# FLUID INCLUSION STUDY OF THE DEEP RESERVOIR AT THE KAKKONDA GEOTHERMAL FIELD, JAPAN

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**SUMMARY** - We studied fluid inclusions mainly in the deep reservoir at the Kakkonda Geothermal Field, Japan. The minimum Th (homogenization temperature) of liquid–rich inclusions are useful to make predictions of the underground tcmpcrature also in the deep reservoir, however it is necessary to notice that some minimum Th are lower than borehole temperatures over 50 degrees. Both polyphase inclusions and liquid–rich inclusions above the neo–granitic pluton are considered to have been produced as the following; the ascending fluid which was the same as the type C to E or the type B inclusions (Sasaki et al., 1994) was diluted with the meteoric fluid. The distribution of the minimum Th represents the high temperature zone, which is regarded as an up–flow at present, in the north–westem deep reservoir. The distribution of polyphase inclusions in the north–western shallow reservoir is similar to the upper limit of Anhydrite, thus it suggests an up–flow in the early geothermal system.

## 1.INTRODUCTION

The Kakkonda geothermal field is located in the north–eastern part of Japan (Fig.1). It is one of the most active liquid–dominated geothermal systems in Japan. The Kakkonda geothermal power station began to generate 50MWe of electricity in 1978. Several production wells deeper than 2,000m have been drilled at the Kakkonda geothermal field since 1986. Five of these wells (Well–13, 19, 20, 21, 22) have reached a neo–granitic pluton in the deep reservoir. Muramatsu(1984) and Muramatsu et al.(1989) found that the minimum Th (homogenization temperature) of the fluid inclusions are useful to make predictions of the underground temperature in the shallow reservoir at the Kakkonda geothermal field, because the minimum Th are in good agreement with the measured downhole temperatures by logging. We studied fluid inclusions mainly in the deep reservoir; we measured not only Th and Tm (final melting point of ice) of liquid–rich inclusions but also disappearance temperatures of the bubble and Halite in polyphase inclusions. This paper presents an application of fluid inclusions as a geothermometer, origins of fluids drawn from fluid temperatures and salinities, and a geothermal system based on this fluid inclusion study at the Kakkonda geothermal field.

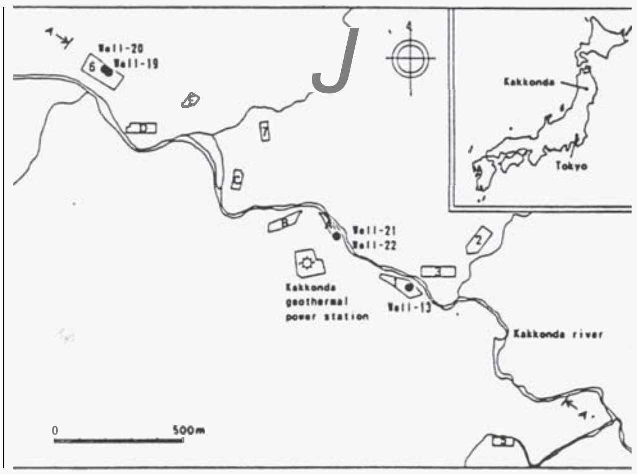



Figure 1– Distribution of well bases at the Kakkonda geothermal field.
A to E and 1 to 7 represent the well basts. Closed circles indicate the positions of well heads. Five wells in this figure reached the neo–granitic pluton in the deep reservoir.

## 2. GEOLOGY

The geology of the Kakkonda reservoir is as follows (e.g. Kato et al., 1993; Kato and Doi, 1993). That is, it consists of Tertiary formations, Pre–Tertiary formations, old intrusive rocks and a neo–granitic pluton (Fig.2). The tertiary is divided into Yamatsuda F., Takinoue-onsen F., Kunimitoge F. The neo–granitic pluton whose K-Ar age is 0.34 to 0.14Ma (Doi et al., 1993) is a part of the heat source of this reservoir. Many old intrusive rocks such-as Torigoeno–taki dacite and Matsuzawa dacite are also present.

