the temperature increases almost linearly to 1000 m in depth, and is constant between 1000 and 1500 m. The temperature increases again at the deeper levels. For this reason, the variogram pattern of this well belongs to the local maximum type.

In a conclusion, temperature deviation gives a typical variogram pattern in most wells. If this conclusion is accepted, it is expected that special temperature distribution can be estimated accurately by kriging. This is one of the next jobs.

5. CONCLUSIONS

The temperature data of the Yanaizu-Nishiyama geothermal field has been analyzed statistically and geostatistically. The analysis gives the following suggestions and conclusions:
1) the temperature profile is sufficiently approximated by Equation (1),
2) if the data shallower than 1000 m are used, the temperature at the deeper levels can be estimated by Equation (1) with a sufficient accuracy,
3) temperature deviation defined by Equation (2) gives a typical variogram in most cases, and therefore,
4) it is expected that temperature distribution pattern in a geothermal field is accurately estimated by the combination of statistical trend analysis and geostatistical kriging.

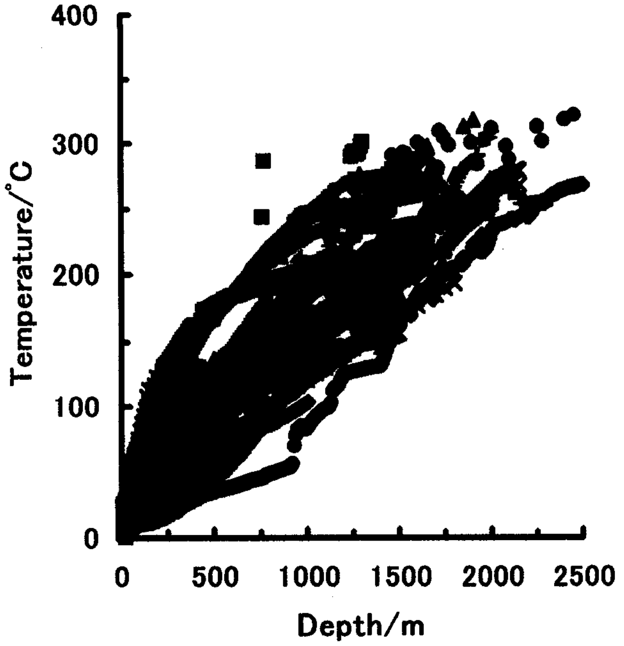

Fig. 1. Temperature profiles of the wells in the Yanaizu-Nishiyama geothermal field, whose data are treated here.

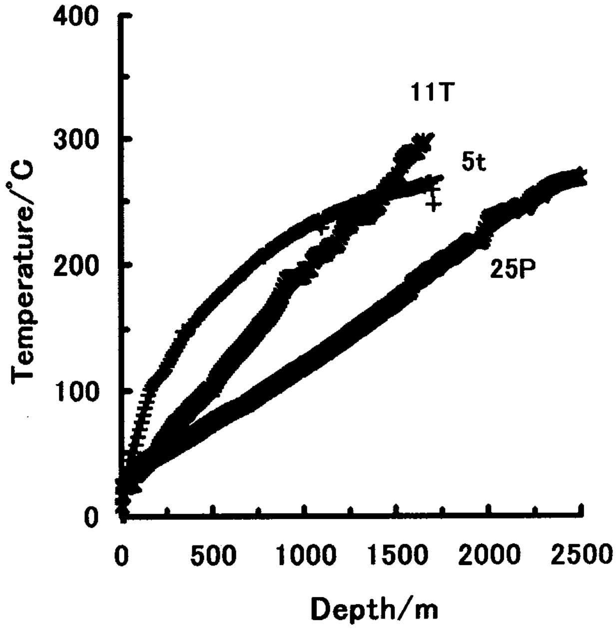

Fig. 2. Temperature profiles and regression curves of Well 84N-5t, Well 86N-11T and Well 90N-25P which are deeper than 1500 m, and small in variance.

