Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

TWO DIFFERENT ROLES OF FRACTURES IN GEOTHERMAL DEVELOPMENT

Mineyuki Hanano
Japan Metals & Chemicals Co., Ltd., 1-3-6 Saien, Morioka-city, Iwate 020-0024, Japan, email: hananom@jmc.co.jp

Key Words: geothermal resource, geothermal reservoir, fracture, permeability, natural convection, well production

ABSTRACT

Heat, fractures and fluid are the fundamental elements of geothermal resources. From a different viewpoint, existence of natural hydrothermal convection to form convective geothermal resources, and fluid production from wells, are the important factors for geothermal development. The fractures play two different roles in geothermal development. One is contribution for the onset of the natural convection in geothermal systems, and the other is contribution as flow paths to connect wells to the reservoir for fluid production. Since the ascending velocity of natural convection in geothermal reservoirs is order of 10^{-9}m/s, fractures from very small to very large permeabilities contribute to the first role. However, in-flow velocity of single-phase liquid within fractures in the vicinity of the well face ranges from 10^{-1} to 10^{1}m/s for example. Thus, only fractures of very high permeability can contribute to the second role. We extend this discussion based on field data.

1. INTRODUCTION

Geothermal reservoirs currently developed for commercial electric power generation are characterized by the existence of natural convection within the systems. Three fundamental factors are required for the formation of convective geothermal resources for their occurrence and for the heat extraction from the reservoirs; 1) heat, 2) fractures, 3) fluid .

Among them, the heat is the geothermal energy itself. It also enables the onset of natural convection by giving buoyancy resulting from the reduction of density caused by thermal expansion. It also helps the onset of natural convection by reducing viscosity of the fluid. These effects due to high temperature make the onset of natural convection easier by 10 times or more (e.g. Garg and Kassoy, 1981). The fluid is the transport material for the heat. It carries heat as sensible and/or latent heat.

The fluid flows through fractures in rocks. Permeability of geothermal reservoirs is caused by fractures of various lengths and widths (e.g. Grant et al., 1982). Therefore, importance of fractures in geothermal development has been well recognized. In this paper, I point out that there are two different roles of fractures in geothermal development; 1) contribution to occurrence of natural convection in geothermal systems to form convective geothermal resources, 2) contribution to high degree of permeability around wells which enables in-flow around the wells with low enough flow resistance at a very high flow rate. It has apparently never been discussed from this viewpoint. Thus, I will discuss these points based mainly on field data.

2. CONTRIBUTION TO OCCURRENCE OF GEOTHERMAL RESOURCES

2.1 Example of Natural Hydrothermal Convection

Geothermal reservoirs are always located within zones of upflow in hydrothermal convection systems (e.g. Grant et al., 1982). One of the reasons is its higher rate of heat transport from great depth, compared with that of zones of heat conduction.

Fig.1 shows relations between ascending velocities within porous geothermal reservoirs and their temperature profiles. This clearly indicates that temperature profiles become curved upward when active upflow exists because of the heat transport by the ascending fluid. On the other hand, they become linear when upflow is very weak or zero because the heat transport is dominated by heat conduction.

Temperature profiles of wells in and around the Kakkonda geothermal field are shown in Fig.2. Confer to e.g. Nakamura and Sumi (1981), Hanano (1995, 1998) and Hanano and Kajiwara (1999), for details of the Kakkonda geothermal system. Well (1) in these figures is a typical production well in the Kakkonda shallow reservoir. Its temperature profile indicates the existence of active upflow. The ascending velocity in the natural state of the Kakkonda shallow reservoir is about 5×10^{-9}m/s (Darcy velocity) (Hanano, 1998; Hanano and Kajiwara, 1999). Thus, fluid needs approximately 6,300 years to vertically ascend 1km in the reservoir. In this case, temperature of the ascending hot water is approximately 230°C. Thus, heat flux associated with the upflow is approximately 4W/m^2, because density and specific enthalpy of the ascending hot water are 830kg/m^3 and 990kJ/kg, respectively.

