Petrochemical Profiling of The Aureole of The Kakkonda Granite Using Cuttings Samples Along The Well Wd-la, Northeast Japan

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ABSTRACT

Multi-component chemical analyses were carried out on 186 cuttings samples taken from every 20 m depth interval along the well WD-1a that was drilled into a depth of 3,729 m in the Kakkonda geothermal field, Japan and penetrated an upper part of a neo-granitic pluton below 2,860 m. Profiling of the various components with depths provides information on the magma chamber, contact metamorphism, water-rock interactions and geothermal reservoirs. Combination of the components CaO, CO_2 and S or heavy metals indicates the distribution of older fractures as well as the present lost circulation zones. A cavity-rich zone in only 1 m depth interval of the inner plutonic rim that has been observed in core samples is petrochemically recognized as the greater anomaly in a 110 m depth interval. The profile of the H_2O (+) component is broadly proportional to that of the MgO component due to the prevalence of chlorite. A dehydration trend toward the plutonic contact by contact metamorphism is probably first given in detail. High concentration of low angular fractures in the high grade metamorphic aureole is explained by the hydraulic fracturing at the dehydration front of a cordierite-forming reaction.

Introduction

During the last two decades, geothermal drillholes have penetrated young plutonic bodies in and beneath geothermal reservoirs at many geothermal fields in the world (Muraoka, 1993). They seem to demonstrate an empirical idea on a possible role of high-level magma chambers as being essential geothermal heat sources. Another important aspect is that most of those drillholes indicate the presence of lost circulation zones at a depth near upper boundaries of the plutonic bodies, such as Tongonan (Yock, 1982), Sumikawa (Maeda, 1991), Kakkonda (Kato and Sato, 1995), Nyuto (Muraoka, 1993) and Mutonovsky (Kiryukhin, 1993). Their geneses are still open to questions and are critically important for the future exploitation strategy to deep geothermal reservoirs. We shall call those categories plutonic-rim reservoirs hereafter.

A deep geothermal exploration well WD-1a was drilled into a depth of 3,729 m in the Kakkonda geothermal field, Northeast Japan from January 1994 to July 1995 by the New Energy and Industrial Technology Development Organization (NEDO) in tight technical cooperation with the Geological Survey of Japan (GSJ) (Figure 1; e.g. Muraoka et al., 1995; Ikeuchi et al., 1996; Uchida et al., 1996). The well penetrated an entire shallow hydrothermal convection zone, an entire contact metamorphic aureole and a part of a neogranitic pluton named the Kakkonda

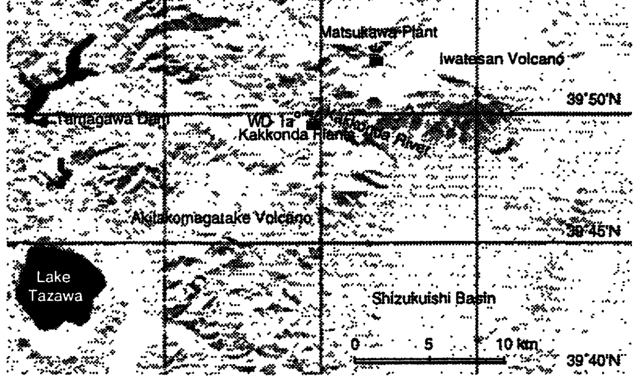

Figure 1. Location of the well WD-1a in the Hachimantai volcanic field, Northeast Japan.

Granite (Kanisawa et al., 1994). In a master plan, the well WD-1a was anticipated to encounter deep reservoirs at a depth near 3,000 m on the contact of the Kakkonda Granite, because deep reservoirs had been already hit in a high probability at other portions of the upper plutonic boundaries by the drillings of the Japan Metal and Chemicals Co., Ltd. (JMC, Doi et al., 1990; Kato and Sato, 1995). WD-1a actually penetrated the contact of the Kakkonda Granite at a depth of 2,860 m, but no lost circulation zone was, unfortunately, encountered. However, the well provided us fruitful information on the nature of deep geothermal systems. The recovered temperature of the well indicates a boiling point-controlled profile up to 380°C bu a depth of 3,100 m and a conduction-controlled profile with a very high gradient up to 500°C by the bottomhole (Figure 2). An inflection point of the temperature profile at the depth of 3,100 m and at the temperature of 380°C would reveal the brittle-plastic boundary. The well demonstrates that the temperature constrains the brittle-plastic boundary and the consequent fracture distribution constrains the deepermost of hydrothermal convection.

Irrespective of the deep reservoirs themselves, WD-1a also provided us clues to consider of geneses of the plutonicrim reservoirs. The observation of core samples and FMI logs of WD-1a detected a zone of extremely high concentrations of low angular fractures in the contact metamorphic auerole of the Kakkonda Granite at depths from 1,770 to 2,860 m (very contact), although the present permeability of the zone is not necessarily high. Another observation of core samples is that a zone of abundant miarolitic cavities was found at depths from 2,936.4 to 2,937.6 m. This zone spans only 1 m depth interval in WD-1a but gives evidence of the presence of porous part within the upper plutonic body.

