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CURRENT STATE OF DEVELOPMENT OF DEEP GEOTHERMAL RESOURCES IN THE WORLD AND IMPLICATIONS TO THE FUTURE

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ABSTRACT

This paper summarizes a part of the results of Subtask (A) “Exploration Technology and Reservoir Engineering” in the IEA Task “Deep Geothermal Resources”. Deep geothermal resources were here defined as geothermal resources at a depth greater than 2500 meters considering availability of the worldwide information. Primarily, we review a current state of development of deep geothermal resources in the world based on the information obtained through the Task excursions and literatures. It is no doubt that development of shallow geothermal resources is more economical than that of deep geothermal resources. Nevertheless, deep geothermal drillings have actually been made in the world for the various reasons: to overcome the development site restriction, to expand the capacity of existing shallow reservoir, to compensate the pressure decline in existing shallow reservoir and to discover large-scale reservoirs. We shall refer to examples in Kakkonda, Palinpinon, The Geysers, Larderello, Ohaaki, Dexie Valley, Salton Sea and Cerro Prieto. Secondly, we discuss general factors controlling deep geothermal systems. These factors are the tectonic regimes, depth of heat sources and brittle-plastic transition.

1. INTRODUCTION

As one of energy technology collaboration programs of the International Energy Agency (IEA), the Implementing Agreement on Geothermal Energy (GIA) came into effect at Sendai, Japan in March 1997. GIA contains three active Tasks, “Environmental Impact”, “Hot Dry Rock” and “Deep Geothermal Resources”. The Task “Deep Geothermal Resources” is a four-year program from 1997 to 2000 and consists of Subtask A: Exploration Technology and Reservoir Engineering, Subtask B: Drilling and Logging Technologies, and Subtask C: Material Evaluation Program. The Task is led by Japan and the Operating Agent is the New Energy and Industrial Technology Development Organization (NEDO). This paper tries to summarize a part of the results of the Subtask A “Exploration Technology and Reservoir Engineering” of the Task “Deep Geothermal Resources”.

Deep geothermal resources were defined as geothermal resources at a depth greater than 3000 meters in this Task, however, the depth threshold is here revised into 2500 meters considering availability of the worldwide information. Primarily, we review a current state of development of deep geothermal resources in the world based on the information obtained through the Task Excursions and literatures. It is no doubt that development of shallow geothermal resources is more economical than that of deep geothermal resources. Nevertheless, deep geothermal drillings have actually been made in the world for the various reasons: to overcome the development site restriction, to expand the capacity of existing shallow reservoir, to compensate the pressure decline in existing shallow reservoir and to discover large-scale reservoirs. We shall primarily refer to examples in Kakkonda, Palinpinon, The Geysers, Larderello, Ohaaki, Dexie Valley, Salton Sea and Cerro Prieto. Secondly, we shall discuss general factors controlling those deep geothermal systems in the viewpoint from heat source, reservoir and fluid.

2. REVIEW OF DEEP GEOTHERMAL FIELDS

There are two types of magma-tectonic settings of geothermal fields in the world, contraction and extension tectonic fields. An easiest criterion to distinguish them is to use the dominant types of faults. If the region is dominant in reverse faults, it is categorized into contraction tectonic fields. These examples are the Kakkonda and Palinpinon geothermal fields. If the region is dominant in normal faults, it is categorized into extension tectonic fields. Those examples are the Larderello, Ohaaki and Dexie Valley geothermal fields. A region dominated with strike-slip faults is intermediate in nature, however, it is traditionally categorized into contraction tectonic fields. The Geysers geothermal field is a known example of this type.

2.1 Kakkonda

The Kakkonda geothermal field is situated at the southern part of the Hachimantai volcanic area in the Northeast Japan arc that is a typical contraction tectonic field. Kakkonda I and II geothermal power plants that produce 50 and 30 MWe, respectively, are operated by the Tohoku Electric Power Inc. and the steam is supplied by Japan Metals and Chemicals Co. Ltd. (JMC) and Tohoku Geothermal Energy Co. Ltd. The Kakkonda I power plant feeds a shallow reservoir at a depth from 1.0 to 1.5 km that is developed with fractures in the Miocene strata. During the exploration for the Kakkonda II power plant, several wells of 2.5 to 3 km class have been drilled by JMC and reached a deep reservoir at the upper rim of a tonalite plutonic body called the Kakkonda granite (Doi et al., 1998). The deep reservoir can, therefore, be categorized into a plutonic-rim reservoir (Muraoka et al., 1998). The tonalite plutonic body plays a role of a heat source and the temperature of the exploration well WD-1a reached 500 °C, exceeding a conventional boiling point curve (Muraoka et al., 1998). The deep reservoir is usually 350 °C in temperature and pH of deep fluid at the plutonic rim originally ranges from 3.2 to 4.5 at atmospheric condition (Yanagiya et al., 1996). On the other hand, brine was collected from the deeper part of the Kakkonda granite at the bottom of WD-1a (Kasai et al., 1998).