On the other hand, Well (3) is located about 5km away from Well (1). There does not exist active hydrothermal convection at the location of Well (3), so that heat transport is dominated by the heat conduction. Since the temperature gradient at Well (3) is about 0.2K/m, heat flux is approximately 0.4W/m^2, assuming that the thermal conductivity of the rock medium is about 2W/m·K. This is only 10% of that of the location of Well (1).

Temperature of Well (3) reaches 300°C at a depth of 1.5km, which is higher than that of Well (1). However, due to the lack of natural hydrothermal convection, heat flux at the location of

Well (3) is only 10% of that of Well (1), as described above. Based on this fact, natural hydrothermal convection is absolutely needed to transport large enough quantity of heat from great depth to exploitable depth for commercial utilization. Recent study indicates that ascending velocities in various convective geothermal reservoirs are of the same order of magnitude (e.g. Kato et al., 1999).

Natural convection in geothermal systems occurs when fluid contained within fractures gains large enough buoyancy as a result of heating by heat sources. The Rayleigh number is a good criterion to test the possibility of the onset of natural convection (e.g. Garg and Kassoy, 1981). However, permeability and buoyancy are the key parameters for the onset of the natural convection in porous media. The natural convection may not occur if one of the two factors (i.e. permeability and buoyancy) is not sufficient, though the other is large enough. In the case of Well (3), there may be large enough buoyancy, because temperature at 1.5km depth is 300^{o}C. Therefore, the lack of permeability is the reason why natural hydrothermal convection does not exist at the location of Well (3).

2.2 Permeability Required for Natural Convection

Necessary level of vertical permeability for the onset of natural convection in geothermal reservoirs of about 200 to 250^{o}C is approximately 10^{-15}m^2 (e.g. Straus and Schubert, 1977). This means that this level of permeability is required as an average all over the entire system to form convective geothermal resources. This level of permeability is easily obtained when we test core samples which contain networks of small open fractures. This minimum required permeability is reduced to about 10^{-16}m^2 when the reservoir temperature is 350^{o}C because of enhancement of buoyancy and reduction of fluid viscosity.

Permeability of geothermal reservoirs is caused by fractures of various lengths and widths as described above. Since the relation between permeability k and aperture of an ideal flat open fracture b is $k=b^2/12$ (e.g. Witherspoon et al., 1979), theoretical aperture of an open fracture which gives permeability of 1.0×10^{-15}m^2 is 1.1×10^{-7}m. It is very thin. Thus, we can conclude that there are countless number of such small fractures within geothermal reservoirs.

At the location of Well (3), there must be a lot of such small fractures. However, they may be filled with minerals and/or they are not connected each other. Thus, there is not enough permeability of the onset of natural convection.

Ascending velocity of upflow in geothermal reservoirs is in the order of 10^{-9}m/s as described above. This is very slow. Thus, such a slow fluid flow may exist within fractures of very thin aperture calculated above. This suggests that fractures of such a low permeability can contribute to the onset of natural convection in geothermal systems. Thus, almost all the fractures in geothermal systems, from very small to very large, as a whole, contribute to the onset of natural convection in geothermal systems to form geothermal resources which is to be commercially developed. This is the first role of fractures.

3. CONTRIBUTION TO WELL PRODUCTION

The second role of fracture is the contribution to well production, i.e. contribution to high degree of permeability around wells which enables in-flow around the wells with low enough flow resistance at a very high flow rate.

3.1 Example of Flow Around a Well

Fig.3 is a spinner log during an injection test of a production well in a geothermal field in Japan. This well encountered a permeable fractured zone at around 2,618m depth and resulted in total lost circulation. The spinner log indicates that all of the injected water flowed into the reservoir through several fractures between 2,672 to 2,706m depth. This is very narrow compared with the total length of the open-hole section. Thus, this clearly indicates that the fluid flow into and/or out from the well occurs only through fractured zones which have very high permeability instead of the whole well face.

Fig.4 is a photo of the Daifunto of the Oyasu hot spring in Akita, Japan. As seen in this photo, steam and hot water, flow out only from the fractures developed in the cliff; i.e. fractures of recognizable sizes from a distance. Neither the steam nor hot water flows out from the cliff wall where there is no visible fracture. This phenomenon reminds us the in-flow of geothermal fluid into the wellbore from the reservoir formation; in this case the cliff wall is thought to be the well face of the open-hole section.