The Kakkonda hydrothermal system consists of two reservoirs with different characteristics, the shallow reservoir and the deep reservoir. A boundary of the two reservoirs was indicated by a rapid increase in borehole temperatures around the 1,500m depth (Doi et al., 1988, 1990). The shallow reservoir is very permeable with temperatures of 230-260°C. On the other hand, the deep reservoir is less permeable with a temperature range of 300–350°C and over. Productive fractures in the deep reservoir exist at the margin of the neo–granitic pluton and its neighboring pre–Tertiary formation (Kato et.al., 1993). These two reservoirs are hydraulically connected to each other, and are included in a single hydrothermal system (Hanano and Takanohashi, 1993). The north–westem high temperature zone in the shallow reservoir is an up–flow at present (Fig.2). The upper limit of Anhydrite also suggests the up–flow.

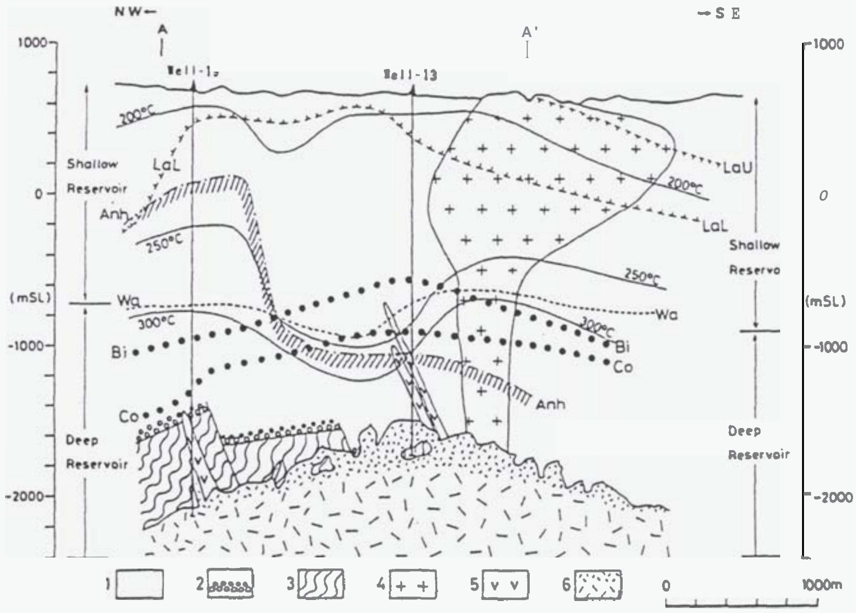



Figure 2– Schematic geologic cross section of the Kakkonda geothermal field (Kato et al., 1993).
The figure is a section along the Kakkonda river, A–A' in Fig.1.
1:Tertiary formation, 2: Basal conglomerate in Tertiary formation, 3: he–Tertiary formation, 4:Torigoeno-taki dacite intrusion, 5:Old tonalite intrusion, 6:Neo–tonalite or quartz diorite pluton. The pluton is composed of medium grained rock facies and is partly pegmatitic at the margin. LaU:Upper limit of laumontite, LaL:Lower limit of laumontite, Anh:Upper limit of anhydrite, Wa:Lower limit of wairakite, Bi:Biotite isograd, Co:Cordierite isograd.

## 3. SAMPLE AND EXPERIMENT

We studied fluid inclusions mainly in the deep reservoir at the Kakkonda geothermal field. Five wells in Fig.1 which reached the neo–granitic pluton in the deep reservoir arc also included as an object of this study. Most samples of Quartz, Calcite and Anhydrite were picked fiom cuttings, however some samples were veinlet selected from cores. Most of the observed inclusions were liquid–rich inclusions. . We sometimes observed an intimate coexistence of vapor–rich and liquid–rich inclusions; these inclusions were trapped in the boiling fluid. Some polyphase inclusions with Halite were also obsewed.

