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# THE FLUID GEOCHEMISTRY AND RESERVOIR MODEL FOR THE KAKKONDA GEOTHERMAL SYSTEM, OBTAINED BY NEDO'S DEEP-SEATED GEOTHERMAL RESERVOIR SURVEY, JAPAN.

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## ABSTRACT

In the discharge test of WD-1b in 1998, liquid samples showed pH of 2.0-4.5 and chloride concentration of *ca.* 10,000ppm at the weir box. In the Kakkonda geothermal field, deep wells (with excess enthalpy) generally discharge liquid of pH 3-5 at the weir box, whereas shallow wells discharge liquid of pH 7-8. $\delta D$-$\delta^{18}O$ and He-Ar-$N_2$ compositions show that the geothermal fluid is mainly meteoric water, and that a magmatic fluid is a rare contribution. The acidity of WD-1b and other deep wells is presumed to originate from the $H_2S$-$HSO_4$-$SO_4$ system depending on fluid temperature and/or from a negligible HCl generated by hydrolysis of chloride salts in the reservoir. We estimate by comparing $\delta D$ ($H_2O$) in fluid inclusions to the reservoir waters that the hypersaline metal-rich brine sampled from WD-1a was trapped in Kakkonda Granite during crystallization, and that a small amount of meteoric water permeated into a heat conduction zone in the Kakkonda Granite. A schematic model for the Kakkonda geothermal system is constructed from these results of NEDO's project.

## 1. INTRODUCTION

The Kakkonda geothermal field is located in northeastern Japan and is a liquid-dominated geothermal system (Fig. 1). The 50 MWe Kakkonda No.1 power station began operation in 1978 and the 30 MWe No.2 power station started operation in 1996. About 70 wells ranging in depth from 1,000m to 2,000m have been drilled; geothermal fluid is produced from Tertiary formations. Recently, five deeper wells ranging from 2,463 to 3,000m depth were drilled into the pre-Tertiary formation and a neo-granitic pluton, the Kakkonda Granite. The Kakkonda Granite is one of the heat sources in this area, intruded into Tertiary formations (Doi *et al.*, 1998). The shallow zone is permeable, and its temperature before exploitation was 230-260°C, whereas the deep zone is less permeable (production is limited to the vicinity of old intrusive rocks and the upper contact of the Kakkonda Granite), and its temperature is >300-350°C. The boundary between the two zones is characterized by a rapid increase of temperature at *ca.* 1,500m depth, however, the two zones are connected hydraulically to each other.

NEDO began drilling a deep survey well WD-1, in 1994 to investigate potential for deep-seated geothermal resources by drilling a 4,000m well and conducting a comprehensive research program (e.g., *Special issue of Geothermics for Kakkonda*, 1998). Drilling ceased at 3,729m total drilled depth because of safety concerns, i.e., high gas ($CO_2$ and $H_2S$) and the difficulty in controlling drilling. The borehole temperature of WD-1a (sidetracked at 1,685m) was estimated to be 500-510°C at the well bottom after a standing time of 159 hours, and the temperature profile indicated the existence of a zone of heat conduction below a depth of 3,100-3,200m in the Kakkonda Granite (Ikeuchi *et al.*, 1998). Unfortunately, WD-1a did not encounter any productive fractures, so fluid samples near the well bottom were collected by reverse circulation. Kasai *et al.* (1998) reported on the formation of borehole fluid by a mixing model and by assessment of phase relations in the system $H_2O$-NaCl.

The discharge test of WD-1b (sidetracked at 2,194m and drilled to 2,963m depth) was conducted for about three months from July to November in 1998, though interrupted for about two months because of damages caused by a big earthquake that occurred near Kakkonda on 3 September.