Based on the above discussion, we now have the following conceptual model. Fig.5 is a schematic image of in-flow to a well through a penny shaped open fracture. Fluid flows only through the fracture which intersects the well, and then flows into the well. In this case, the in-flow through the fracture can be approximated to be horizontal radial flow within a very thin space between flat parallel plates. Thus, velocity of the in-flow becomes larger as the flow approaches the well (Fig.5). The velocity is very small at a distance from the well but it is very large in the vicinity of the well. This suggests that the fracture needs very high permeability around the well but much lower permeability is sufficient at a distance. Thus, permeability distribution within the fracture need not be uniform. This is the characteristic of fractures which should be encountered by a well for successful fluid production. Fluid flows into the production fracture both vertically and horizontally through fractures which intersect the production fracture, as a result of the pressure draw down within the production fracture.

3.2 In-flow Velocity and Permeability Around a Well

Let us consider steam production from a liquid-dominated geothermal reservoir of about 250^{o}C. Assuming that steam production from a well is 50t/h at well head pressure of 0.6 MPaA, total production, i.e. steam and hot water, is about

250t/h. In most cases under such a condition, fluid flows into the well as single-phase liquid and then flashes in the wellbore. In this case, the horizontal radial in-flow velocity of the single-phase liquid is 10^{-1} to 10^{1}m/s at the well face (inter-fracture velocity), assuming that there is only one production fracture intersecting the well and that aperture of the parallel plate fracture intersecting the well is 10^{-2} to 10^{0}m and the diameter of the well is 216mm (8.5 inches). This horizontal in-flow velocity is larger by 10^{8} to 10^{10} than the ascending velocity of the natural convection of geothermal systems as described above. This clearly indicates that fractures which act as flow paths between reservoirs and wells should have very high permeability which enables low enough flow resistance to permit such a high velocity in the fractures in the vicinity of wells.

Permeability-thickness product (kh) of production wells in liquid-dominated geothermal fields obtained by single-well pressure transient tests ranges 10^{-12} to 10^{-10}m^{3} (e.g. Grant et al., 1982). Thus, horizontal permeability of fractures related to fluid production from the production wells is 10^{-12} to 10^{-8}m^{2} assuming the same fracture aperture employed above. These values are 10^{3} to 10^{7} times larger than 10^{-15}m^{2}, which is the approximate minimum required vertical permeability for the onset of the natural convection in geothermal reservoirs, as described above.

This result clearly indicates that fractures of permeabilities lower than 10^{-12} to 10^{-8}m^{2} are unable to act as the flow paths to connect wells to reservoirs for commercial steam production. Thus, they cannot be feed zones of wells. This is because their flow resistance is so high that they are unable to sustain high enough fluid velocity for fluid production because of too large pressure draw down. However, note that the permeability values, i.e. 10^{-12} to 10^{-8}m^{2}, are tentative only for the case discussed above and are not necessarily a representative of that of the actual productive fractures, because the values strongly depend on fluid temperature, fluid pressure, number of productive fracture and fracture aperture.

3.3 Is Production Always Possible within Convective Geothermal Reservoirs?

It is well known among geothermal field engineers that wells of heat conductive temperature profiles may not produce large amount of geothermal fluid constantly for a long time, for commercial power generation. Thus, all of the production wells for commercial geothermal power generation are drilled within geothermal reservoirs which are parts of natural hydrothermal convection systems.

Then, is steam production always possible from wells drilled in convective geothermal reservoirs? The answer is no. Fig.6 shows temperature profiles during warm-up after drilling of a production well in a geothermal field in Japan. It is clear that there exists natural hydrothermal convection in this reservoir. Thus, the reservoir is made of fractured porous media whose bulk average of vertical permeability is greater than 10^{-15}m^{2}. Thus, fractures in the reservoir make up a network to allow fluid circulate in the reservoir. However, the well did not encounter any fracture which could cause total lost circulation or that of similar magnitude during the drilling of its open-hole section, as seen in the lost circulation record (Fig.6). Thus, the well did not produce any steam. This clearly indicates that a drilling target should be carefully examined even in a convective geothermal reservoir.