We measured Th of the liquid–rich inclusions and disappearance temperatures of the bubble and Halite in polyphase inclusions by the heating method. We also measured Tm of liquid–rich inclusions by the freezing method. Most of the data were measured with a combined heating–freezing stage of Muramatsu's own production. The procedure of these measurements was described in Muramatsu et al.(1989). Some data were measured with a FLUID INC. adapted USGS Gas–Flow Heating/Freezing System.

## 4. RESULTS

### 4.1 Th of Liquid–rich Inclusions

We measured many Th of liquid–rich inclusions in the deep reservoir. Fifteen wells were chosen as an object of this measurement; they were drilled after 1985. The distribution of Th of liquid-rich inclusions for Well–19 is shown in Fig.3 as an example. The solid line in Fig.3 represents the shut–in borehole temperature for Well–18. We regarded it as the borehole temperature for Well–19, because Well–18 is close to Well–19. This borehole temperature increased rapidly around the 1,500m depth, and was over 300°C in the deep reservoir. It was considered to be over 350°C below the 2,000m depth. The minimum Th of the 1,620m, 1,735m and 1,875m depth in the deep reservoir were lower than borehole temperatures about 20 degrees.

We compared part of the minimum Th with the borehole temperatures in the deep reservoir (Fig.4). Nine wells were chosen as an object of this comparison. Standing time for the loggings was 19 days to 2 years and 11 months, however we also had to choose some loggings whose standing time was only 23 to 77 hours. From Fig.4 we may conclude that many minimum Th are almost equal to the borehole temperatures or they are lower than those at most 20 degrees, though several minimum Th are lower than those over 50 degrees. It is when the borehole temperatures are over 300°C that

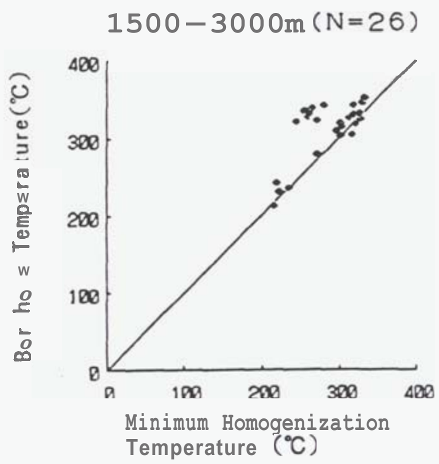
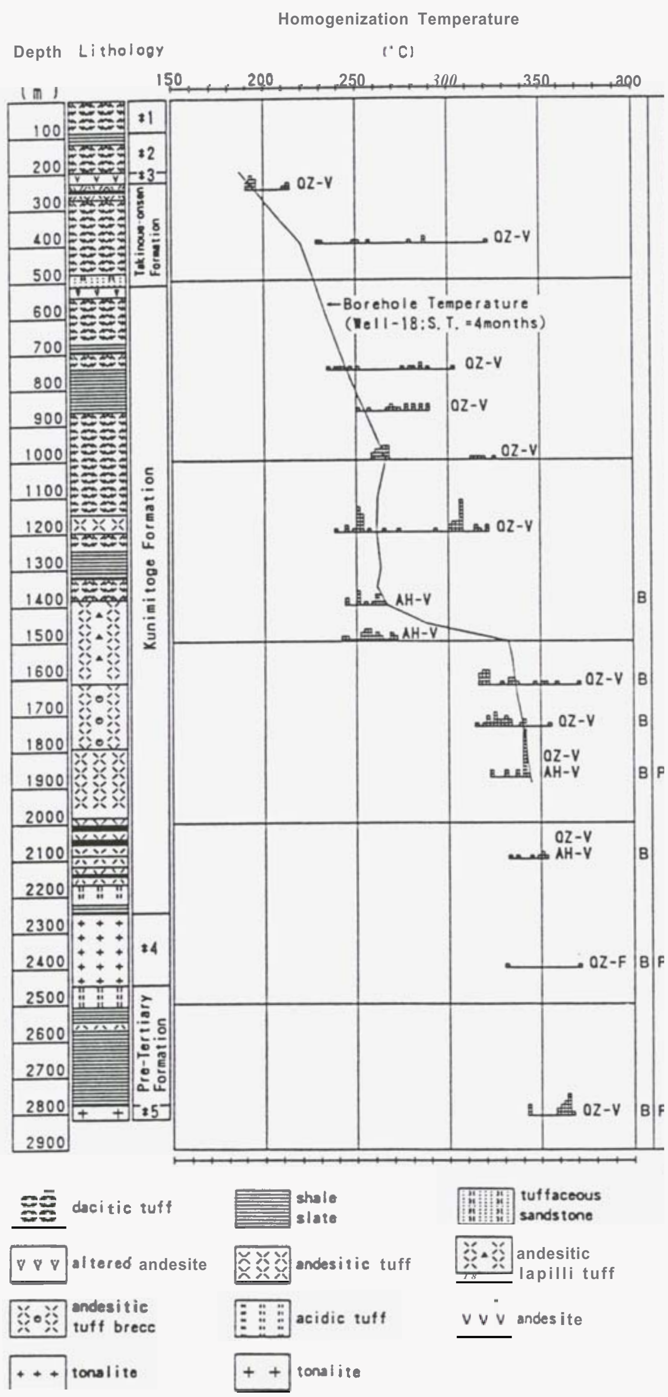