## 2. RESULTS AND DISCUSSION

### 2.1 Characteristics of borehole fluid sampled from WD-1a

Hypersaline metal-rich liquid (*ca.* 40 wt % total chloride species) was obtained from a depth of 3,708m in the Kakkonda geothermal system (Kasai *et al.*, 1998). Sampling of WD-1a was conducted by reverse circulation after a standing time of about 196 hours with temperature recovering to >500°C. Tritium content and the relationship between $\delta D$ and $\delta^{18}O$ showed that the river water that was circulated in the well had mixed with an isotopically heavy fluid during the standing time of 196 hours. Phase separation occurred during temperature recovery, concentrating the hypersaline liquid in the bottom of the well. This original hypersaline liquid has a salinity of *ca.* 55 wt % NaCl *eq.*, consisting of Na-Fe-K-Mn-Ca chloride, rich in Zn and Pb but poor in Cu, Au and Ag.

### 2.2 Result of the discharge test of WD-1b

We monitored physical and chemical properties of fluid discharged from WD-1b (deeper than 2,625m depth) for *ca*. 3 months. WD-1b was not so productive; its steam and liquid flow rates were less than ten ton/h and approximately one ton/h respectively. WD-1b pH descended from approximately 4.5 to 2.0 (pH at 20°C), and its chloride concentration increased from approximately 2,000 to 10,000ppm with time, with a large fluctuations, and halite scale (max. 10cm) precipitated in a surface flow line at the initial stage of the discharge test. We presumed at first that the acidity of WD-1b and other deep wells originated from a negligible amount of HCl (Akaku *et al.*, 1997), that was generated by hydrolysis of concentrated salts (NaCl, KCl, $CaCl_2$, $FeCl_2$ and so on) due to low permeability and temperature higher than 300°C in the reservoir. This mechanism for HCl generation is suggested for the superheated reservoir such as The Geysers and Los Humeros (Truesdell *et al.*, 1989; Bischoff *et al.*, 1996; Verma *et al.*, 1998). However, we have a doubt to adopt this mechanism to Kakkonda, because deep wells in Kakkonda produce liquid to some extent. Then we presume a possibility that pH is controlled by the $H_2S$-$HSO_4$-$SO_4$ system depending on fluid temperature. That is, pH is neutral at 300-350°C by $H_2S$-$HSO_4$, whereas pH is more acidic by complete dissociation of $HSO_4$ to $SO_4$ as fluid temperature decreases (Lichti *et al.*, 1998).

### 2.3 Characteristics of geothermal fluid in the Kakkonda geothermal system

Liquid chemistry

Deep wells discharge excess enthalpy fluids of pH 3-5 at *ca*. 20°C, whereas shallow wells discharge normal enthalpy fluids of pH 7-8 at *ca*. 20°C (Yanagiya *et al.*, 1996). Chemical composition of liquid from WD-1a (borehole fluid), WD-1b and the Kakkonda wells is shown in Fig. 2. Dissolved solids content is relatively high in deep wells, but is small in shallow wells. The fluid pH's are neutral in the reservoir, including in the deep zone where no acid alteration in the Kakkonda Granite is observed. There is some tendency for wells of higher enthalpy to be more acidic at the weir box in the Kakkonda geothermal field. As a result of discharge from a wellbore, pH in shallow wells becomes slightly alkaline at the weirbox owing to release of $CO_2$ and $H_2S$ from the fluid ascending in the well. In contrast, deep wells become slightly acidic, as mentioned above.

The Na-K-Mg geoindicator (Giggenbach, 1991) shows that WD-1b and deep well fluids are in partial equilibrium at initial stage of exploitation, whereas shallow well fluids are in full equilibrium (Fig. 3). The composition of deep well fluids has changed toward those of shallow wells with time. The reservoir temperature at present, calculated using the Na/K geothermometer, is about 240°C for shallow wells and 260-280°C for deep wells respectively.