Fig.7 is a case of well M-12 in Matsukawa, Japan which is an extreme example of this phenomenon. Matsukawa is a vapor-dominated geothermal field where there is a very active hydrothermal convection in the reservoir (e.g. Hanano et al., 1993). M-12 was a deviated well and drilled into its primary target shown as a circle; its diameter was 20m. However, it did not encounter any productive fracture in the target circle and drilled through it without any lost circulation. Thus, the open hole section of M-12 was back-filled and cemented. Then, it was side tracked from the bottom of the casing pipe. The side-tracked leg encountered a productive fracture which caused total lost circulation, right after the start of the side-track.

However, note that the total lost circulation was located in the target circle of which the original leg drilled through without any lost circulation. Three dimensional distance between the lost circulation of the side-tracked leg and the original leg was only 10m. This clearly indicates that number of productive fractures is limited and so is their distribution even though there is an active hydrothermal convection in the reservoir.

Based on the above discussion, we may conclude as follows. There are a large number of fractures of different lengths and apertures, i.e. different permeabilities, in geothermal reservoirs. Thus, many fractures intersect well faces. However, only the fractures of high enough permeability which ensure low enough flow resistance for in-flow around wells can act as flow paths from the reservoir to the wells for fluid production. All other fractures of lesser permeability cannot act as flow paths because of too large pressure draw down due to too large flow resistance. Thus, no matter how large the number of fractures with low permeabilities intersects a well, the well cannot be productive. Thus, commercial steam production is not possible if a well does not encounter a fracture of large enough permeability, even though the geothermal reservoir is included in a natural hydrothermal convection system in which fluid continuously circulates within fractures by buoyancy. It is only possible when wells encounter productive fractures which cause large amount of lost circulation. This is the second role of fractures.

4. SIZES AND PERMEABILITIES OF FRACTURES FOR TWO DIFFERENT ROLES

There are many fractures of different sizes, e.g. lengths and apertures, and permeabilities in the reservoir. The number of large fractures (larger permeabilities) is less than that of small fractures (less permeabilities). Their relation is fractal (e.g. Turcotte, 1992). The relation between number of fractures N and sizes of fractures, i.e. permeabilities of fractures, is illustrated in Fig.8. As describe above, permeability of a fracture is related to the fracture aperture. Since a fracture aperture is usually proportional to the fracture length, the fracture length L is employed as the horizontal axis in Fig.8.

As discussed above, fractures needed for the onset of natural convection in geothermal systems are those of low permeability. Thus, almost all the fractures from very small to very large can contribute to it (Fig.8). However, fractures of high enough permeability only enable well production as discussed above. Thus, fractures which can contribute to the well production are limited to those of high permeability (Fig.8). These fractures cause large amounts of lost circulation, i.e. total lost circulation or similar magnitude, when they are encountered during drilling. Relatively smaller lost circulation also occurs when wells encounter slightly smaller fractures than the productive ones. However, the fractures which cause such smaller lost circulation are not large enough for well production. Thus, fractures which cause lost circulation have a slightly wider range in size, i.e. permeability, than that of the productive fractures (Fig.8).

5. CONCLUSION

There are three fundamental factors required for the convective geothermal resources for their occurrence and for the heat extraction from the reservoirs; 1) heat, 2) fractures, 3) fluid. From a different viewpoint, the most important factors for the conventional geothermal development are 1) existence of natural hydrothermal convection to form liquid- or vapor-dominated geothermal resources, and 2) fluid production from wells to supply steam to turbine generator systems.

Based on the above discussion, we can conclude that fractures play two different roles in geothermal development; 1) contribution for the onset of natural convection in geothermal systems to form geothermal resources; this is given by most of the fractures of different sizes, and 2) contribution as a flow path to connect wells to the reservoir to let the fluid flow into and/or out from the wells; this is given only by fractures of high enough permeability. This concept is a fundamental characteristic of geothermal reservoirs and steam production, and one should be wary of the role of fractures when discussing permeability in geothermal reservoirs.