In order to evaluate lithology, water-rock interactions and nature of deep reservoirs, multi-component chemical analyses were carried out on 186 cuttings samples taken from every 20 m depth interval along the well WD-1a. WD-1a was drilled using rotary methods, so that only cuttings samples were continuously available. Sport cores, about 3 m each, were taken from thirteen depths of WD-1a and provided valuable information on borehold geology. However, it is not enough to profile borehole "continuum geology" of WD-1a. The accuracy in sampling depths of drill cuttings may be roughly ± 5 m and may obscure some site-dependent information. Nevertheless, easier and continuous availability of cuttings would be still advantageous in profiling wells. This paper describes multi-component chemical analyses on cuttings samples of WD-1a and discuss what kinds of geothermal information are extracted from them. A particular attention will be focused on the geneses of the plutonic-rim reservoirs.

Analyses of Cuttings Samples

186 samples of cuttings were collected from every 20 m depth interval along the well WS-1a. Where cuttings were already spent by NEDO, alternative samples were collected 5 m away from the objective depth. Before analyses, impurities such scraps as borehole cements and drill strings were extracted by hand-picking water the stereoscope. Then, Ag, Al, As, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, Ga, Hg, K, La, Mg, Mn, Mo, Na, Ni, P, Pb, Sb, Sc, Sr, Ti, Tl, U, V, Wand Zn were analyzed by the Inductively Coupled Plasma - Atomic Emission Spectroscopy (ICP-AES) method. Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Th, Tm, U and Yb were analyzed by the Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) method. Al_2O_3, CaO, Cr_2O_3, Fe_2O_3 as total irons, K_2o, MgO, MnO, Na_2O, P_2O_5, SiO_2 and TiO_2 were analyzed by the ICP-AEs method. Ignition loss (L.O.I.) was measured after heating to the temperature 1,000^{0}C in a furnace. Ba, Cs, Hf, La, Nb, Rb, Sr, Ta, Y and Er were analyzed by the ICP-MS method. H_2O (+) and H_2O (-) were analyzed by the apparatus that could detect thermal conductivity of materials drawn from the fusion chamber. S and C were analyzed by the Infra Red Analyzer. Inorganic CO_2 was analyzed by the gasometric detector. FeO was analyzed by the titration method. Many components were thus analyzed and only restricted numbers of components will be treated in this paper.

Lithology-Indicative Components

A depth variation diagram of the components SiO_2, Al_2O_3, MgO and total iron oxides as Fe_2O_3 in weight % are shown in

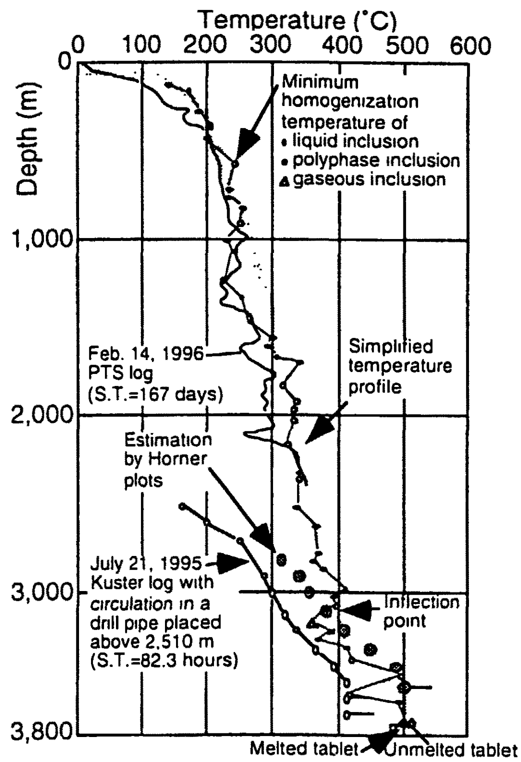

Figure 2. Synthesis of the temperature profile of WD-1a by conventional logging tools, temperature melting tablets, minimum homogenization temperature of fluid inclusions and estimated temperature by the Horner method. A shaded curve shows the simplified temperature profile of WS-1a. Redrawn from Ikeuchi et al. (1996) and Uchida et al. (1996).

Figure 3. The diagram of those relatively immobile components well display lithology of WD-1a. Through the entire section, a reciprocal variation is found between SiO_2, and Al_2O_3 components whereas MgO and Fe_2O_3 components are roughly proportional to each other in harmony with Al_2O_3 component. Broadly speaking, silica and ferromagnesian contents classify lithology into three distinctive sections: granitic rocks at depths below 2,860 m, andesitic volcanic rocks at depths from 2,860 to 1,400 m and dacitic or rhyolitic volcanic rocks at depths above 1,400 m. The intercalated sediments are similar to those underlying volcanic rocks in composition and they were likely reworked from those volcanic rocks.

A section at depths below 2,860 m is most homogeneous due to the tonalitic rocks of the Kakkonda Granite. Mixed cuttings of granitic and wall rocks are only found in the sample taken from the very contact at a depth 2,860 m indicating that errors in sampling depths of cuttings are not more than ± 20 m and empirically less than ± 5 m. An increase in a SiO_2 component and constant decreases in MgO and Fe_2O_3 components toward the roof zone of the plutonic body suggest a compositionally zoned magma chamber. However, another diagram of CaO, Na_2O and K_2O components for this section indicates a little more complicated relation that a compositional anomaly related to the miarolitic cavity zone with only 1 m depth mentioned above spans at least 55 m at depths of 2,905to 2,960 m and probably spans more than 115 m at depths from 2,905 m to 3,020 m (Figure 4). Multi-component variations of this section will be discussed elsewhere in a separated paper from the viewpoint of igneous petrology.

