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# ESTIMATION OF SUBSURFACE TEMPERATURES USING FLUID INCLUSIONS AND VITRINITE REFLECTANCES IN THE AKAN GEOTHERMAL AREA, HOKAIDO, JAPAN

**M. YAGI, T. UCHIDA AND K. FUKASAWA**

**JAPEX Research Centre, Japan Petroleum Exploration Co. Ltd., Japan**

SUMMARY - Five hundred microthermometric measurements were made on fluid inclusions and approximately 700 measurements of vitrinite reflectance (Ro) were performed on core samples taken from wells in the Akan geothermal area, Hokkaido, Japan. The homogenization temperatures (Th) in samples from below 1,000 m in the well AK-7 are in close agreement with the present subsurface temperatures (up to 292°C). An abrupt increase of the Ro ratio with depth occurs in AK-7 and is attributed to the present thermal regime.

## 1. INTRODUCTION

Japan Petroleum Exploration (Japex) has explored the Akan geothermal area (Fig. 1) since 1980 with Unocal Corporation under a joint-venture partnership. New Energy and Industrial Technology Development Organization (NEDO) drilled eight wells there with total depths of 500 to 1,500 m from 1989 to 1990. Among these wells, AK-7 recorded the highest measured temperature of 292°C, and discharged a large amount of steam with minor liquid. This indicates a commercial geothermal reservoir. Samples for fluid inclusion and vitrinite reflectance measurements were taken from four wells, including AK-7.

Vitrinite reflectance, a thermal maturation parameter, is used to characterize (Ro) the degree of heating of sedimentary rocks, not only in oil fields but also in high temperature geothermal fields (Price, 1983 ; Barker, 1991). In order to estimate peak temperatures by using stable Ro values, a linear relationship between mean Ro and the homogenisation temperatures of fluid inclusions (Th) for burial heating and/or hydrothermal metamorphism conditions was obtained by Barker and Goldstein (1990) and Barker and Pawlewicz (1994).

The purpose of *this* study is to apply the Ro and fluid inclusion geothermometers to the Akan geothermal area in order to estimate peak temperatures and to construct its thermal history. We also examined how rapidly Ro values increased in vitrinite exposed to high temperatures by comparing Ro and fluid inclusion temperature data with the natural-state subsurface temperatures calculated from temperature log data.

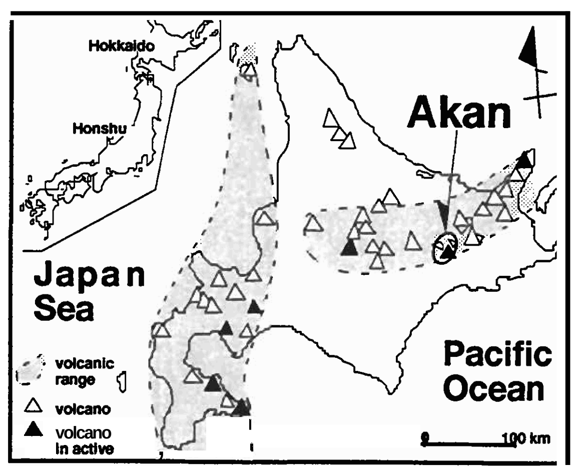


Figure 1. Locality of the Akan geothermal area in Hokkaido.

## 2. GEOLOGICAL SETTING

Akan is located in a volcanic range that extends through Kamchatka to Kuril (Fig.1). The most recent volcanic activity in the Akan area was the formation of a central cone of the Me-Akan Volcano between 2,000 and 13,500 years ago (NEDO, 1991). Surface geothermal manifestations, such as steaming ground and surface alteration, occurs at the foot of Mt. Furebetsu in the **Akan** volcanoes.