ACKNOWLEDGEMENTS

I would like to thank management of Japan Metals & Chemicals Co., Ltd. (JMC) for their permission to publish this paper, colleagues at JMC and JMC Geothermal Engineering Co., Ltd. for their daily discussions, and the referees for their review of the manuscript.

REFERENCES

Bredehoeft, J.D. and Papadopulos, I.S. (1965) Rates of vertical groundwater movement estimated from the earth's thermal profile. *Water Resour. Res.*, Vol.1, pp.325-328.

Garg, S.K. and Kassoy, D.R. (1981) Convective heat and mass transfer in hydrothermal systems. In: *Geothermal Systems*, L. Rybach and L.J.P. Muffler (Ed.), Wiley, New York, pp.37-76.

Grant, M.A., Donaldson, I.G. and Bixley, P.F. (1982) *Geothermal Reservoir Engineering*. Academic Press, New York, 369pp.

Hanano, M. (1995) Hydrothermal convection system of the Kakkonda geothermal field, Japan. *Proceedings of the World Geothermal Congress, 1995, Florence, Italy*, Vol.3, pp.1629-1634.

Hanano, M. (1998) A simple model of a two-layered high-temperature liquid-dominated geothermal reservoir as a part of a large-scale hydrothermal convection system. *Transport in Porous Media*, Vol.33, pp.3-27.

Hanano, M. and Kajiwara, T. (1999) Permeability associated with natural convection in the Kakkonda geothermal reservoir. *Trans. Geotherm. Resour. Council*, Vol.23, 351-360.

Hanano, M., Kotanaka, K. and Ohyama, T. (1993) A quarter century of geothermal power production at Matsukawa, Japan. *Geotherm. Resour. Council Bull.*, Vol.22, pp.32-47.

Kato, M., Kaneko, K. and Hanano, M. (1999) Velocities of convective ascending flow in liquid-dominated hydrothermal convection systems. *Proc. 24th Workshop Geotherm. Res. Eng.*, Stanford Univ., pp.164-167.

Nakamura, H. and Sumi, K. (1981) Exploration and development at Takinoue, Japan. In: *Geothermal Systems*, L. Rybach and L.J.P. Muffler (Ed.), Wiley, New York, pp.247-272.

Saito, S. (1990) Recent geothermal drilling activities and technologies in Matsukawa, Kakkonda and Mori, Japan. *Chinetsu (J. Jap. Geotherm. Energy Assoc.)*. Vol.27, pp.325-355. (in Japanese)

Straus, J.M. and Schubert, G. (1977) Thermal convection of water in a porous medium: effects of temperature- and pressure-dependent thermodynamic and transport properties. *J. Geophys. Res.*, Vol.82, pp.325-333.

Turcotte, D.L. (1992) *Fractals and Chaos in Geology and Geophysics*. Cambridge, 221pp.

Witherspoon, P.A., Wang, J.C.Y., Iwai, K. and Gale, J.E. (1979) Validity of the cubic law for fluid flow in a deformable rock fracture. *Water Resour. Res.*, Vol.16, pp.1016-1024.

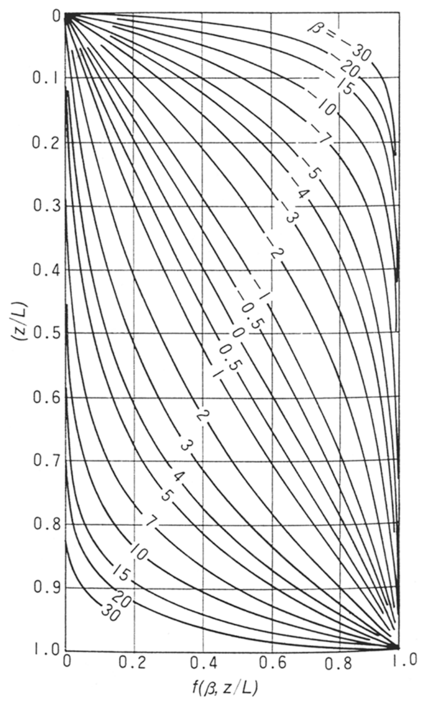

Fig.1 Dimensionless temperature profiles in half infinite porous media as a function of dimensionless steady fluid velocities (Bredehoeft and Papadopulos, 1965). Z/L: Relative depth, f: Relative temperature, β: Relative fluid velocity (positive downward).