A section at depths from 2,860 to 2,660 m is composed of pre-Tertiary slate and andesitic rocks but this section seems a transition zone from granitic to andesitic rocks in compositions

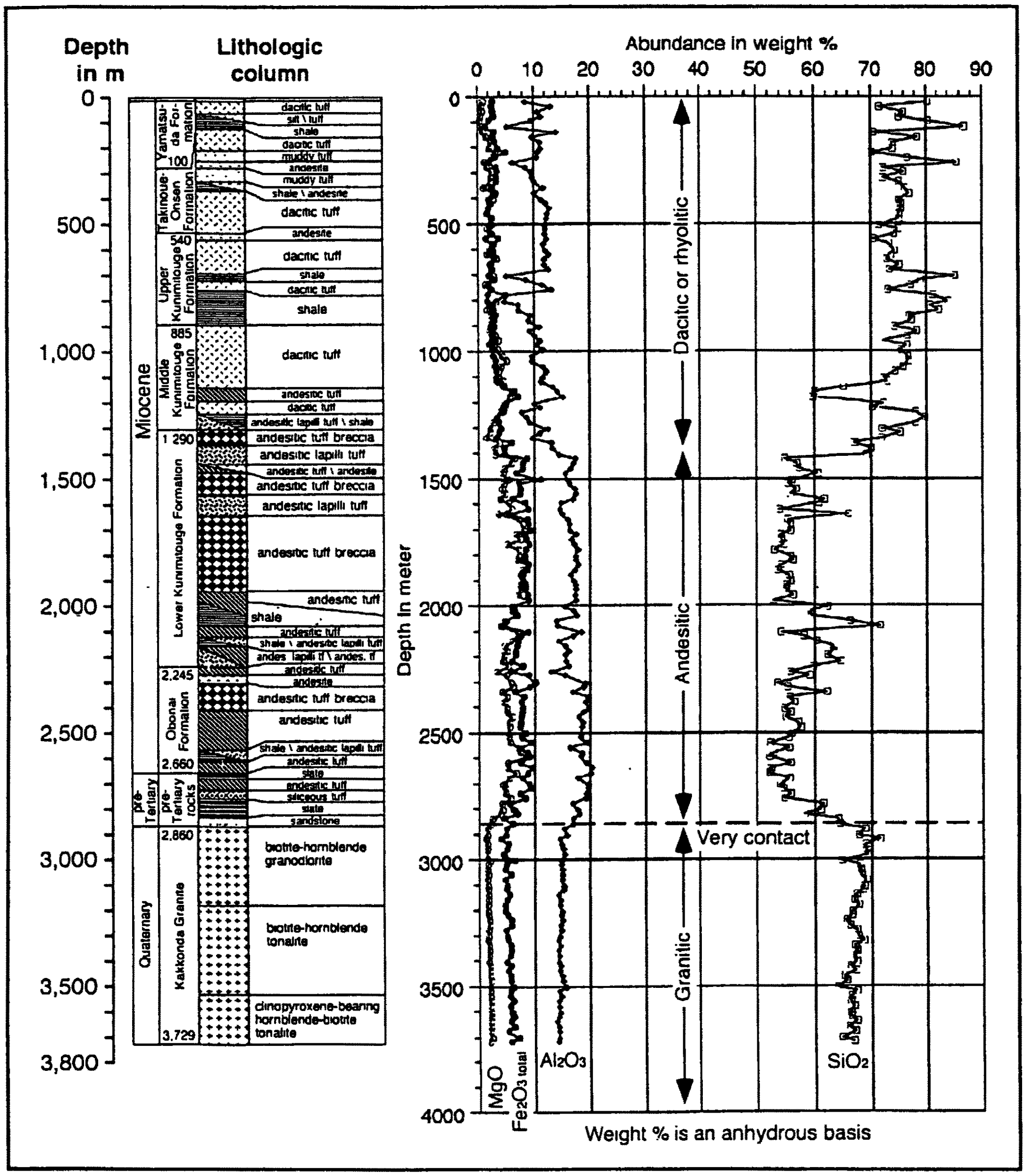

Figure 3. Profiles of the components SiO_2, Al_2O_3, MgO and total iron oxides as Fe_2O_3 with the lithologic column of WD-1a (Uchida et al., 1996).

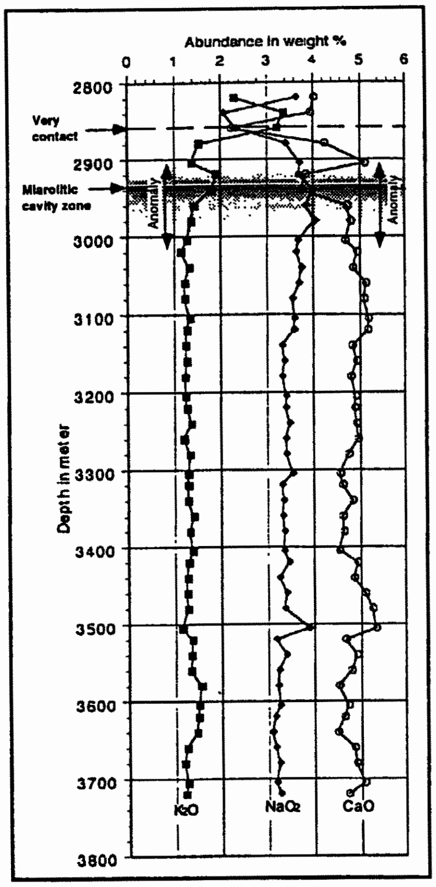

Figure 4. Profiles of the CaO, Na_2O and K_2O components within the Kakkonda Granite.