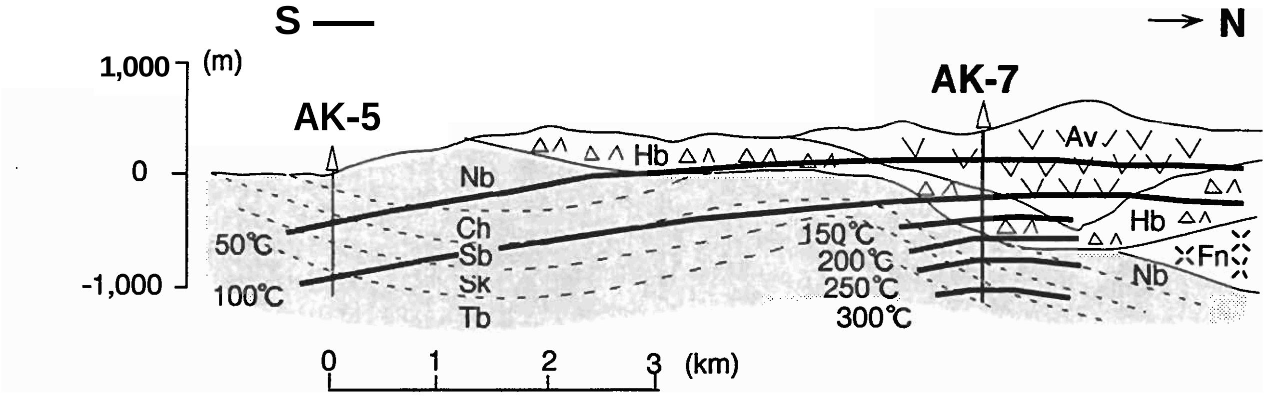


**Figure 2** Geological cross section of the Akan geothermal area cut through AK-5 and AK-7. Temperature contours estimated by temperature logs are also plotted on the section. Key ; Tb: Tetsubetsu Formation, Sk: Shitakara F., Sb: Shakubetsu F., Ch: Charo F., and Nb: Nuibetsu F. of Paleogene age. Fn: Fukushinai F. of Miocene age, Hb: Akan F. of Pliocene age, and Av: Akan Volcanic Member of Quaternary age (NEDO, 1991). See text for a description of geology.

Paleogene to Neogene sedimentary and volcanic rocks underlie Quaternary volcanic rocks in the Akan area : sandstone and mudstone are accompanied by abundant coal beds of Eocene to Oligocene age, and pyroclastic rocks of Miocene to Pliocene age (Matsui, 1962 ; Kaiho, 1984). The rocks older than Miocene have undergone regional hydrothermal alteration genetically associated with Miocene submarine volcanism, as well as burial diagenesis.

## 3. SAMPLES AND ANALYSES

Fluid inclusions in quartz and calcite veins, and organic matter including vitrinite particles were collected from cores. Homogenization temperature measurements (Th) were performed using a heating and freezing stage of U.S.G.S. gas-flow type. Ro data were measured using a Carl Zeiss microscope photometer (model MPM-03) with a stable light source after the operator selected a vitrinite particle. The operational and methodological factors in measurement of Ro restrict the precision to one decimal place even though the precision of microphotometry is 0.01%.

Two vertical wells, AK-5 and AK-7, were chosen for this study for the following reasons. The wells are only 6 km apart, and the same Paleogene formations occur in both. The rocks in AK-5 underwent hydrothermal alteration in the Miocene but have not experienced the present geothermal activity. On the other hand, those of AK-7 not only underwent hydrothermal alteration in the Miocene but also during the present geothermal activity, up to approximately 300°C.

## 4. RESULTS AND DISCUSSION

### 4.1 Fluid Inclusion Thermometry

The most common inclusions are liquid-rich with uniform liquid-vapor ratios. Vapor-rich inclusions, with varying vapor-liquid ratios, are also present. Th data from AK-7 are plotted with the equilibrium subsurface temperature calculated from repeated temperature logging runs (Fig.3). Th values below 1,000 m in AK-7 are almost consistent with the equilibrium subsurface temperatures. Also, a remarkable cooling at depths shallower than 1,000 m is shown (Fig. 3).

The $CO_2$ contents of fluid inclusions in Akan, estimated by crushing (Sasada et al., 1986), range from 0.10 to 0.15 mol percent (i.e. 3,000-4,000 ppm) which is almost equivalent to the content of $CO_2$ discharged from AK-7. Accordingly, the depression of Tm caused by $CO_2$ equals 0.1°C maximum. Therefore, it is estimated that the depression of Tm by more than 0.1°C is caused by NaCl present within the fluid inclusions (Hedenquist and Henley, 1985). Boiling in reservoirs is presumed by the pattern of Th distribution and the existence of fluid inclusions with different vapor-liquid ratios. The abrupt decrease in Tm from 0 to more than 1.5°C (i.e. an increase of equivalent NaCl in fluid inclusions from 0 to 2.4 wt % ) at a certain Th exceeds the possible boiling curve at different depths in AK-7. The abrupt depression of Tm is corroboration for recognition of boiling in reservoirs.