2.2 Palinpinon

The Palinpinon geothermal field lies at the south of Negros Island, the Philippines. Palinpinon I geothermal power plant that produces 112.5 MWe has been operated since 1983. Palinpinon II power plant of 80 MWe was installed in Nasuji at 1993, in Okoy at 1994 and in Sogongon at 1996. Reservoir fluid ranges in an average pH value from 6.8 to 7.1 and consists of 40 wt % of steam and 60 % of hot water. There are 68 production wells and 18 injection wells. The deepest well is 3800 m and its bottom temperature is 320 °C. Some wells at Nasuji area penetrated the Nasuji diorite. This can partly be called deep geothermal resources and may partly be called a plutonic rim reservoir (Vasquez and Javellana, 1997; Garcia, S.E., oral communication, 1998).

2.3 The Geysers

The Geysers geothermal field is the largest developed geothermal field in the world. The performance peaked in 1987 producing 2043 MWe, however, the subsequent decline occurred in too much evacuated areas (Barker et al., 1992). This field is also known as a vapor-dominated geothermal system. The temperature is constrained by the maximum enthalpy point on the two phase separation line (White et al., 1971), so that the reservoir temperature is roughly close to 250 °C within a depth interval of gas-static portions (Figure 1). The steam reservoir exists primarily within Mesozoic Franciscan greywacke and underlying 2.4 – 0.9 Ma “felsite” batholith (Thompson and Gunderson, 1992). The apical top of the felsite complex is as shallow as 1.2 km and fractures for the steam reservoirs are roughly developed in the contact metamorphic aureole (Beall and Box, Jr., 1992). An active fault type is strike-slip faults and the field is subject to contraction tectonics. More than 600 wells have been drilled and some of them are deeper than 2.5 km. Therefore, a part of the Geysers geothermal field is called the deep geothermal system.

2.4 Larderello

The most active country on the research and development for deep geothermal resources is undoubtedly Italy, because more than 140 wells have been drilled to a depth greater than 2.5 km in Tuscany and Latium since the 1970s (Baldi et al., 1997). Normal fault zones are developed in the Tyrrhenian Sea (southeastern) side of Italy, so that the most geothermal fields are subject to extension tectonics. Broadly speaking, the Larderello geothermal field is an extent to a large area with 30 km in E-W by 20 km in N-S. The Larderello geothermal field is known as a vapor-dominated geothermal system and limestone often plays a role of reservoirs. Shallow reservoir is close to 250 °C. However, this area contains an area of 300 °C or higher at 3000 m below sea level. The Monteverdi zone is an eastern part of the Larderello geothermal field and shows a hotter part as high as 350 °C at 3000 m below sea level. Extent of the high temperature area is consistent with a shallow area of the seismic reflection surface called “K-horizon” that lies at a depth of 3 or 4 km.

2.5 Ohaaki

The Ohaaki geothermal field lies in the Taupo Volcanic Zone, New Zealand, that is a typical extension tectonic field. Production for the 114 MWe Ohaaki power station commenced in 1988, but pressure drawdown has resulted in cold water inflow. Three deviated deeper wells, BR47, BR48 and BR49 has been completed by June 1995 (Carey, 1997). Their drilled depths, vertical depths and maximum temperatures are 2983, 2243 and 2798 m respectively, 2336, 1858 and 2080 m respectively, and 302, 295 and 290 °C respectively. All the wells penetrated the Cretaceous greywacke, but permeable zones were not found.

2.6 Dexie Valley

The Dexie Valley geothermal field lies at the Basin and Range Province, United States, that is a typical extension tectonic field with dominant normal faults. The Dexie Valley geothermal power plant operated by Oxbow Geothermal Corporation is producing 62 MWe. The reservoir is situated along the active Stillwater normal fault system that bounds the Dexie Valley to the southeast and the Stillwater Range to the northwest. Four production wells range in the depth from 2,300 to 3,000 m and in the reservoir temperature from 220 to 250 °C (Hickman et al., 1999). The geothermal resources may be categorized into deep geothermal resources in the broader definition of this paper.