Isotope hydrology

We calculated the δD and $\delta^{18}O$ values in the reservoir (Fig. 4) using isotope data from steam condensate and separated liquid, multiplied by their mass ratio, even though the ratio is erratic for deep wells due to their excess enthalpy. The relationship between δD and $\delta^{18}O$ shows that the geothermal fluid originates mainly from local meteoric water, and shallow wells have changed toward heavier composition caused by an incursion of re-injected water, whereas deep wells have an isotopically light composition, originated from meteoric water precipitating at higher altitude in the mountains. Fig. 4 indicates the deep fluid trapped in the Kakkonda Granite, estimated by WD-1a, by a star (δD=-32‰, $\delta^{18}O$=-0.6‰, Kasai *et al.*, 1998). It is evident that the δD-$\delta^{18}O$ isotopic properties of the Kakkonda geothermal fluids is likely to be an expression of mixing of meteoric water with the deep fluid, then modified by an incursion of re-injected water during exploitation.

Gas chemistry

Gas composition is slightly different between shallow wells and deep wells depending on their temperature. The amount of total gas is high in deep wells compared to shallow wells. D'Amore (1991) shows graphically both reservoir temperature and steam fraction in the reservoir for equilibria among gases. WD-1b establishes gas equilibrium at the highest temperature (280-310°C) among the Kakkonda wells (Fig. 5). Change of gaseous composition reveals also a decrease of reservoir temperature during exploitation. He-Ar-$N_2$ diagram (Giggenbach, 1991) shows that gaseous component of the Kakkonda geothermal fluids originate mainly from air dissolved in meteoric water descending to the reservoir, rather than a contribution of magmatic gas fed from deeper part in the reservoir (Fig. 6). Unfortunately, we could not estimate the origin of gaseous component by using $^3He/^4He$-$^4He/^{20}Ne$ composition, because of a disturbance of natural state by He purged for a pressure transient test conducted in the Kakkonda field.

### 2.4 δD in $H_2O$ from fluid inclusions in the Kakkonda reservoir

The temperature measured in WD-1a was 500-510°C at the well bottom of 3,727m depth (equal to *ca*. -3,020m (a.s.l.)); the temperature profile indicated the existence of a heat conduction zone below a depth of 3,100-3,200m (equal to *ca*. -2,400 to -2,500m (a.s.l.)) in the Kakkonda Granite system (Ikeuchi *et al.*, 1998). We measured δD ($H_2O$) of fluid inclusions in quartz to evaluate a hydrothermal convection to heat conduction transition (Ikeuchi *et. al.*, 1998; Doi *et al.*, 1998) and to clarify characteristics of fluids trapped in the Kakkonda Granite (Kasai *et al.*, 1998; Komatsu *et al.*, 1998). We selected 24 samples of quartz from cuttings or cores of WD-1 and WD-1a, and 18 samples of quartz from other wells. We purified samples by an acids washing, an ultrasonic cleaning, a magnetic separation and a density gradient centrifugation with sodium polytungstate to get *ca*. 1.5 to 20g of quartz grains (75 to 250 or 500□m). We decrepitated the inclusions using a heating rate of 10°C/min up to 540 and/or 800°C to extract water from fluid inclusions. Water content ranged from 0.005 to 0.3 wt %, diminishing with depth.

We found a relationship between δD and depth of sample, as shown in Fig. 7(a). δD values can be classified into two groups (A and B). Group A (δD=-110 to -40‰) consists of samples from a hydrothermal convection zone and a distinct region of the Kakkonda Granite, and corresponds approximately to δD of geothermal fluid, re-injected water and meteoric water in Kakkonda (δD= *ca*. -45 to -75‰). On the other hand, Group B (δD=-60 to +20‰) consists of samples from a heat conduction zone in the Kakkonda Granite, beneath *ca*. -1,500m (a.s.l.). Group A has a trend of δD value lightening with depth, and this trend extends below *ca*. -2,500m (a.s.l.). Group B is broadly distributed in the Kakkonda Granite, and corresponds approximately to δD of a magmaic fluid (δD= *ca*. -10 to -30‰, from Giggenbach, 1992a). As to the relation of salinity to δD in the fluid inclusions (Fig. 7(b)), Group B samples from WD-1a have high salinity in both liquid-rich and polyphase inclusions. The δD value (-32‰) of the deep fluid in the Kakkonda Granite estimated from WD-1a also belongs to Group B. We hypothesize that the hydrothermal system that formed the Kakkonda geothermal reservoir has interacted with the heat conduction zone below *ca*. -2,500m (a.s.l.) through a defined passage.