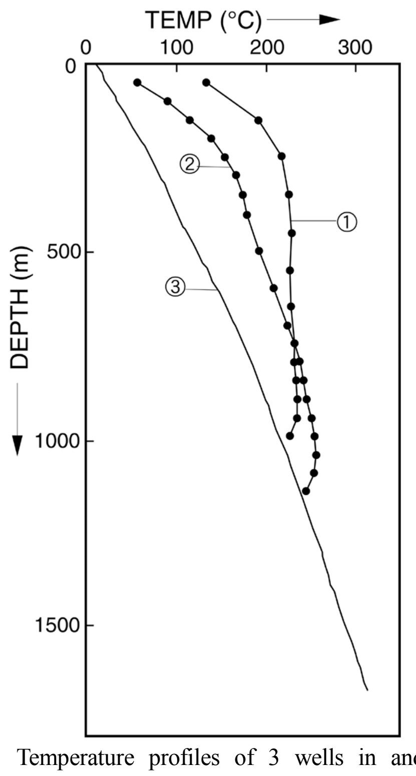

Fig.2 Temperature profiles of 3 wells in and around Kakkonda, Japan (Hanano, 1995). Locations of the wells are shown in Hanano (1995).

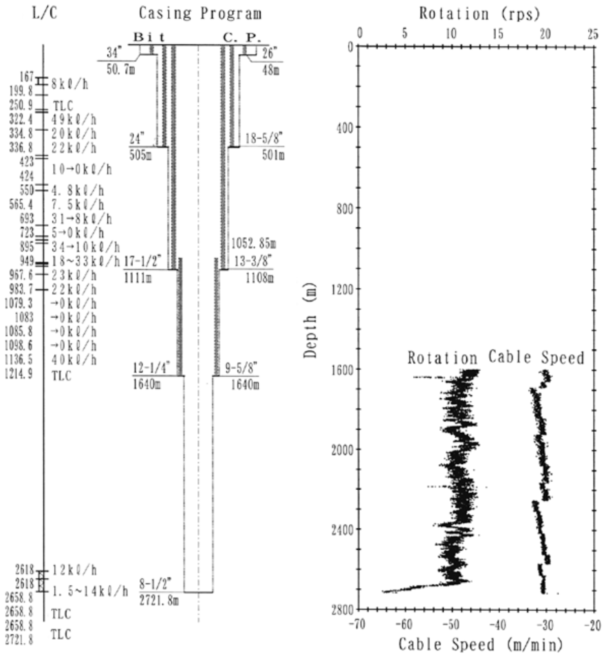

Fig.3 Spinner log of an injection test of a production well. L/C: Lost circulation. TLC: Total lost circulation.

Fig.4 Photo of Daifunto of the Oyasu hot spring, Akita, Japan (taken by Masayuki Tateno).

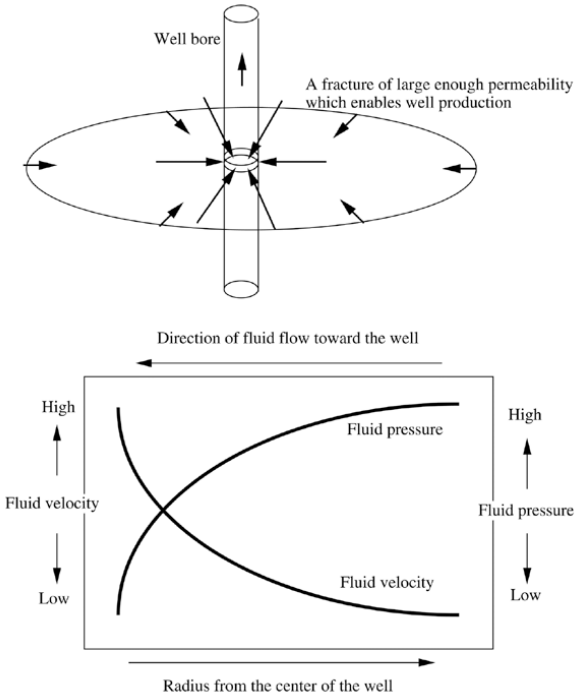

Fig.5 Illustrated in-flow around a production well along with pressure and fluid velocity distribution within the production fracture.