2.7 Salton Sea

The Salton Sea geothermal field is located on the southeastern shore of the Salton Sea. About 285 MWe of geothermal power plants are operated in the field. This is an extent from the East Pacific Rise that consists of rift systems and transform faults. This is a typical extension tectonic field. It is well known that the reservoir fluid taken here is almost 10 times hypersaline more than that of sea water. A well named “State 2-14” was drilled to 3220 m and completed in 1985. A temperature of 355 °C at the bottom of hole was measured and brine was obtained (Figure 1; Ross and Forsgren, 1992).

2.8 Cerro Prieto

Cerro Prieto geothermal field is the second largest developed geothermal field in the world. 620 MWe are produced by the Cerro Prieto geothermal power plant. This is an extent from the East Pacific Rise that consists of rift systems and transform faults. This is a typical extension tectonic field. There are five wells deeper than 3 km: NL-1, M112, M201, M205 and M206. In addtion, 17 wells have recently been deepened, and the wells 618 and 619 have became to be 3335 and 3011 m, respectively (Ocampo et al., 1997). As a result, at least, seven wells are deeper than 3 km.

3. FACTORS OF DEEP GEOTHERMAL SYSTEMS

A geothermal system consists of the trinity; a heat source, reservoir and fluid. Therefore, we shall consider of the genesis of deep geothermal systems in terms of this trinity.

3.1 Heat Source Constraint

Geothermal heat sources of high temperature hydrothermal systems have long been ascribed to high-level magma chambers and their consolidated equivalents, because most high temperature hydrothermal systems occur in the vicinity of composite volcanoes that may mark long-lived magma chambers at shallow depths. Recent geothermal drillholes penetrating young intrusions in and beneath hydrothermal reservoirs undoubtedly demonstrated such an idea. The emplacement depth of magma chambers is a critically important factor controlling the genesis of high temperature hydrothermal systems. This is easily understood by the comparison of thermal conditions from shallower and deeper magma chambers (Figure 2). Hydrothermal convection usually occurs at a depth less than 3 km. At a depth of 3 km, the diagram shows that the shallower magma chamber can raise the original temperature by more than 400 °C through the entire cooling history whereas the deeper chamber can only raise the temperature by 30 °C. It is clear that the former could be a potential geothermal heat source but never on the latter.

In the last two decades, many geothermal drillholes have penetrated young plutonic bodies in and beneath hydrothermal reservoirs. It should, however, be noted that most of them have exclusively been reported from the contraction tectonic fields as shown in Table 1.

This is explained by the effect of large tectonic over-stress in contraction tectonic fields that raises the density of rocks of upper crust amplifying magma buoyancy. This hypothesis is confirmed by the systematic difference in density of drillhole cores between the extension and contraction tectonic fields in Japan (Muraoka and Yano, 1998). The difference is more than twice as much as in terms of the neutral buoyancy depth of magma between extension- and contraction tectonic fields.

3.2 Reservoir Constraint

Reservoir is ultimately controlled by the permeability distribution, and therefore, the reservoir constraint is synonymous to the permeability constraint. Permeability with the increasing depth was semi-logarithmically approximated by Bottomley and Grant (1998), under assumptions that the increasing lithostatic pressure and the increasing rock plasticity will lead to a continuing reduction in permeability with depth. The effect of lithostatic pressure with depth may be allowed by the simple assumption, because it is related to the porosity reduction with depth. However, plasticity with depth is not necessarily simple, because the crustal strength theory is usually drawn at least by the two equations such as the Byerlee's law and the power law creep equation, so that the crustal strength profile usually has a maximum strength at depth.