Figure 4– Minimum homogenization temperature vs. borehole temperature relations in the deep reservoir.




Fiture 3– Distribution of homogenization temperatures of liquid–rich inclusions for Well–19 with measured static borehole temperatures.
*1:Yamatsuda Formation, *2:Takinoue-onsen Formation, *3:Intrusive Rocks, *4:Old Granitic Rocks, *5:Neo-Granite, QZ:Quartz, AH:Anhydrite, V:Vein, F:Fragment, B:Boiling, P:Polyphase inclusion.

some minimum Th are lower than borehole temperatures over50 degrees. This phenomenon is found around the boundary of the shallow and the deep reservoirs (Fig.3) or in and around the Torigoeno-taki dacite and the Matsuzawa intrusions.

### 4.2 Tm of Liquid–rich Inclusions

We measured 67 pairs of Th and Tm of liquid–rich inclusions in the deep reservoir (1,500 to 3,000m depth). Additionally, we measured 32 pairs of these also in the shallow reservoir (0 to 1,500m depth). Most of the wells in the shallow reservoir which were chosen as an object of this measurement were drilled before the beginning of operation in 1978. Th – Tm plot is shown in Fig.5. Th decreases and Tm increases in ascending order. Some Th in the deep reservoir are over 370°C.

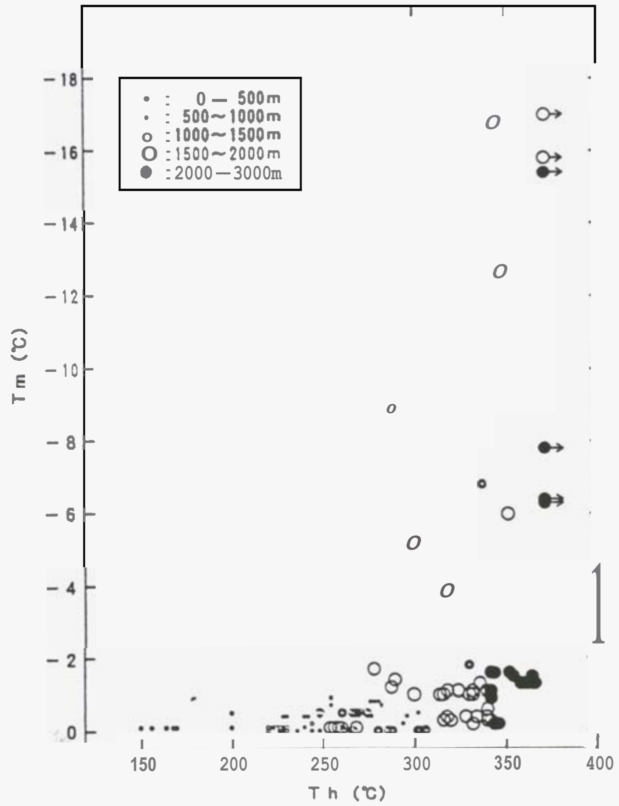



**Figure 5–** Th–Tm plot for liquid–rich inclusions.
Part of data in 0–500m and 500-1000m are cited from Muramatsu(1984).