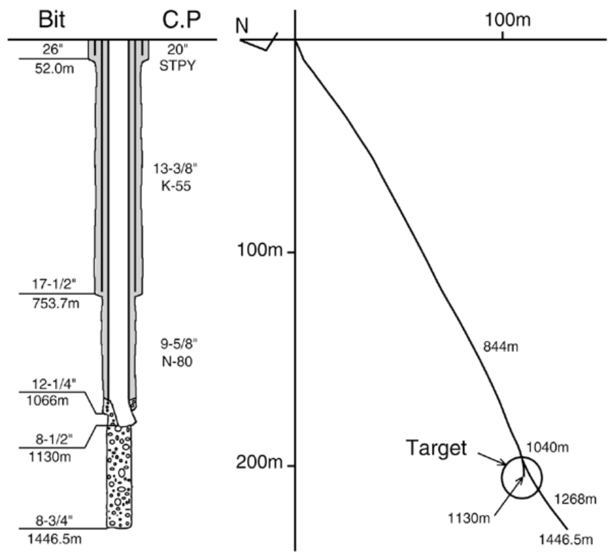

Fig.7 Drilling target and results of well M-12 in Matsukawa, Japan (Saito, 1990).

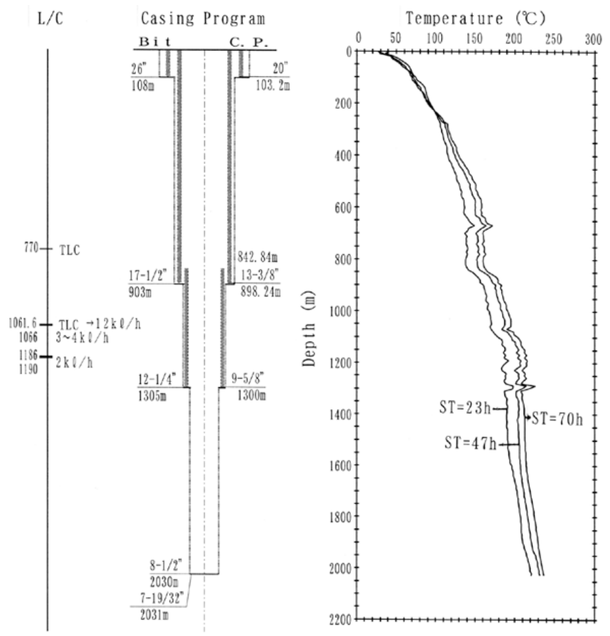

Fig.6 Example of an unproductive well drilled in a convective geothermal reservoir. L/C: Lost circulation, TLC: Total lost circulation, ST: Standing time.

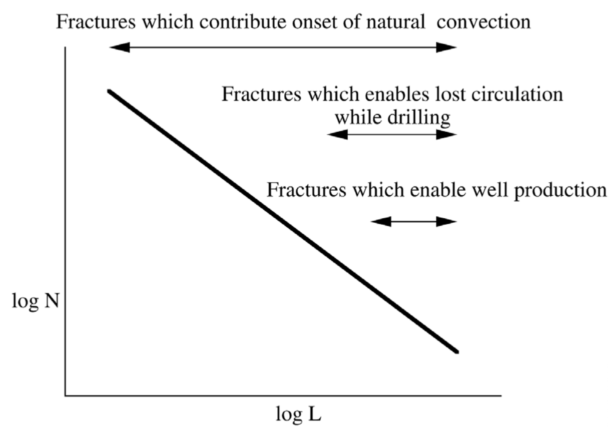

Fig.8 Schematic relationship between fractures of various lengths and roles of fractures. N: Number of fractures, L: Length of fractures.