Brittle-plastic transition has mainly been discussed on a deeper objective like the lithosphere-asthenosphere boundary since the late 1970s (Brace and Kohlstedt, 1980; Kohlstedt et al., 1995). However, there still remains huge ambiguity on the depth profiles on temperature and lithology in such a deeper zone, and those discussions could be still confined to a first-order of approximations. A well WD-1a drilled by NEDO at the Kakkonda geothermal field, Northeast Japan, reached temperature in excess of 500 ºC at the bottom of hole and may be the first well that completely penetrated the brittle-plastic transition where the depth profiles on temperature and lithology were obtained in detail (Muraoka et al., 1998). An application of the theory of the lithosphere strength to this well would provide us more constrained as well as materialized discussions on the brittle-plastic transition. An attempt is here presented on the well WD-1a.
In a brittle field, the strength limit of the lithosphere is approximated by Byerlee's law (Brace and Kohlstedt, 1980; Kohlstedt et al., 1995). In a plastic field, the strength of the lithosphere is expressed by the general equation on the steady-state plastic flow law as follows (Brace and Kohlstedt, 1980; Kohlstedt et al., 1995):

$$\varepsilon = A(\sigma_1-\sigma_3)^n \exp(-H^*/RT)$$

where ε is the steady-state strain rate, A and n are material constants, $(\sigma_1-\sigma_3)$ is the differential stress, H* is the activation enthalpy, R is the gas constant and T is the absolute temperature. To simulate the conditions of the well WD-1a, we assume ε to be 10^{-12} for tectonically active regions (Fournier, 1991), n and H* to be 2.4 and 219 $kJmol^{-1}$ for quartz diorite (Kirby and Kronenberg, 1987), and T to be a temperature-depth profile of the well WD-1a as shown in Fig. 1 (Muraoka et al., 1998). The remaining parameter is only a material constant A. The material constant A ranges from 10^{-19} to 10^{49} $Mpa^{-n}s^{-1}$ depending on a given rock or mineral species and it is difficult to determine in an a priori reasoning. However, we already know that the permeability of the well WD-1a decreases below a depth of 3,100 m probably due to the plasticization as seen in the inflection point on the temperature-depth profile as shown in Figure 3. For adapting the constant A to this observation, we assume A to be $10^{-0.85}$ $Mpa^{-n}s^{-1}$. An obtained strength profile of the earth's crust along the well WD-1a is shown in Figure 4. Because of such a rough parameterization of A, the position of the strength curve on the plastic field is not necessarily determinative, and the diagram is still schematic. Nevertheless, we can draw some aspects through this lesson as follows:

(1) Four points of DSCA (Differential Strain Curve Analysis) stress ratio measurements by NEDO (1996) are well explained by the strength profile drawn by Byerlee's law and the power law creep equation as shown in Figure 4. Particularly, an approach of σ_1 to σ_3 at the deepest DSCA stress ratio measurement point evidently indicates the dramatic strength weakening accommodated by the plastic field as shown in Figure 4.

(2) Because the temperature inflection is sharp at a depth of 3,100 m, the brittle-plastic transition may apparently be expected at that depth. However, graphical representation makes it clear that the brittle-plastic transition in a strict sense probably lies at a shallower depth like 2,400 m where the maximum differential stress is obtained. A zone of very high concentration of low-angle fractures is observed in the depth interval from 1,770 to 2,860 m (Muraoka et al., 1998), and it has likely been derived from this apical stress concentration zone.

Although plastic flow strongly depends on the temperature, the meaning of the temperature inflection at a depth of 3,100 m could have primarily been a threshold of permeability due to plasticization which bounded a hydrothermal convection zone and a thermal conduction zone. The threshold of permeability might have sharpened a depth limit of hydrothermal convection. It might have sharpened the temperature inflection, and then the temperature inflection might have enhanced a strength inflection point as a function of the temperature inflection. In other words, brittle-plastic transition observed at a depth limit of hydrothermal convection has a self-sharpening nature.

Porosity-induced permeability may simply decrease with depth but, as shown in Figure 4, concentration of fractures may form a maximum at some depth, 2.4 km in this case. Therefore, there still remains an increasing factor regarding the permeability with depth. However, if the temperature exceeds 380 °C at a depth of a few km, fractures can be reduced (Muraoka et al., 1998).

3.3 Fluid Constraint

Brine commonly appears in the deep geothermal systems such as the Salton Sea and Kakkonda geothermal fields, because the high temperature condition exceeds the conventional boiling point curve and enters the two-phase region.

4. CONCLUSIONS

(1) In the last two decades, many geothermal drillholes have penetrated young plutonic bodies in and beneath hydrothermal reservoirs, and most of them have exclusively been reported from the contraction tectonic fields (Table 1). This is explained by the effect of large tectonic over-stress in contraction tectonic fields that raises the density of rocks of upper crust amplifying magma buoyancy. This hypothesis is, in fact, confirmed by the systematic difference in density of drillhole cores between the extension and contraction tectonic fields in Japan (Muraoka and Yano, 1998).