### 4 3 Disappearance Temperatures of Bubble and Halite in Polyphase Inclusions

We observed some polyphase inclusions with Halite at 25 different depths in the deep reservoir. We observed them at 10 different depths also in the shallow reservoir. Most of the polyphase inclusions were observed in Quartz, however some of them were observed in Anhydrite. The horizontal distribution of the polyphase inclusions is shown in Fig.6, and the vertical distribution is shown in Fig.7. The polyphase inclusions are in the deep reservoir, in and around the Matsuzawa intrusion, and in the shallow part below D and E bases. The shallowest depth among them is the 190m of Well–150.

We measured the disappearance temperatures of the bubble and Halite in some polyphase inclusions. Homogenization temperature vs. salinity plot for polyphase inclusions is shown in Fig.8. The salinities of polyphase inclusions are obtained from the disappearance temperatures of Halite before the bubble; they are over 30%. The homogenization temperatures are the disappearance temperatures of the bubble after Halite; they are over 284°C. Neither a bubble nor Halite in some polyphase inclusions disappears over 370°C. As shown in Fig.8, three data in the shallow reservoir (the 540m depth of Well–41) are included in the deep reservoir data area.

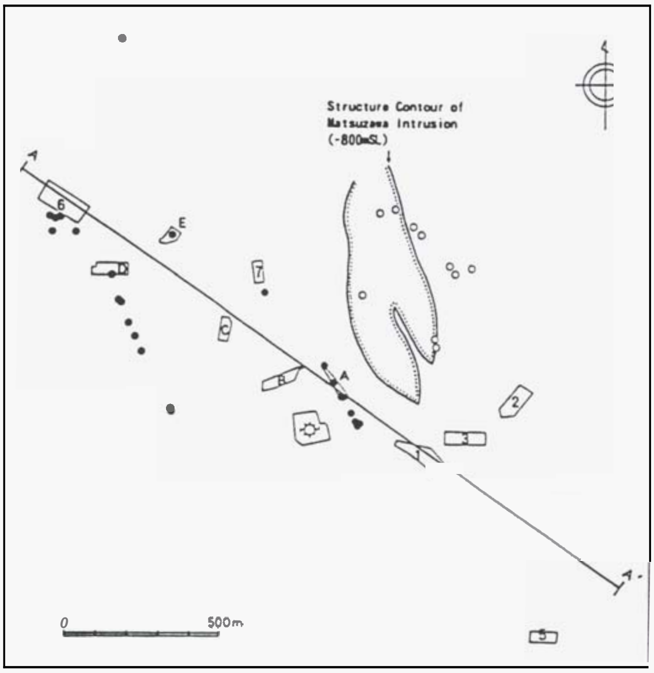



**Figure 6–** Horizontal distribution of polyphase inclusions. Open circles indicate the positions of polyphase inclusions in and around the Matsuzawa intrusion. Closed circles represent the positions of those except the open circles above.