As judged from the abrupt decrease of Tm and the other evidence of boiling in the reservoir, the vertical position of boiling seems' to generally deepen

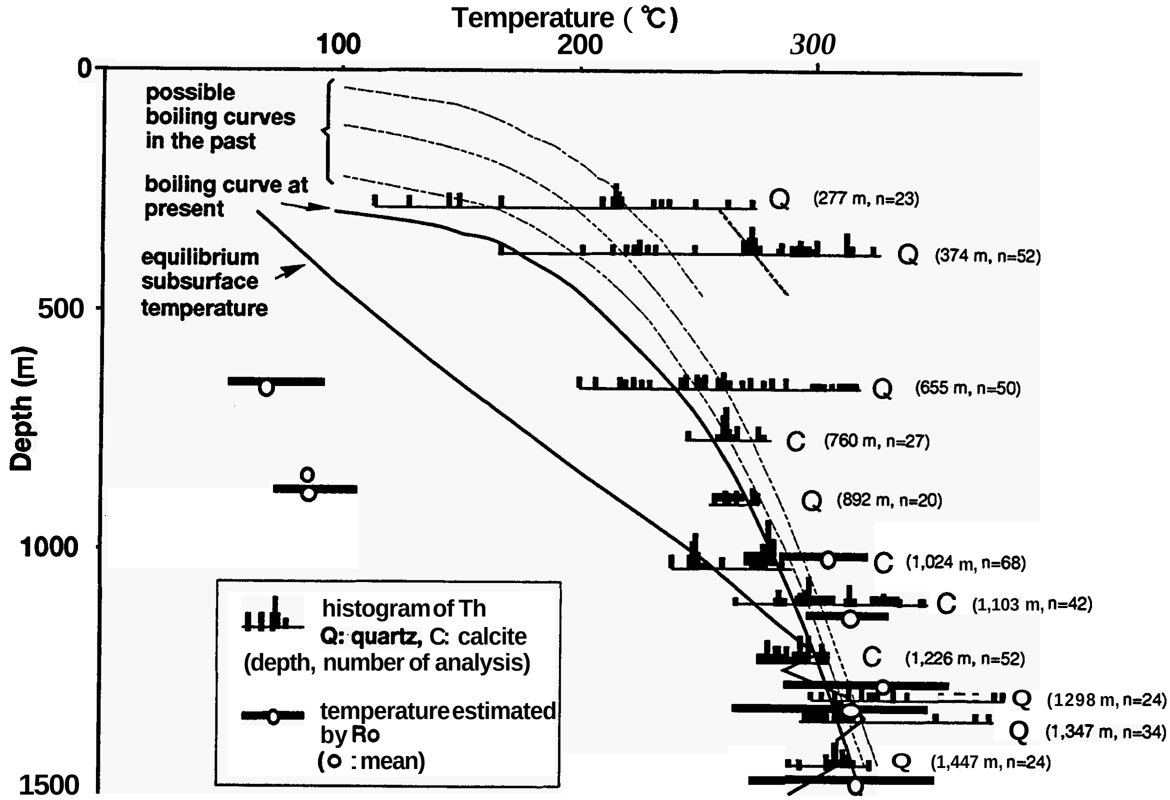


**Figure 3** Homogenization temperatures of vapor-liquid fluid inclusions are plotted versus depth in AK-7. The equilibrium subsurface temperature, the present boiling curve, and the possible boiling curves in the past are drawn. The temperatures estimated by Ro are also shown.

probably with a change of a piezometric surface around the site of AK-7 under the present thermal regime. A boiling event is not recognized in AK-5. The maximum subsurface temperature, calculated from temperature logs, is merely 109°C at a depth of 1,200 m in. Most of Th values at depths in AK-5 are 20 to 30°C higher than the present temperatures (Fig. **4).**

### 4.2 Vitrinite Reflectance

Barker and Goldstein (1990) calibrated an epithermal geothermometer that related the peak temperature to vitrinite reflectance. The Ro geothermometer is based on data from geothermal systems in western North America, such as Salton Sea and Imperial Valley. It is used here to estimate peak temperature from Ro.