(Figure 3). A possible explanation of the gradation may be ascribed into abundance of dikes branched from the Kakkonda Granite as confirmed in some cores.

Fracture-Indicative Components

Most of the reservoirs in the Northeast Japan are characterized by network-type fractures that consists of small-scale reverse faults and strike-slip faults, where a sampling resolution of 20 m would be enough to pick up a flanking section of a fracture swarm that consists of a number of small fractures.

Because calcite and anhydrite are typical of vein-filling minierals, the diagram of CaO, CO_2 and S components will exhibit fracture distribution as shown in Figure 5. Limestone is not common in the Neogene strata in the Northeast Japan arc. As has been expected, many spikes of those components are observed in this diagram. When both CaO and CO_2 simultaneously form a spike, it may be calcite-rich veins. When both CAO and S simultaneously from a spike, it may be anhydrite-rich veins. An average CaO contents are the highest in the granitic rocks at depths below 2,860 m, moderate in the andesitic volcanic rocks at depths from 2,860 to 1,400 m and the lowest in the dacitic or rhyolitic volcanic rocks at depths above 1,400m. Taking account of this background, high amplitude of spikes is concentrated at depths from 1,400 to 2,860 m which are relatively close to a zone of extremely high concentration of low angular fractures detected by the FMI logs at depths from 1,770 to 2,860 m. Heavy metals and affinity components are also shown in the diagrams of the components Ms, Pb, Zn, Ba, V and Cu components (Figure 5). Heavy metals tend to form many spikes in a wide depth interval from 1,120 to 1,540 m and its apex seems to lie at a dpeth of 1,180 m.

Abudnace of H_2O

Profiles of H_2O (-) and H_2O (+) components are shown in Figure 6. In the analytical procedure, H_2O (-) and H_2O (+) components are separated by a threshold of a heating temperature at 110^0C and are expectatively called surface moisture water and crystalline water, respectively. Distinctive profiles of H_2O (-) and H_2O (+) components in Figure 6 shows that the analytical scheme was well attained. The profile of the H_2O (-) component reflects the present moisture content so that it simply increases toward the shallower permeable zone. In contrast, the profile of the H_2O (+) component reflects abundance of OH-base in hydrous silicates that is not only a function of the pressure (lithostatic) and temperature but also a function of the fugacity of water when mineral recrystallization occurred. The profile of the H_2O (+) component has a maximum at depths from 1,600 to 2,000 m and decreases toward the shallower as well as deeper parts.

A meaning of the profile of the H_2O (+) component is given from the fact that the profile is broadly proportional to that of the MgO component (Figure 6). This is mainly ascribed to the predominance of chlorite that is the most ubiquitous hydrous mineral in WD-1a, expecting the Kakkonda Granite below 2,860 m nd the upper Miocene above 540 m, both of which have been free from the "Green Tuff Alteration" during the middle Miocene age. In the upper Miocene above 540 m, smectite and sericite/smectite mixed layer mineral are dominat instead of chlorite. Sericite and biotite are also major hydrous minerals in WD-la but may be less than chlorite because the profile of the K_2O component is not proportional to that of the H_2O (+) component. Once rocks were suffered by the "Green Tuff Alteration", most of mafic minerals were recrystallized into chlorite and other minerals. Pre-tertiary rocks weakly metamorphosed into prehnite-pumpellyite metagraywacke facies before the "Green Tuff Alteration" and also are predominant in chlorite. Thus, the present abundance of the H_2O (+) component reflects the present abundance of chlorite, expecting the Kakkonda Granite below 2,860 m and the upper Miocene above 540 m.

However, the present abundance of chlorite does not necessarily mean the abundance of chlorite formed at the middle Miocene age. This is typically found in the high-grade part of contact metamorphic aureole of the Kakkonda Granite at depth from 1,740 m to 2,860 m, where the H_2O (+) and MgO components tend to decrease toward the plutonic body. This may be ascribed to the decomposition and dehydration reaction of chlorite in contact metamorphism by the Kakkonda Granite as a magmatic heat source. Stepwise decreases of those components in this section may be controlled by each mineral isograd as shown in Figure 6. Particularly, the cordierite isograd at a depth of 2,020 m seems to cause an abrupt decrease in the H_2O (+) and MgO components.

A section shallower than 2,020 m is a present-day hydrothermal convection zone. Low anomalies on the profile of the H_2O (+) component tend to coincide with a lost circulation zone or permeable zone and high anomalies coincide with an impermeable zone. Figure 6 shows a profile of oxidation index $Fe_2O_3/(Fe_2O_3+FeO)$ of cutting samples. This shows a reciprocal relation to the profile of the H_2O (+) component in this section.