### 2.5 Geochemical model for the Kakkonda geothermal system

We constructed a schematic model for the Kakkonda geothermal system (Fig. 8), based on results of NEDO's project as described above.

The Kakkonda Granite acts as the main heat source for the Kakkonda geothermal system. We think that the hydrothermal system has extended gradually to the deeper part of the reservoir as the Kakkonda Granite cooled. The shallow zone is permeable, and its initial temperature was 230-260$^{o}$C prior to exploitation, whereas the deep zone is less permeable, limited to the upper contact of the Kakkonda Granite, and the temperature is >300-350$^{o}$C. The boundary between those two zones is characterized by a rapid increase of reservoir temperature at *ca*. -800m (a.s.l.). However, the two zones are hydraulically connected to each other.

Geothermal fluid originates mainly from meteoric water, and a magmatic fluid is a rare contribution. A small amount of meteoric water probably permeates into the Kakkonda Granite below *ca*. -2,500m (a.s.l.), based on the temperature profile and the distribution of salinity (Komatsu *et al.*, 1998) and δD ($H_2O$) in fluid inclusions in the reservoir. The origin of hypersaline fluid obtained from WD-1a is a brine and gas trapped along grain boundaries (Fujimoto *et al.*, 1998) during solidification of magma (Giggenbach, 1992b; Cline and Bodnar, 1994). This original fluid has subsequently interacted with the circulating meteoric water through fine fractures induced by thermal stress. We think that the deep fluid initially had a high salinity, prior to a disturbance induced by the exploitation. In the natural state, deep fluid ascended slowly to the shallow zone because of low permeability in the deep zone, while mixing with shallow fluid and changing composition by interaction with surrounding rock. As a result of pressure drawdown during exploitation, the shallow and deep wells changed chemical composition corresponding to an incursion of re-injected water and/or surrounding shallow fluid of low temperature to the productive zones.

WD-1b and other deep wells discharge slightly acidic liquids due to the $H_2S$-$HSO_4$-$SO_4$ system depending on fluid temperature and/or a negligible HCl from hydrolysis of chloride salts in the reservoir. Shallow wells produce slightly alkaline waters owing to release of $CO_2$ and $H_2S$ from the fluid ascending in the well.

Based on this history of the Kakkonda reservoir, we anticipate that pH of deep wells will gradually become neutral or alkaline as their enthalpy decrease and their waters mix with shallow fluids during exploitation.

## 3. CONCLUSIONS

In the discharge test in 1998, we obtained liquid samples discharged from WD-1b, with a pH of 2.0-4.5 at *ca*. 20$^{o}$C and chloride concentrations of *ca.*10,000ppm at the weir box. In the Kakkonda geothermal field, deep wells generally discharge excess-enthalpy fluids with a pH of 3-5 at the weir box, whereas shallow wells discharge normal enthalpy fluids of pH 7-8. The difference of fluid chemistry between the deep and shallow zones depends on their reservoir temperature. δD-$\delta^{18}$O and He-Ar-$N_2$ compositions show that geothermal fluid originates mainly from meteoric water, with a small initial contribution of magmatic fluid. The acidity of WD-1b and other deep wells is presumed to originate from the $H_2S$-$HSO_4$-$SO_4$ system depending on fluid temperature and/or from a negligible HCl generated by hydrolysis of chloride salts in the reservoir. The Kakkonda Granite acts mainly as a heat source for the Kakkonda geothermal reservoir. The origin of hypersaline metal- rich fluid obtained from WD-1a is a brine and gas trapped during solidification of magma in the Kakkonda field. The δD ($H_2O$) of fluid inclusions falls into two groups. Group A (δD=-110 to -40‰) corresponds to a hydrothermal convection zone, whereas Group B (δD=-60 to +20‰) corresponds to a heat conduction zone in the Kakkonda Granite. The δD value (-32‰) of the deep fluid estimated by WD-1a also belongs to Group B. We suggest that the hydrothermal system that formed the Kakkonda geothermal reservoir has interacted with a heat conduction zone below *ca*. -2,500m (a.s.l.) through a narrow passage.