(2) Dramatic strength weakening occurs at a temperature above 380 °C, because it is accommodated by the plastic field (Muraoka et al., 1998). The higher temperature condition excludes any brittle fractures. Therefore, to exploit deep geothermal resources, we have an optimum temperature range that is not necessarily high. However, a maximum stress attains at a depth of the brittle-plastic transition and the dense fractures may be expected at the depth. This depth may be one of targets for the deep geothermal resources.

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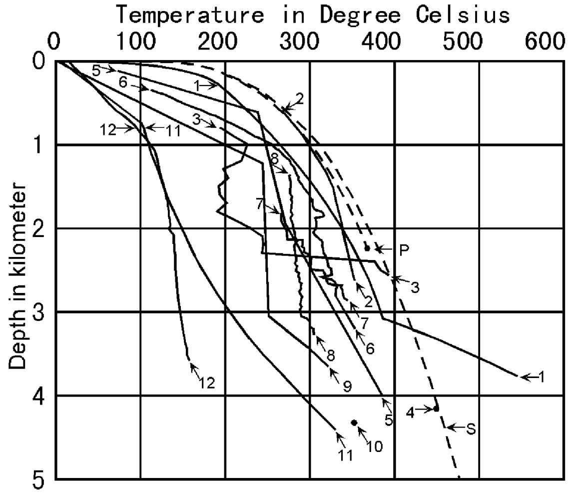

Figure 1. Published temperature-depth profiles of deep geothermal wells in the world. P: A boiling point depth curve of pure water and its critical point, S: A boiling point depth curve of 10 wt % NaCl water (Fournier, 1987), 1: WD-1a, Kakkonda, Japan (Muraoka et al., 1998), 2: Bulalo, Philippines (Otte et al., 1990), 3: Cavarretta et al., (1983), 4: Monte Amiata, Italy (Bertini et al., 1995), 5: Larderello, Italy (Otte et al., 1990), 6: State2-14, Salton Sea, USA (Ross and Forsgren, 1992), 7: Northwest Geysers, USA (Walters et al., 1992), 8: The Geysers, USA (Walters et al., 1992), 9: The Geysers, USA (Otte et al., 1990), 10: M-205, Cerro Prieto, Mexico (Mario et al., 1997), 11: GT-2, Fenton Hill, USA (Burns and Potter, 1995), 12: GPK-1, Soultz, France (Baria et al., 1995)

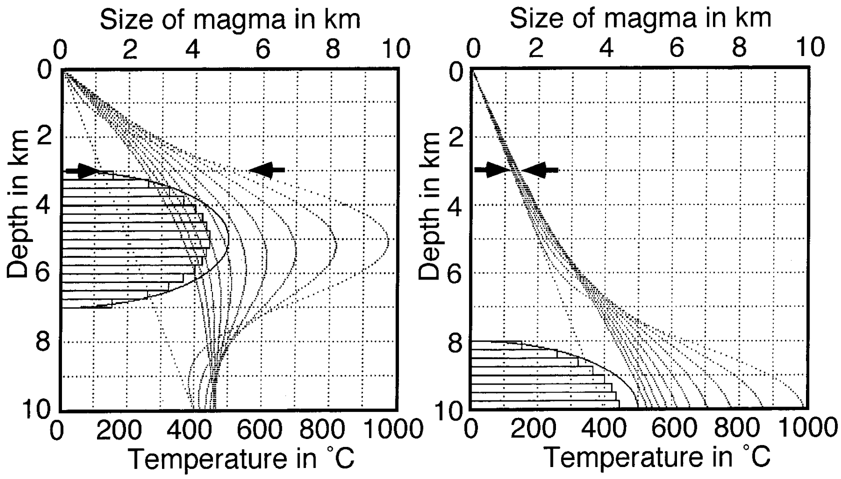

Figure 2. Effect of depth of magma bodies in thermal conductions calculated by the slab-stacked model of Muraoka and Matsubayashi (1994). Magma bodies are shown by the equivolume ellipsoids in a half section. Ten consecutive curves in both diagrams show thermal diffusions along axes of magma bodies from 20 Ka to 200 Ka with every 20 Ka increment after the intrusion of magma.