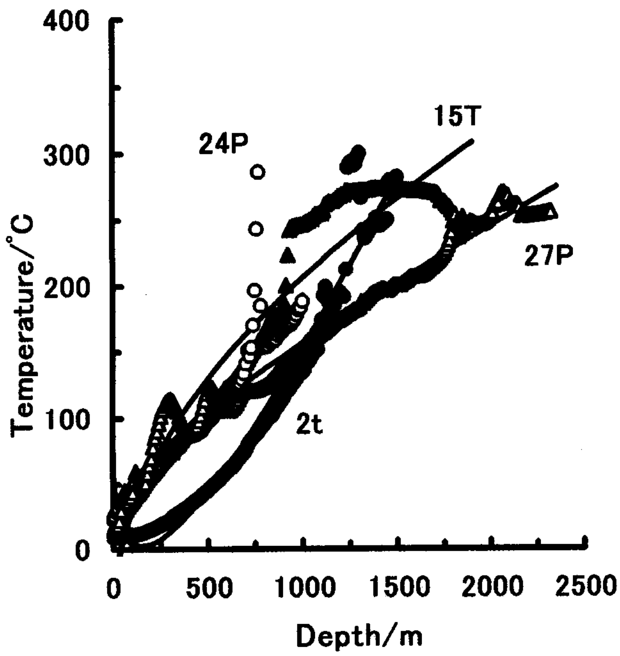

Fig. 3. Temperature profiles and regression curves of Wells 84N-2t, 87N-15T, 90N-24P and 92N-27P which variance values are large.

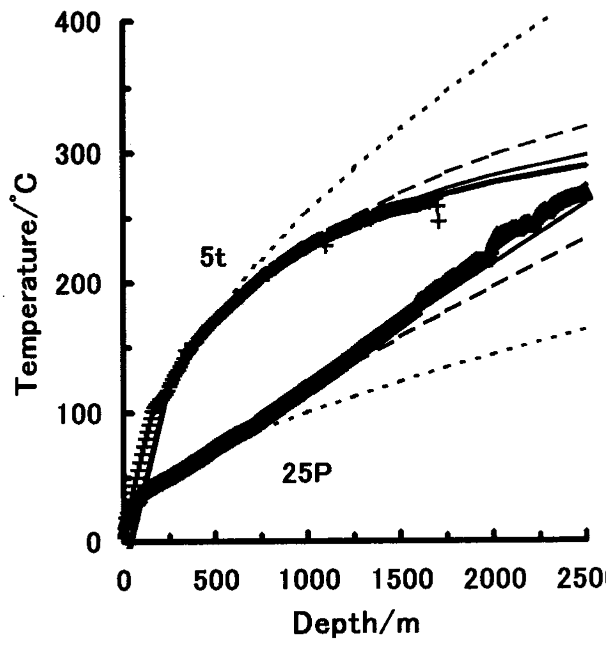

Fig. 4. Estimated temperature profiles at deeper levels of Wells 84N-5t and 86N-25T. The dotted, dashed and thin solid lines correspond to the estimations based on the data shallower than 500, 1000 and 1500 m, respectively. The thick solid lines show the regression curves.

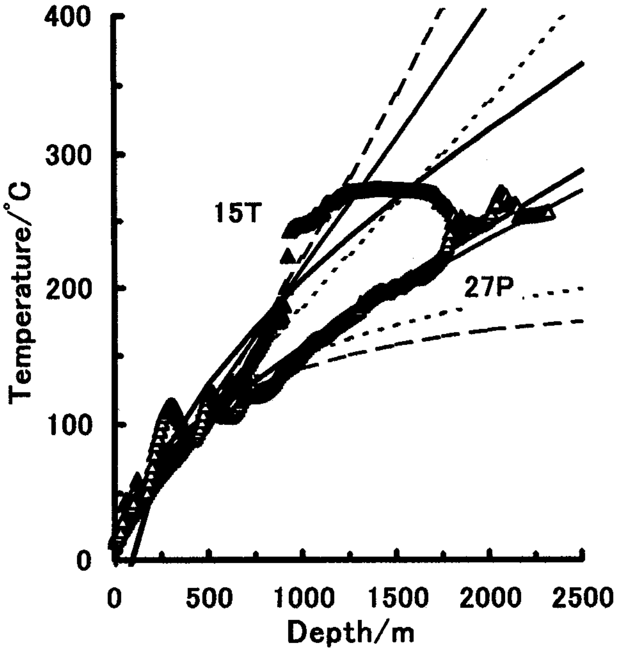

Fig. 5. Estimated temperature profiles at deeper levels of Wells 87N-15T and 92N-27P. The lines are the same as Fig. 4.