The results of Ro measurements are shown in Table 1, and the peak temperatures estimated from these Ro values are plotted against Th and the equilibrium subsurface temperature (Figs. 3 and **4).** In AK-7, a discontinuity occurs at 1,000 m in the peak temperatures estimated from vitrinite reflectance. Ro abruptly increases across this depth from 0.6 to 3.2 %, which approximately equals a temperature range from 85 to 300°C. The increase in the ratio of Ro is more than 5 times over a transition zone of about 100 m at a depth of around 1,000 m (Fig. 5). This is almost coincident with the examples in Cerro Prieto reported by Barker and Elders (1981).

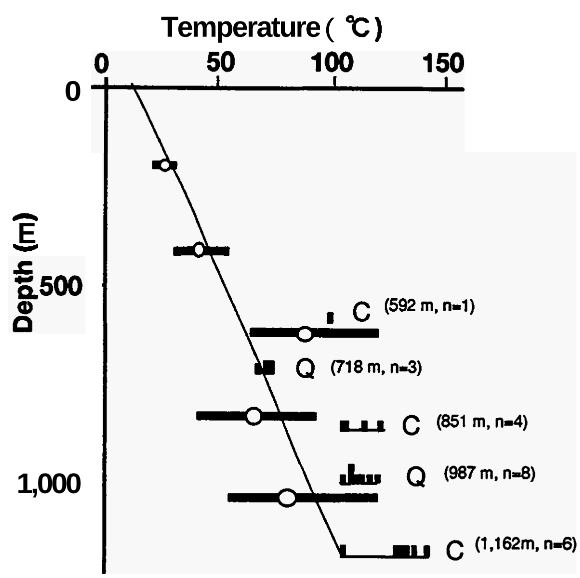


**Figure 4.** Homogenization temperatures of vapor-liquid fluid inclusions are plotted versus depth in AK-5. The equilibrium subsurface temperature and the temperatures estimated by Ro are also shown. Symbols are the same as those in Figure 3.

Table 1 List of vitrinite reflectance (Ro values) in AK-7 and AK-5.

| Depth (m) | Age | Form. | Mean Ro (%) | No. | Ro Range (%) |
|---|---|---|---|---|---|
| **AK-7** | | | | | |
| 687.15 | Pliocene | Akan | 0.53 | 13 | 0.48-0.59 |
| 845.00 | Pliocene | Akan | 0.61 | 1 | |
| 879.60 | Pliocene | Akan | 0.61 | 6 | 0.56-0.68 |
| 1,019.65 | Oligocene | Charo | 3.24 | 17 | 2.80-3.57 |
| 1,127.70 | Oligocene | Charo | 3.47 | 19 | 3.00-3.90 |
| 1,281.30 | Eocene | Shakubetu | 3.94 | 25 | 2.84-4.75 |
| 1,322.70 | Eocene | Shakubetu | 3.42 | 26 | 2.45-4.34 |
| 1,474.95 | Eocene | Shitakara | 3.01 | 31 | 2.38-3.88 |
| **AK-5** | | | | | |
| 208.95 | Oligocene | Nuibetsu | 0.36 | 58 | 0.30-0.40 |
| 421.45 | Oligocene | Charo | 0.43 | 96 | 0.41-0.48 |
| 618.66 | Eocene | Shakubetu | 0.61 | 53 | 0.50-0.77 |
| 832.55 | Eocene | Shitakara | 0.51 | 69 | 0.44-0.63 |
| 1,028.27 | Eocene | Tetubetsu | 0.56 | 132 | 0.48-0.71 |

The Paleogene formations, characterized by abundant coal beds are present, both in AK-7 and AK-5. These formations underwent a regional alteration event in the Miocene. Foraminifera of Paleogene age (Kaiho, 1984), shows rocks at a depth interval from 0 to 1,200 m (T.D.) in AK-5 correlates with those from 986 to 1,500 m in AK-7 (Fig. 5).

Vitrinite reflectance of samples from AK-5 range from 0.3 to 0.6 %, which approximately matches the temperature range from 30 to 100°C. These are almost consistent with the present temperatures, except for samples from a depth of 618 m (Fig.4). The maximum Th in AK-5 is 137°C, and that measured on temperature logs is 109°C. This indicates that AK-5 has not undergone intensive geothermal activity hotter than 137°C, in contrast to AK-7.