Table 1. Comparison of magma bodies beneath geothermal fields between the extension- and contraction-tectonic settings (See Muraoka

and Yano, 1998 on the original data sources)

Regional field	Representative field	**Tectonic settings**	Major fault type	Magma pluton	**Depth of top of pluton**
Iceland	Nesjavellir	**Extension tectonics** Spreading ridge	Normal fault	Lack (dike complex)	
Salton Trough	Cerro Prieto	**Extension tectonics** Spreading ridge	Normal fault	Lack (dike complex)	
Tuscany	Monteverdi	**Extension tectonics** Subduction zone	Normal fault	Low-velocity body	**7km?**
Taupo	Ohaaki	**Extension tectonics** Subduction zone	Normal fault	Magnetized body	**4km?**
Kyushu	Hachobaru	**Extension tectonics** Subduction zone	Normal fault	Heat body	**4km?**
The Geysers	The Geysers	**Contraction tectonics** Slab windows	Strike-slip fault	The Geysers felsite	**1.20km**
Philippines	Tongonan	**Contraction tectonics** Subduction zone	Reverse fault	Mahiao diorite	**1.60km**
Kamchatka	Mutnovsky	**Contraction tectonics** Subduction zone	Reverse fault	Mutnovsky diorite	**1km**
Northeast Japan	Nyuto	**Contraction tectonics** Subduction zone	Reverse fault	Nyuto diorite	**1.34km**
	Kakkonda			Kakkonda granite	**1.95km**

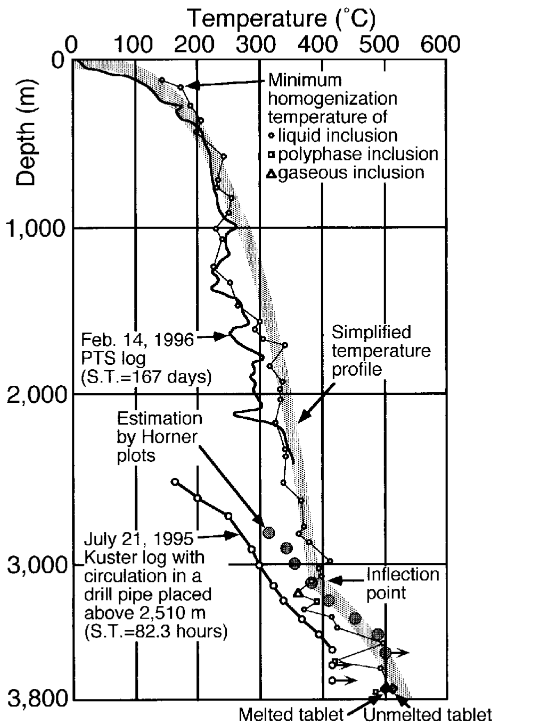

Figure 3. Synthesis of the various temperature profiles along the 3,729 m well WD-1a (Muraoka et al., 1998).

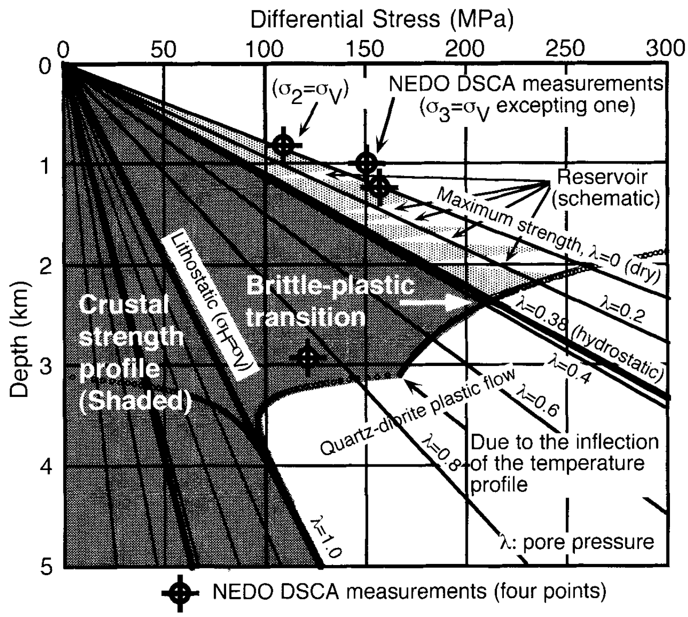

Figure 4. A model of the crustal strength profile (shaded) along WD-1a at the Kakkonda geothermal field, Northeast Japan. λ is the pore pressure representing from zero (λ=0) to lithostatic (λ=1). Four points show the DSCA stress ratio measurements by NEDO (1996) assuming that the vertical stress (σ_3 or σ_2) is equal to the lithostatic stress.