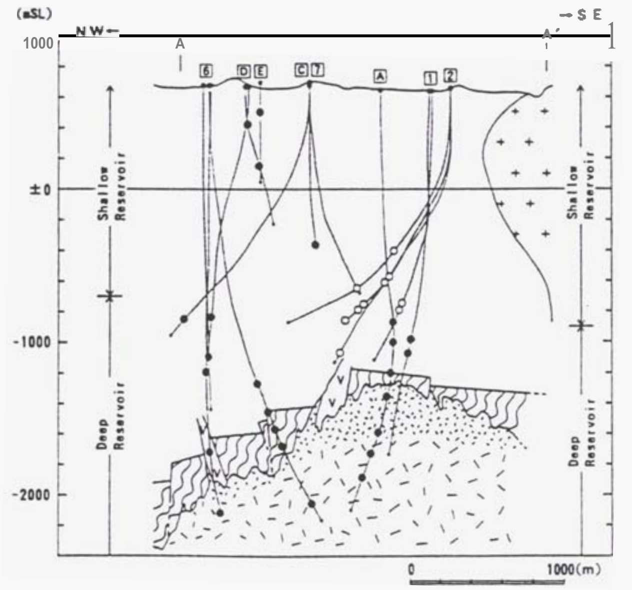
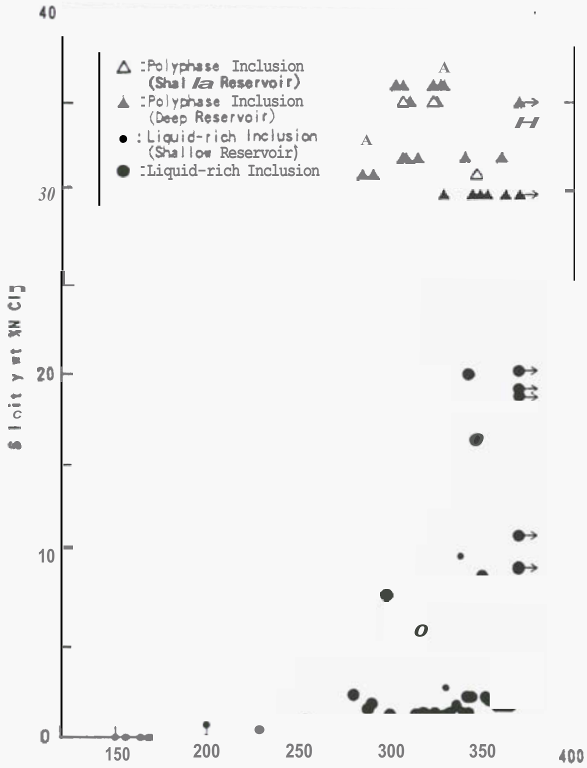



**Figure 7–** Vertical distribution of polyphase inclusions on cross–section in Fig.6.
All of the data in Fig.6 are projected on this figure. A letter or figure in a square represents the base. The symbols about geology are the same as Fig.2.




## 5. DISCUSSION

### 5.1 Application of Fluid Inclusions as Geothermometer

Muramatsu(1984) and Muramatsu et al.(1989) found that the minimum Th of the fluid inclusions are in good agreement with the measured borehole temperatures by logging in the shallow reservoir at the Kakkonda geothermal field. We found that many minimum Th of liquid–rich inclusions are almost equal to the borehole temperatures in the deep reservoir or they are lower than those at most 20 degrees, though several minimum Th are lower than borehole temperatures over 50 degrees (Fig.4). Thus the minimum Th of liquid–rich inclusions are useful to make predictions of the underground temperature also in the deep reservoir at the Kakkonda geothermal field, however it is necessary to notice that some minimum Th are lower than borehole temperatures over 50 degrees.

### 5.2 Origins of Fluids

Th of liquid–rich inclusions decreases and Tm increases in ascending order as shown in Fig.5. The freezing point depression is caused by the dissolution of salt and $CO_2$ in liquid. We estimated $CO_2$ contribution for the freezing point depression as the following on the basis of the result of crushing experiments; 0.1°C or 0.2°C for the shallow reservoir and 0.2°C for the deep reservoir. Salinities (wt.%NaCl equivalent) were obtained after the $CO_2$ contribution was took from Tm. Th vs. salinity plot for liquid–rich inclusions with those for polyphase inclusions is shown in Fig.8.