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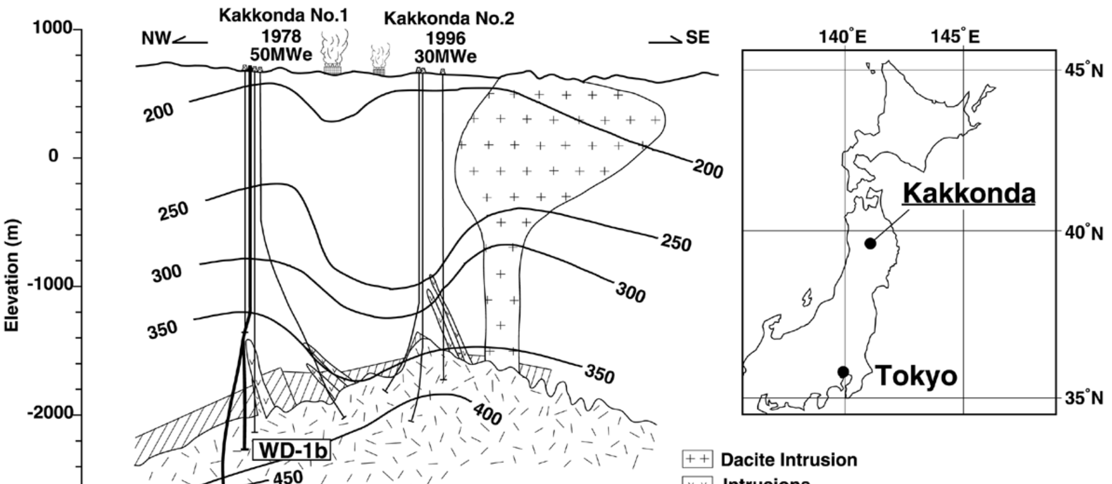