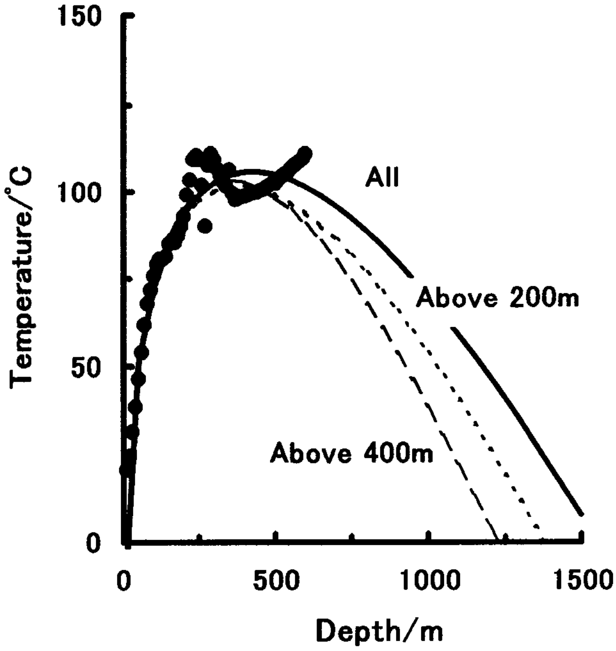

Fig. 6. Estimated temperature profiles at deeper levels of Well 52-NY-1. The dotted and dashed lines correspond to the estimations based on the data shallower than 200 and 400 m, respectively. The thick solid lines shows the regression curves. The variance is small, but the estimate is not good.

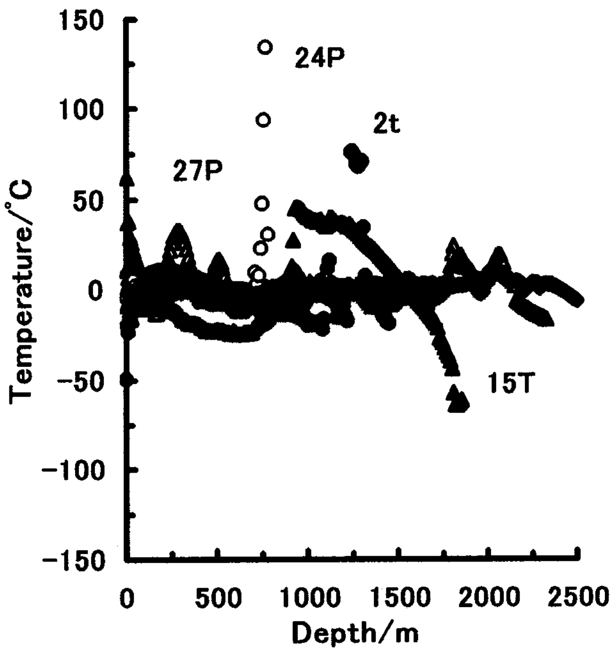

Fig. 7. Temperature deviation of Wells 84N-2t, 84N-5t, 86N-11T, 87N-15T, 90N-24P, 90N-25P and 92N-27P.

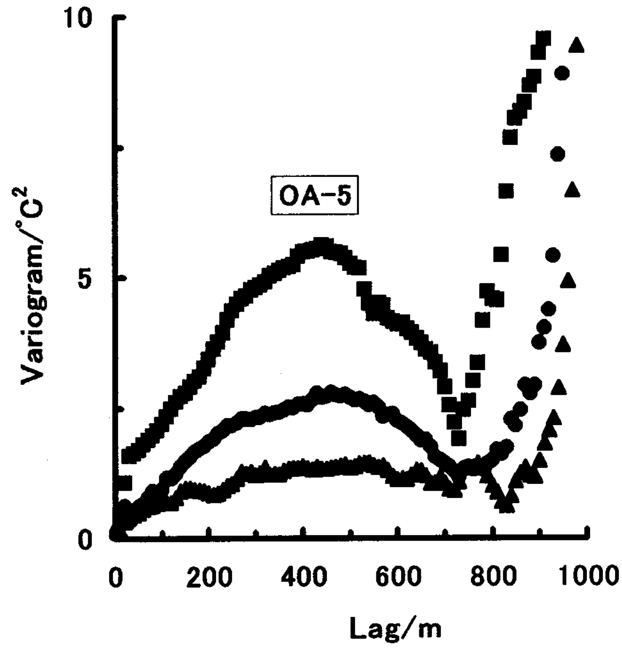

Fig. 8. Variograms of the wells, in which the variances are less than 5 °C^2. Plotted are Wells N57-OA-1, N57-OA-2 and N57-OA-5.