Sasaki et al.(1994, submitted) showed the homogenization temperatures and salinities for fluid inclusions observed in igneous quartz of the neo–granitic pluton from the Kakkonda geothermal system (Fig.9). The type B to E in Fig.9 are as follows.

Type B: liquid–rich inclusion (the same inclusion as the liquid–rich inclusion in Fig.8),

Type C: Halite–bearing polyphase inclusion (the same inclusion as the polyphase inclusion in Fig.8),

Type D: Halite– and Fe–chloride–bearing polyphase inclusion,

Type E: Halite–, Sylvite–and Fe–chloride–bearing polyphase inclusion.

Sasaki et al.(submitted) interpreted them as the following. That is, the type B inclusions are considered to have trapped the geothermal fluids presently circulating in the neo–granitic pluton that are probably of meteoric origin. Conversely, the type E inclusions are considered to have trapped the hydrothermal fluids equilibrated with the neo–granitic pluton at high temperatures. The type C and type D inclusions have trapped fluids generated by mixing of highly saline fluids with low salinity fluids. The dominant fluids circulating in the neo–granitic pluton might have changed from the highly saline fluids to the meteoric low salinity fluids.

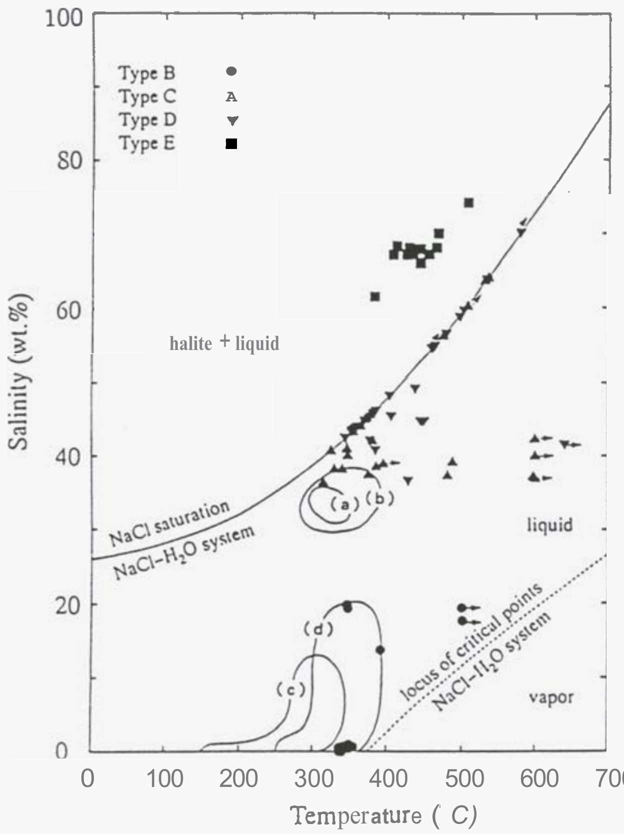



**Figure 9–** Homogenization temperatures vs. salinities plot of fluid inclusions from the Kakkonda geothermal field (modified Sasaki et al., submitted).

Type B to E are described in the text. The (a) to (d) are cited from Fig.8.

(a):polyphase inclusion in shallow reservoir, (b):polyphase inclusion in deep reservoir, (c):liquid–rich inclusion in shallow reservoir, (d):liquid–rich inclusion in deep reservoir.

We superimposed the data in Fig.8 on Fig.9. The data area of the polyphase inclusions (a) and (b) is near that of the type C and D inclusions, and the data area of the liquid–rich inclusions (c) and (d) is near that of the type B inclusions. The polyphase inclusions (a) and (b) originate from the type C to E inclusions; the ascending fluid which was the Same as the type C to E inclusions was diluted with the meteoric fluid. As a result, the (b) inclusions were produced above the neo–granitic pluton in the deep reservoir, and the (a) inclusions were produced in the shallow reservoir. The liquid–rich inclusions (c) and (d) originate from the type B to E inclusions, however we could not determine which type they originate from. The (d) inclusions were produced above the neo–granitic pluton in the deep reservoir; the ascending fluid which was the same as the type C to E inclusions was diluted with the meteoric fluid, or after that, the type B fluid was diluted in the same process. The (c) inclusions were produced in the shallow reservoir; the ascending fluid which was the same as the (d) inclusions was diluted with the meteoric fluid. Thus the (a) to (d) inclusions are considered to have been produced as the following; the ascending fluid which was the same as the type C to E or the type B inclusions was diluted with the meteoric fluid.