**Fig.1 Location and geothermal cross-section of the Kakkonda field.**

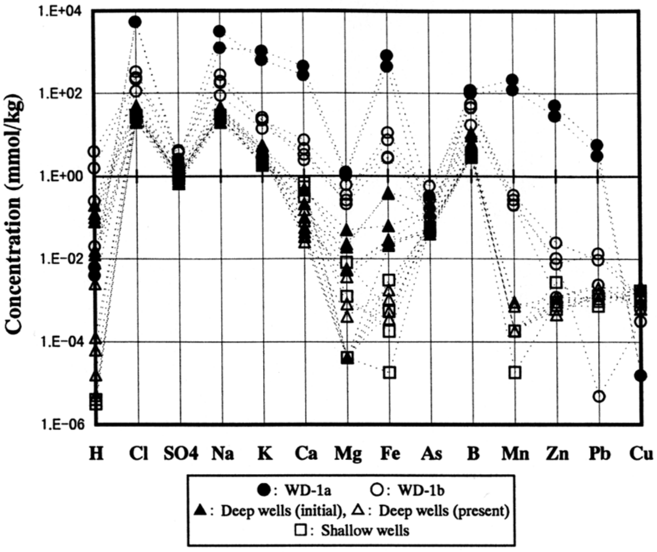


**Fig. 2 Comparison of major composition in liquid discharged from the Kakkonda geothermal wells.**

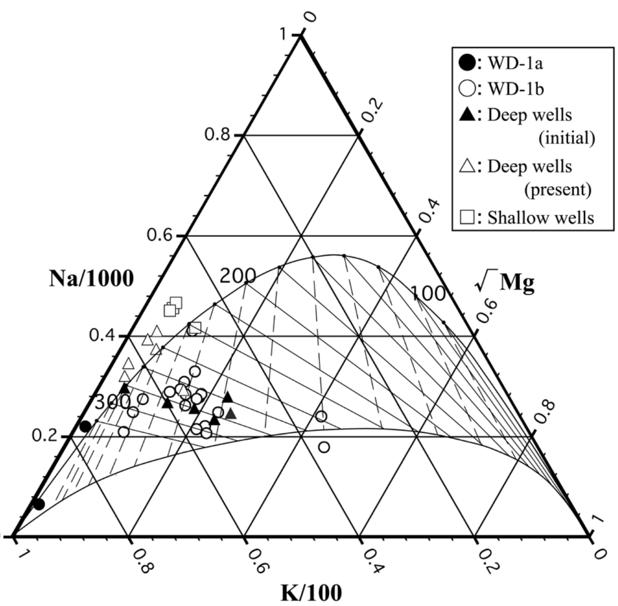


**Fig. 3 Na-K-Mg geoindicator for liquid discharged from the Kakkonda geothermal wells.**

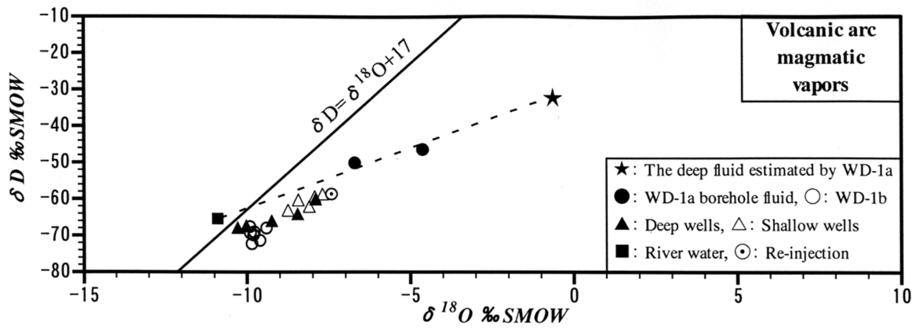


**Fig. 4 Relationship between δD and δ[18]O for the Kakkonda geothermal fluid.**

Volcanic arc magmatic vapors from Giggenbach (1992a).

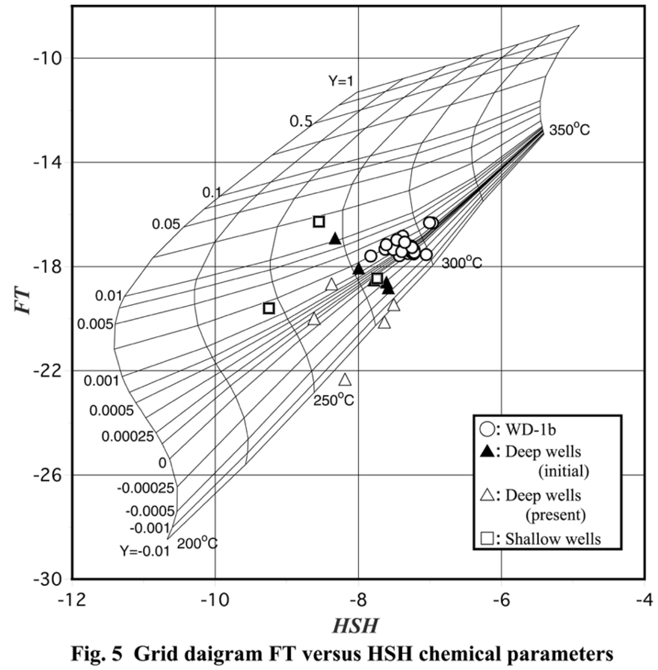


**Fig. 5 Grid daigram FT versus HSH chemical parameters of temperature and steam fraction.**

(FT=4log($H_2/H_2O$)-log($CH_4/CO_2$), HSH=3log($H_2S/H_2O$)-log($H_2/H_2O$) from D'amore (1991))