Discussion

Petrochemical profiling of cuttings samples of WD-1a contains various information on the evolution of the magma chamber, contact metamorphism, water-rock interactions and geothermal reservoirs, because solid phases tend to preserve the integrated past records rather than fluid phases. Identification of mineral species by the X-ray diffractometer is still ongoing on the same 186 samples but following preliminary discussions will be given.

What is Known From Petrochemical Profiling of Cuttings

Although many investigators have pointed out that the H_2O component tends to decrease with increasing contact metamorphic grade (e.g. Labotka, 1991; Mason, 1990, p. 64), detailed profiles of water contents of contact metamorphic aureoles have seldom been reported so far, partly because aureoles of older plutons exposed at the ground surface have been suffered with various later alternations and partly because systematic sampling has been difficult at the natural exposures. WD-1a would allow us to avoid these obstacles. The Kakkonda Granite and its contact metamorphic aureole are quite fresh as being younger than 0.3 Ma in K-Ar hornblende ages (Kanisawa, 1994) and the drillhole itself provides us the best sampling tool.

As described above, the H_2O (+) component was mainly stored in chlorite before the contact metamorphism, and it step wisely decreased toward the contact of the Kakkonda Granite due to the contact metamorphism at 0.3 Ma or younger age. Abroad step-down is found at near the contact from 2,600 to 2,860 m. Many isogrands such as cummingtonite (2,320 m), clinopyroxene (2,665 m) and garnet (2,665 m) may contribute to dehydration but individual identification is difficult. The most conspicuous step-down is found at depths from 1,980 to

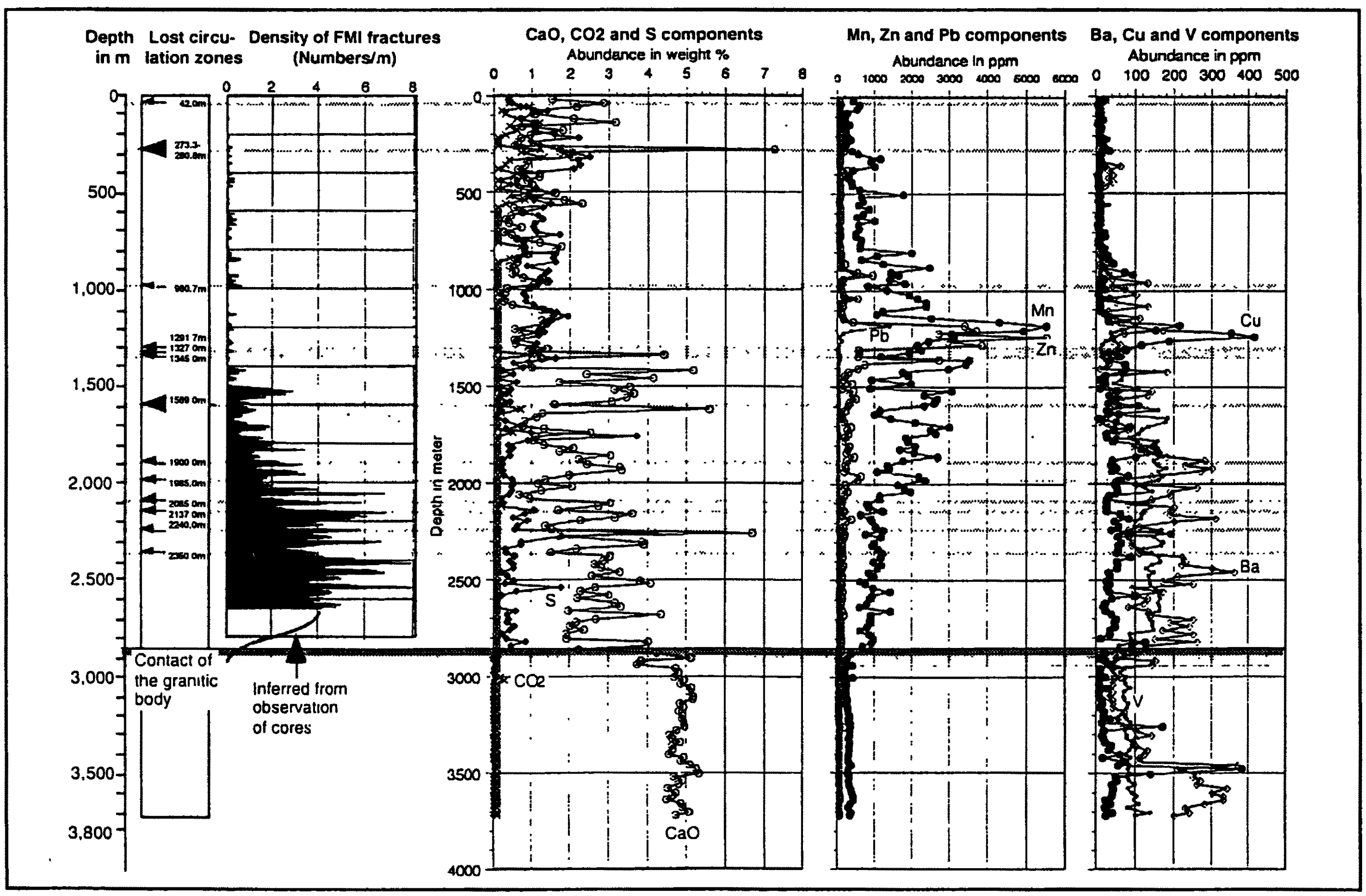

Figure 5. Profiles of the components CaO, CO_2, S (middle), Mn, Pb, Zn (middle right), Ba, V and Cu (right) with the lost circulation zones and the fractures detected by the FMI log (NEDO, 1996).