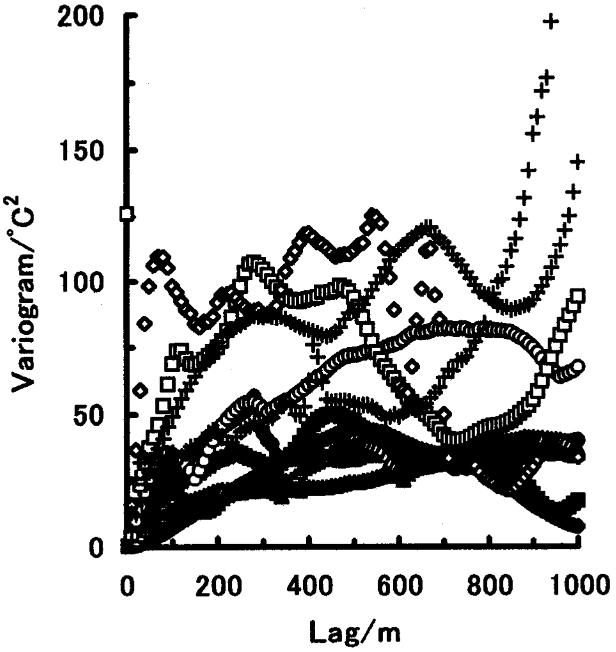

Fig. 9. Variograms of Wells 84N-1t, 84N-5t, 86N-11T, 86N-12t, 86N-13t, 90N-25P, 92N-26P, N-57-0A-4, N-57-0A-6 and N-57-0A-7. The variances are between 5 to 50 °C².

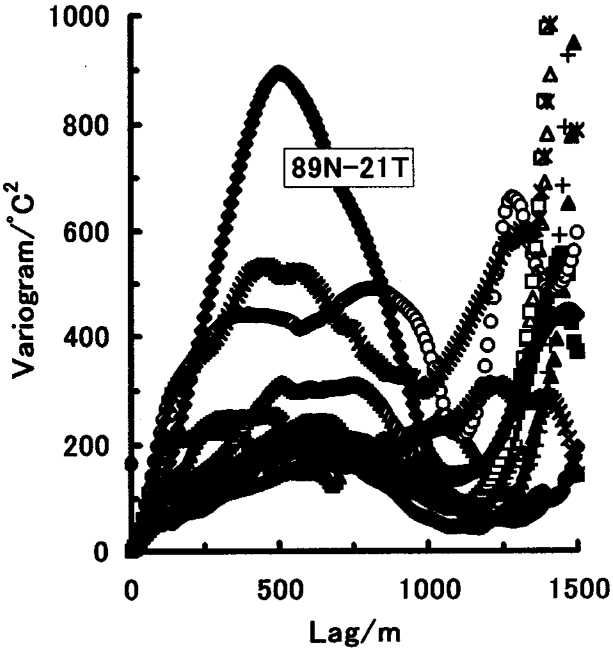

Fig. 10. Variograms of Wells 84N-3t, 85N-6T, 87N-14T, 87N-16T, 87N-18t, 88N-19R, 88N-20R, 89N-21T, 92N-27P, 92N-29R and N-57-0A-3. The variances are between 50 to 300 °C².

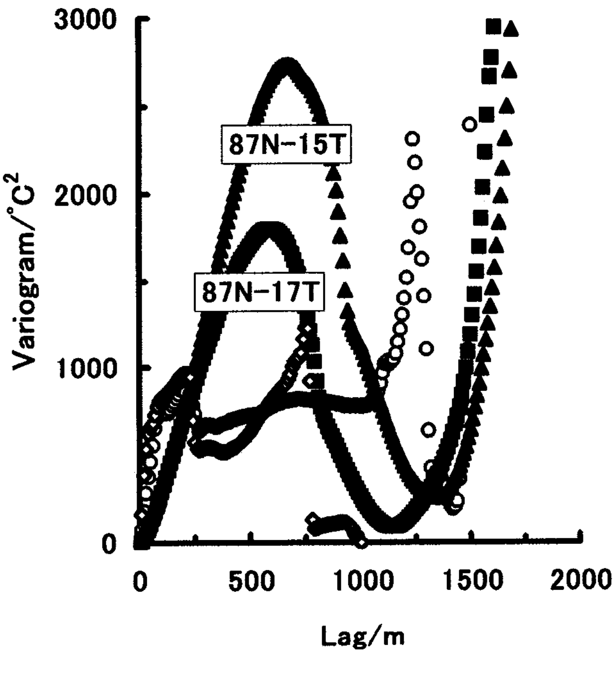

Fig. 11. Variograms of Wells 84N-2t, 87N-15T, 87N-17T and 90N-24P. The variances are more than 300 °C².