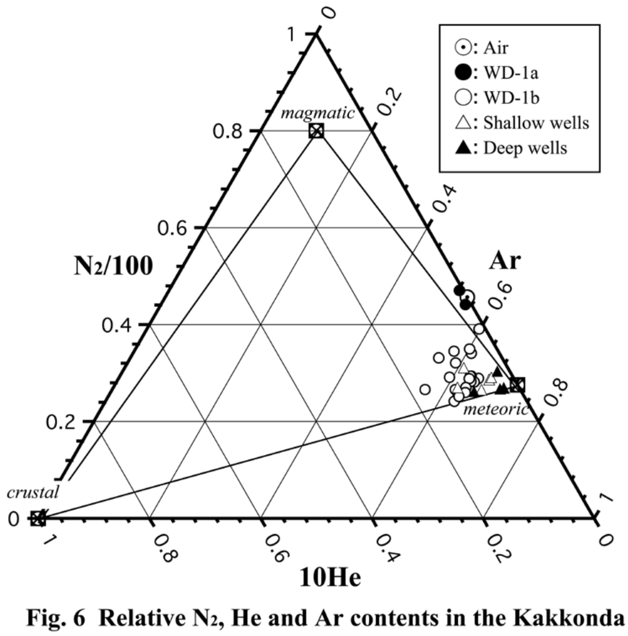


**Fig. 6 Relative $N_2$, He and Ar contents in the Kakkonda gas discharges on molar basis.**

Endmember values from Giggenbach (1991).

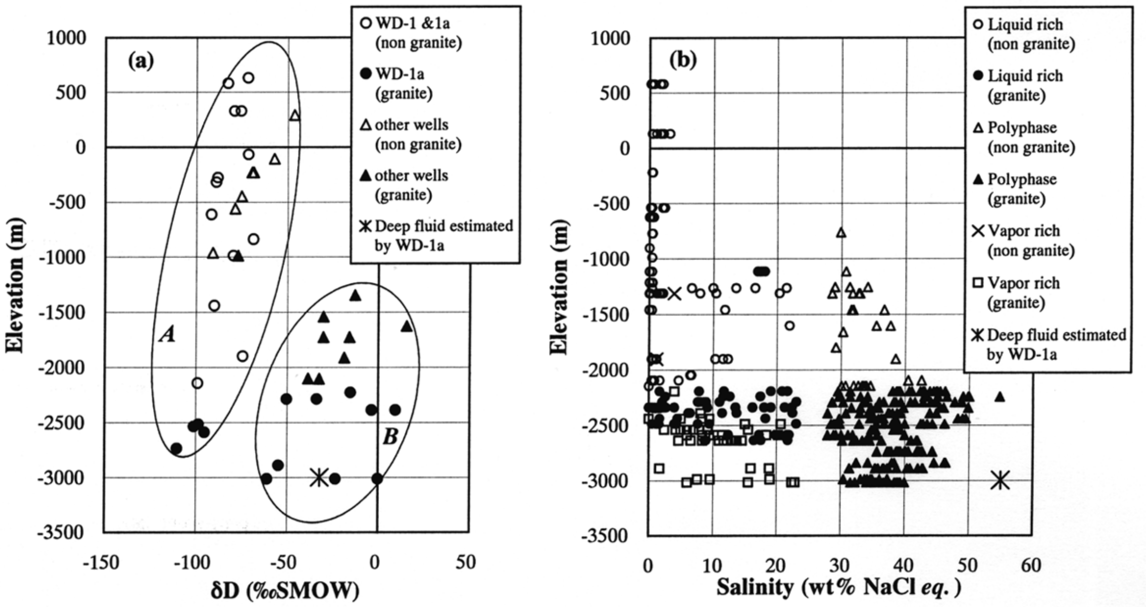


**Fig. 7 Distribution of δD ($H_2O$) of fluid inclusions in the Kakkonda reservoir (a) and salinity of fluid inclusions of WD-1 and WD-1a (b).**