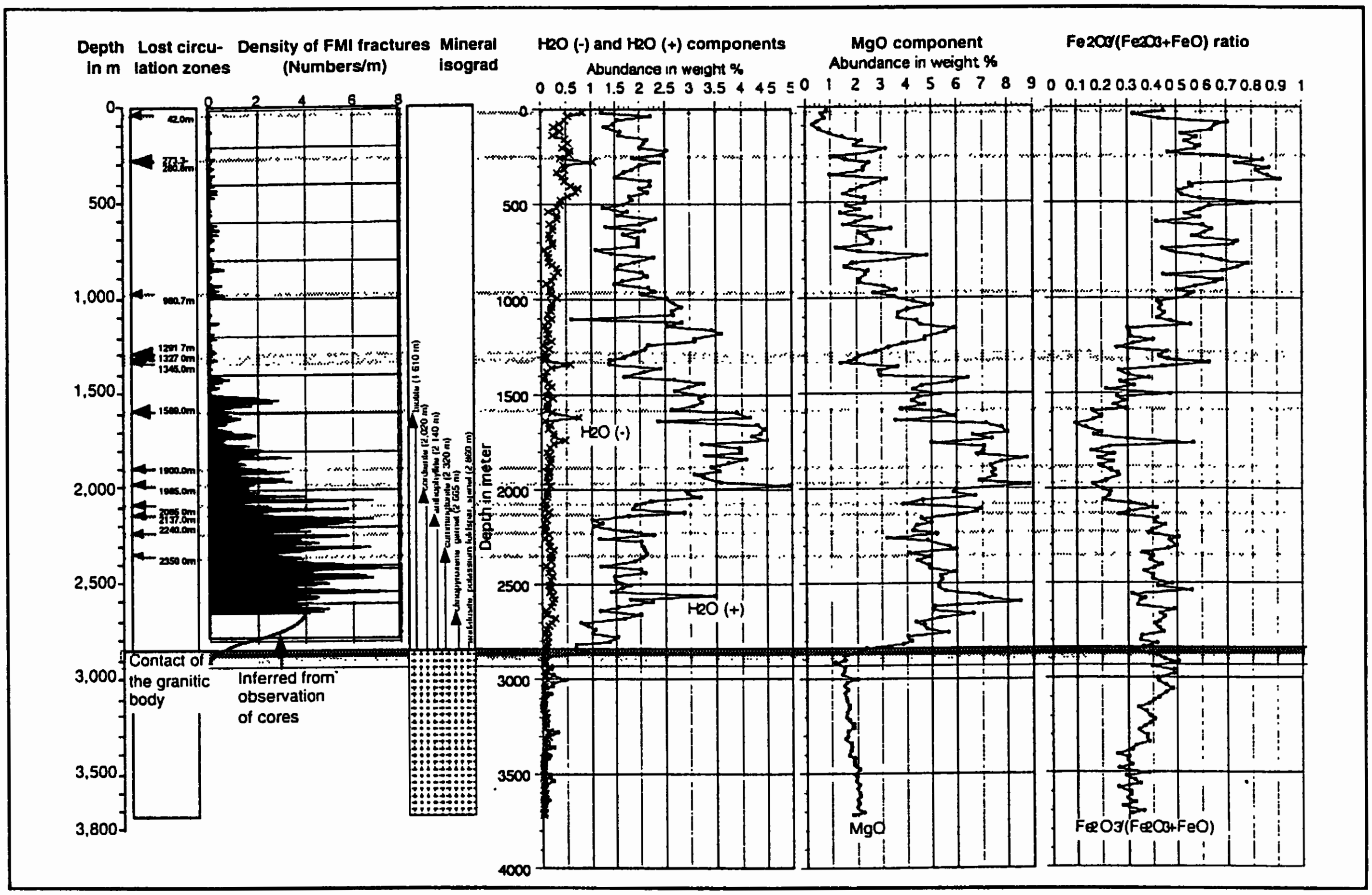

Figure 6. Profiles of the H_2O (-), H_2O (+), MgO components and a ratio of $Fe_2O_3/(Fe_2O_3+FeO)$ with the lost circulation zones and the fractures detected by the FMI log (NEDO, 1996).

2,160 m that precisely coincides with the cordierite isograd at 2,202 m. The reaction may be as follows (Pattison and Tracy, 1991): muscovite + chlorite + quartz = cordierits + biotite + H_2O.

Combination of some components such as CaO, CO_2 and S or heavy metals clarifies the distribution of veins (Figure 5). Those veins are formed at various stages. Some of them correspond to the present lost circulation zones but others are veins formed at earlier stage. The systematic analyses could make it possible to synthesize the history of hydrothermal activity. However, detailed discussion will be done using mineral determination data elsewhere.