It is considered that the present geothermal activity increases Ro within the Paleogene rocks at depths below 1,000 m in AK-7. However, Ro values remained low, approximately 0.6 %, at depths of 845 and 880 m, although these rocks have been exposed to the present geothermal activity at hotter than 200°C. Abrupt increases of Ro occurs at the measured subsurface temperature between 200 and 250°C.

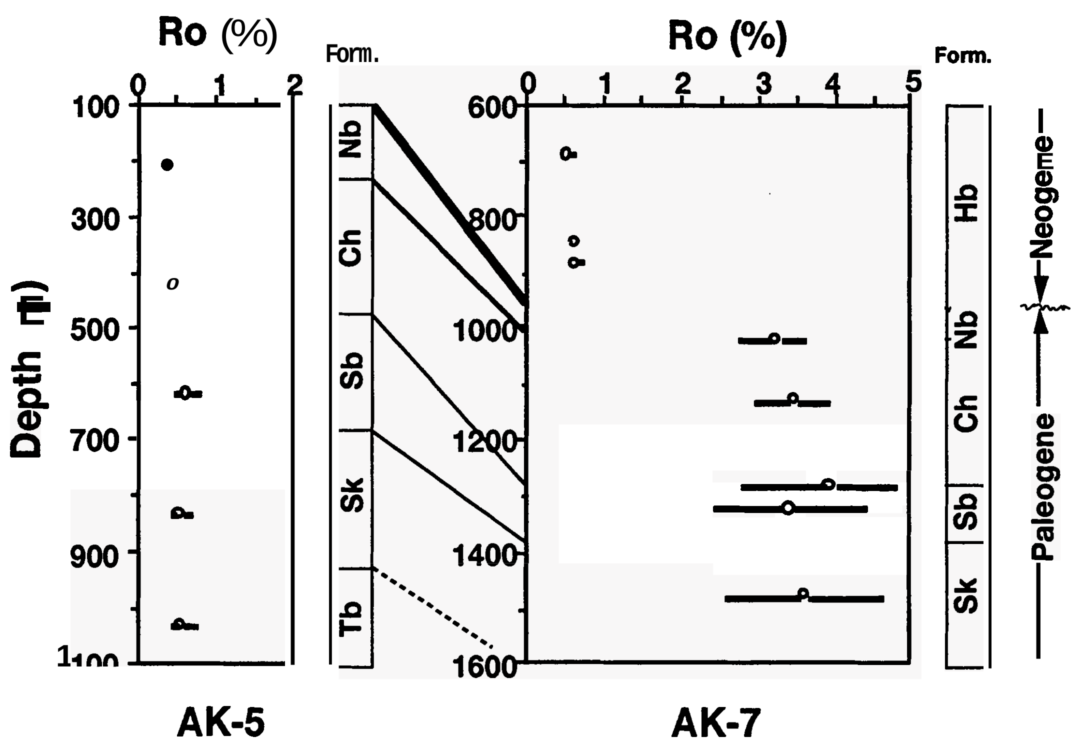


Figure 5 Vertical change of vitrinite reflectance (Ro) in AK-5 and AK-7. Correlation between AK-5 and AK-7 is also shown. Keys are the same as in Figure 1.

In the case of high temperature hydrothermal alteration, organic matter maturation may proceed quickly compared to normal burial diagenesis (Barker, 1991). Within a thermal regime hotter than 250°C, the heating duration is thought to be brief for stabilization of Ro to occur. The duration for the stability reaction of Ro is not revealed over the scale of an experimental study in laboratory (Wang and Abbott, 1991), but is probably over a period of several tens of thousands of years.

## 5. CONCLUSIONS

The homogenization temperatures of samples from depths below 1,000 m in AK-7 are almost coincident with the present subsurface temperatures. It is also estimated that the depth of boiling has descended in AK-7.

The vitrinite reflectance measurements show that all Ro values increased drastically at depths deeper than 1,000 m in AK-7. Below 1,000 m the temperatures calculated from the Ro ratios are in close agreement with not only the measured subsurface temperatures but also the Th of fluid inclusions in alteration minerals formed during the present geothermal activity. Comparison of the temperature profiles between AK-7 and AK-5, suggests that the drastic increment in the Ro values is due to the present geothermal activity at the temperatures higher than 250°C. At temperatures higher than at least 250°C, the duration of heating might not be a significant factor on the scale of geologic time. The Ro geothermometer is thus fairly useful when it is applied to samples from high temperature geothermal fields.

## 6. ACKNOWLEDGEMENTS

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