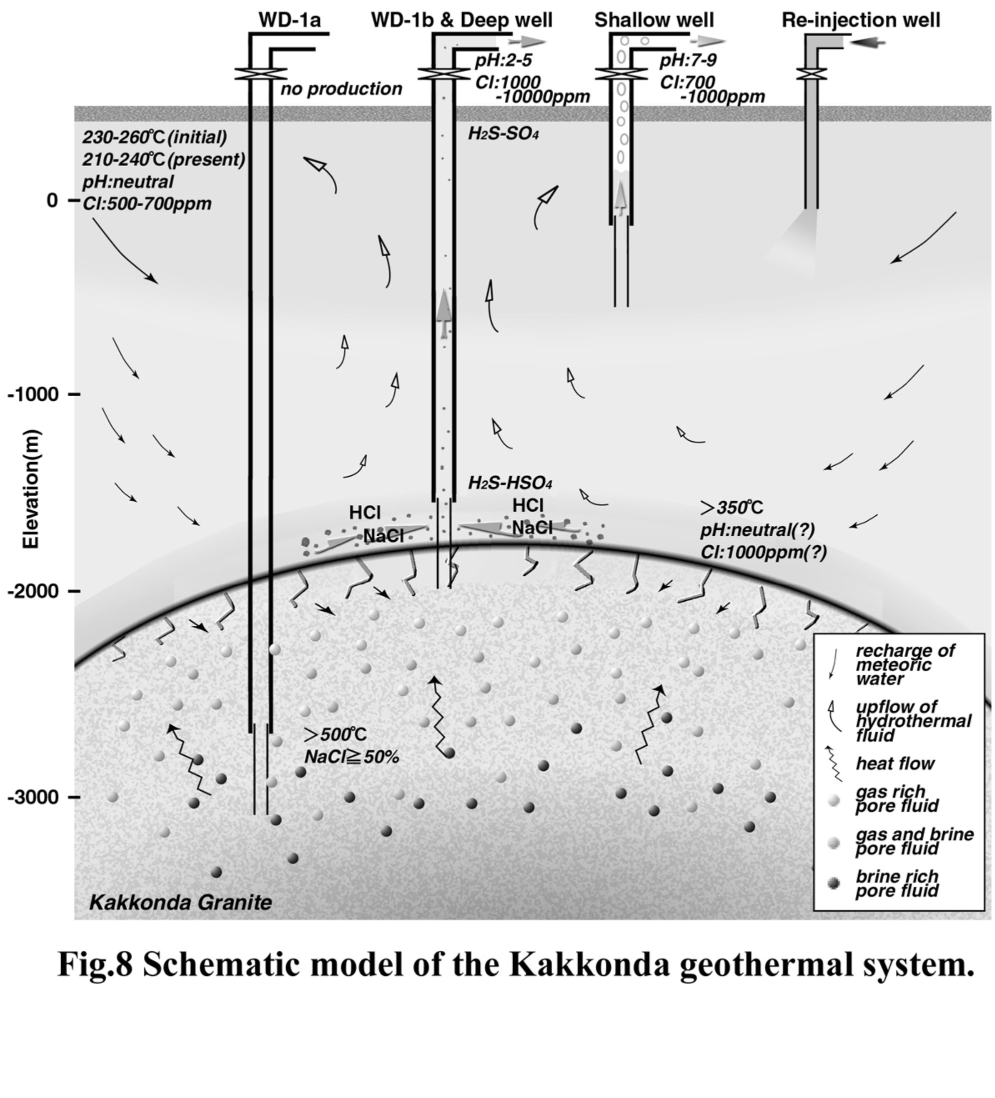


**Fig.8 Schematic model of the Kakkonda geothermal system.**