In a section of the present shallower hydrothermal convection zone above 2,020 m, low anomalies on the profile of the H_2O (+) component coincide with a lost circulation zone or permeable zone and high anomalies coincide with an impermeable zone. This may be a reasonable consequence from the fact that abundance of OH-base is hydrous silicates is not only a function of the pressure (lithostatic) and temperature but also a function of the fugacity of water. If permeability is high, the fugacity of water is difficulty to increase due to the open system, whereas if permeability is low, the fugacity of water could drastically increase (Hanson, 1992). Actually most of the positive spikes of the H_2O (+) component in Figure 6 rather correspond to the negative spikes of the CaO component in Figure 5. The reciprocal profile of oxidation index $Fe_2O_3/(Fe_2O_3+FeO)$ in figure 6 to the H_2O (+) component in the section supports this idea, because the crustal oxygen fugacity should be a function of the fugacity of water controlled by the dissociation equilibrium of waters (Miyashiro, 1965). The reciprocal relation is explained by a simple redox reaction: 2Fe) = 2OH (sheets silicates) = $Fe_2O_3 + H_2O$. Therefore, the high anomaly of the H_2O (+) component and low anomaly of the $Fe_2O_3/(Fe_2O_3+FeO)$ ratio in depths from 1,500 to 2,000 m suggest an impermeable barrier dividing the shallower and deeper reservoirs in the Kakkonda geothermal field.

Significance of the Cavity Zone at the Inner Rim of the Kakkonda Granite

The miarolitic cavity zone at depths from 2,936.4 to 2,937.6 m seems negligible in scales by the observation of core samples. However, the petrochemical analyses of cuttings samples clarified that the related petrochemical anomaly was more extended tp 55 m or 110 m in a depth interval. WD-1a is situated at the western edge of the Kakkonda Granite but to the east the upper boundary comes to be shallower up to depth of only 1,954 m from the ground surface at the JMC Well-21 (Kanisawa et al., 1994). Vapor saturation of magma naturally prefers

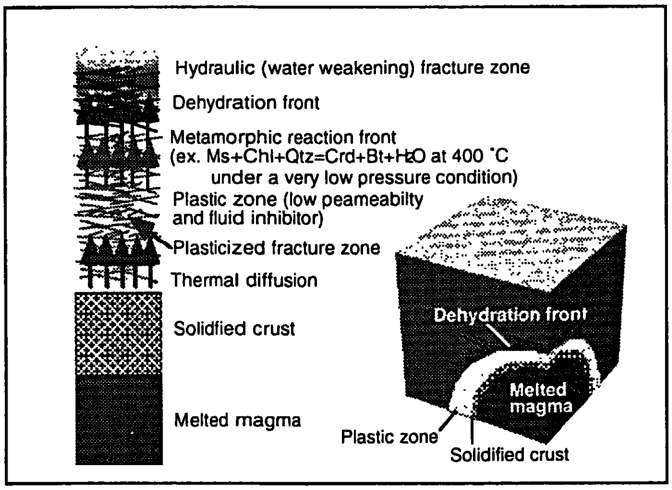

Figure 7. Model of fracturing in the contact metamorphic aureole.

the shallower depth. If the interconnected cavity zone is developed at the greater scale in such and apical zone of the plutonic body, this could be one of candidates for the deep reservoir concerned. Kato and Sato (1995) described that the lost circulation-, injection-and feed points of deep reservoirs in the Kakkonda geothermal field were mostly found within the ± 100 m depth interval from the upper plutonic contact and the maximum number of those points were situated at the inner rim of the Kakkonda Granite. Because the sampling is biased to the shallower side, actual possibility of deep reservoirs would be more biased to the inner plutonic side. The cavity zone with the 1 m depth interval could be thus important, and a failure to encounter deep reservoirs in WD-1a might be attributed to the cavity zone that was too small and too lest interconnected to be a reservoir.

A Model For Fracturing a Dehydration Front of Contact Metamorphic Aureole

Geneses of plutonic-rim reservoirs in the Kakkonda and other geothermal fields are still controversial. One of the important manifestations is the miarolitic cavity zone in the inner rim of the Kakkonda Granite as discussed above. However, it is far away from the shallow reservoirs at depths from 1,500 to 1,000 m. The dense low angular fractures found in the contact metamorphic aureole along SD-1a might be another clue to the genesis of the plutonic-rim reservoirs concerned.

The mineral assemblages of the contact aureole of the Kakkonda Granite have the diagnostic features such as the absence of sillimanite as an aluminosilicate species, prevalence of cordierits and absence of andalusite up to the breakdown of muscovite (sericite) + quartz indicating the type 1a sub-facies series of contact metamorphic facies series (Pattison and Tracy, 1991). This type is known as the lowest pressure facies series less than 200 or 300 Mpa (Pattison and Tracy, 1991). The shallowest depth of the upper surface of the Kakkonda Granite is recognized to be only 1,954 m from the ground surface by Well-21 (Kanisawa et al., 1994) and the greatest depth is 2,860 m by WD-1a where an effort of erosions of the ground surface after emplacement may be roughly compensative with that of accumulations of later volcanic ejecta. Assuming the average rock density to be 2.6 g/cm^3, the overburden pressures of those depths are estimated to be 49.8 Mpa and 72.9 Mpa, respectively. It is consistent with the low pressure requirement of the type 1a sub-facies series. It should be noted that the temperature of the cordierite-forming reaction muscovite + chlorite + quartz = cordierite + biotite + H_2O comes to be very close to 400°C in such low pressure conditions (Pattison and Tracey, 1991). The temperature of the cordierite isograd may be thus comparable with that of the brittle-plastic boundary in WD-1a.