## 5 3 Geothermal System Based on Fluid Inclusion Study

The north–western high temperature zone in the shallow reservoir at the Kakkonda geothermal field is an up–flow at present (Kato et al., 1993; Fig.2). The upper limit of Anhydrite also suggests this. The up–flow is located in an area which is rich with fractures. We drew a cross section showing the distribution of the minimum Th after 1985 (Fig.10). It also represents the high temperature zone below the 6th and D bases, that is, in the north–western area; an up–flow in the deep reservoir is indicated by the isothermal line of 320°C. The minimum Th in the neo–granitic pluton is over 340°C.

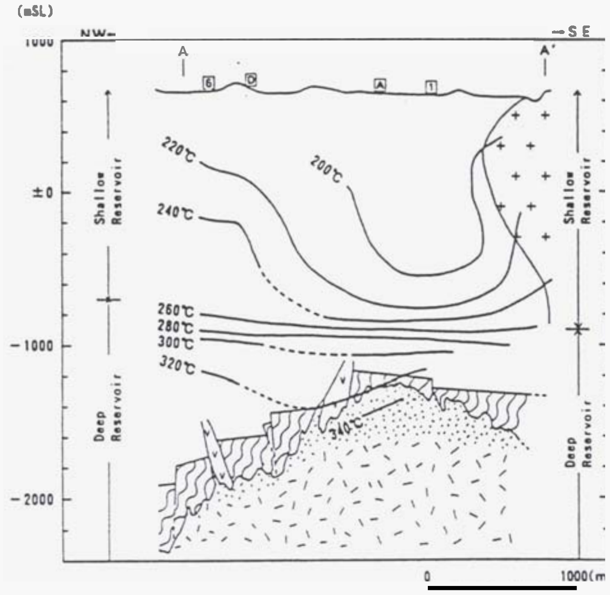



**Figure 10–** Cross section showing the distribution of minimum homogenization temperatures after 1985.

The figure is a section along A–A' in Fig.1 and Fig.6. The symbols about geology are the same as Fig.2.

We observed some polyphase inclusions which are below the D and E bases in the shallow reservoir (Fig.7). They represent that the ascending type C to E (Fig.9) fluids mixed with the meteoric fluid, and that the mixed fluid reached the shallow reservoir in the north–westem area before the type B fluid was produced. That is, the fluid whose salinity was higher than that of the present fluid ascended through the fractures in the north–westem area from the inside of the neo–granitic pluton to the shallow reservoir close to the present surface. The distribution of polyphase inclusions in the north–westem shallow reservoir is similar to the upper limit of Anhydrite, thus it suggests an up–flow in the early geothermal system.

## 6. CONCLUSION

(1) The minimum Th of liquid–rich inclusions are useful to make predictions of the underground temperature also in the deep reservoir at the Kakkonda geothermal field, however it is necessary to notice that some minimum Th are lower than borehole temperatures over 50 degrees.

(2) Both polyphase inclusions and liquid–rich inclusions above the neo–granitic pluton are considered to have been produced as the following; the ascending fluid which was the same as the type C to E or the type B inclusions (Sasaki et al., 1994) was diluted with the meteoric fluid.

(3) The distribution of the minimum Th represents the high temperature zone, which is regarded as an up–flow at present, in the north–western deep reservoir. The distribution of polyphase inclusions in the north–westem shallow reservoir is similar to the upper limit of Anhydrite, thus it suggests an up–flow in the early geothermal system.

## 7. ACKNOWLEDGEMENTS

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