Fluid production in the dehydration process gives rise to a drastic increase in the pore pressure when the permeability of the contact aureole is low (Hanson, 1992). This causes a process of water weakening in rock strength that might promote hydraulic fracturing (Labotka, 1991). A typical dehydration in WD-1a is expected in the cordierite-forming reaction. A special occasion in the Kakkonda geothermal field is that the cordirite-forming reaction occurred at near the temperature condition of the brittle-plastic boundary (Figure 7). This means that the fluids produced in this reaction could not descend downward due to the plastic zone and were inevitably concentrated in the shallower front. Water concentration, water weakening and hydraulic fracturing might have thus occurred in the most effective manner. The contact metamorphic reaction and related dehydration front removed away from the magmatic contact to the present isograd with time after emplacement of the magma body leaving fractures behind them. This idea is well consistent with the fact that the fracture density is particularly high in the depth interval from the plutonic contact at 2,860 m to the present cordierite isograd at 2,202 m (Figure 6). In WD-1a, this dept interval has extremely high concentration of fractures, nevertheless, forms a relatively impermeable zone at present. This paradox may be explained by a sweep process that the fracturing once occurred in front of dehydration reaction but this has been soon erased by the plastic zones coming from its behind. However, again the brittle-plastic boundary was reduced down to the depths of 3,100 m in the present temperature regime and the duration of plastic stage in this interval was relatively short. Therefore, those fractures could be readily reactivated when high angular fractures intersect them and pierce meteoric waters into them.

Acknowldegements

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References

Doi, N., Kato, O. and Muramatsu, Y. (1990) On the Neogranite and geothermal reservoir in the pre-Tertiary rocks at the Kakkonda geothermal field, Iwate prefecture. In *Abstract 1990 Annual Meeting Geothermal Resources Society Japan*, P6*.

Hanson, R.B. (1992) Effect of fluid production on fluid flow during regional and contact metamorphism. *J. Metamorphic Geol.* 10, 87-97.

Ikeuchi, K., Komatsu, R., Doi, N., Sakagwa, Y., Sasaki, M, Kamenosono, H. and Uchida, T. (1996). Bottom of hydrothermal convection found by temperature measurements above 500°C and fluid inclusion study of WD-1 in Kakkonda geothermal field, Japan. Geothermal Resources Council *Transactions* 20, 609-616.

Kanisawa S., Doi, N., Kato, O. And Ishikawa, K. (1994). Quaternary Kakkonda Granite underlying the Kakkonda geothermal field, Northeast Japan. *Japan Min. Petroleum Econ. Geol.* 89, 390-407**.

Kato, O. and Sato, K. (195). Development of deep-seated geothermal reservoir bringing the Quaternary granite into focus in the Kakkonda geothermal field, Northeast Japan. *Resource Geology* 45, 131-144**.

Kiryukhin, A.V. (1993). High temperature fluid flow in the Dachny field of the Mutnovsky hydrothermal system, Russia. *Geothermics* 23, 49-64.

Labotka, T.C. (1991). Chemical and physical properties of fluids. In: *Contact Metamorphism* (Edited by Kerrick, D.M.). Review in Mineralogy 26, pp. 43-104. Mineral Soc. Amer., Michigan.

Maeda, T. (1991). Deep geothermal system and granitic rocks in Sumikawa geothermal field. In *Extended Abstract Geothermal Symposium of Deep Geothermal Systems with Special Reference to Neo Felsic Intrusive Bodies*, Tsukuba, 32-37.

Mason, R. (1990). *Petrology of the Metamorphic Rocks* (2nd ed.). Allen and Unwin, London, 230 p.

Miyashiro, A. (1965). Metamprphic Rocks and Metamorphic Belts. Iwanami, Tokyo, 458p*.

Muraoka, H. (1993). A picture of future geothermal resources from the viewpoint of magma. *Journal Japan Geothermal Energy Association*, 30, 100-126*.

Muraoka, H., Yagi, M., Yasukawa, K., Hisatani, K., Doi, N. And Miyazai, S. (1995). NEDO "Deep-Seated Geothermal Resources Survey": A links of igneous, metamorphic and hydrothermal processes. *Proceedings World Geothermal Congress* '95, Florence, Italy, 1509-1514.

NEDO (1996). FY 1994 Report of the Deep Geothermal Resources Survey Project. 576 p*.

Pattison, D.R.M. and Tracy, R.J. (1991). Phase equilibria and thermobarometry of metapelite. In: *Contact Metamorphism* (Edited by Kerrick, D.M.). Review in Mineralogy 26, pp/ 105-206. Mineral Soc. Amer., Michigan.

Uchida, T., Akaku, k., Sasaki, M., Kamenosono, H., Doi, N. And Miyazaki, S. (1996). Recent progress of NEDO's "Deep-Seated Geothermal Resources Survey" Project. Geothermal Resources Council *Transactions* 20, 643-648.

Yock, D. (1982). Hydrothermal alteration in 410 and 506-D, Tongonan geothermal field. *Proceedings Pacific Geothermal Conference*, Auckland, 439-443.

* In Japanese **In Japanese with English abstract