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DEVELOPMENT OF WELL TRAJECTORY PREDICTION SYSTEM OF DIRECTIONAL WELL AND STUDY OF GEOLOGICAL EFFECT ON DIRECTIONAL DRILLING

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ABSTRACT

As a part of the "Development of high temperature MWD system for geothermal wells", well trajectory prediction system, one of the drilling support system, has been developed by NEDO for well trajectory prediction while drilling and for designing BHA before drilling. This system was designed to be applied for DHM (down hole motor) drilling and for rotary drilling in geothermal areas. Computer programs of the system have been developed based on equations of equilibrium for BHA (bottom hole assembly) (Jogi *et al.*, 1988) to calculate the force acting on a bit, definition to determine the direction of drilling (Ho, 1987) and equation to find resonant RPM (Yew and Zhang, 1994). We verified the program using actual directional drilling data in a geothermal area. Regarding DHM drilling, as well trajectories calculated by the program were mostly consistent with actual field data, we considered that this program could support efficient DHM drilling. However, in some cases for rotary drilling the results from the program were not consistent with actual data. We considered the actual well trajectory in rotary drilling had the tendency to be affected not only by force acting on the bit, but also geological effects. For estimating and rejecting geological effects, we developed a new program to calculate bit and rock anisotropy index by an inversion method and tested it using actual rotary drilling data. We found it possible to improve the well trajectory prediction by applying bit and rock anisotropy index. We have examined such geological effects with this program using drilling and geological data of deep geothermal wells (WD-1a and WD-1b) drilled by NEDO. In this study, anisotropy indexes of these adjacent two wells (WD-1a and WD-1b) were similar. And, strong correlation was observed between bit anisotropy index calculated by the inversion program with actual directional drilling data and geological boundary as confirmed by drilling. Well trajectory was seriously affected by geological effect at the geological boundary. If we can estimate the geology of a new well from other nearby well data, it will be possible to improve drilling efficiency by this system. Next our task is to study other geological and downhole factors affecting well trajectory and reflect such study results to improvement of geothermal drilling.

1. INTRODUCTION

Since the drilling cost accounts for a large part of geothermal development in Japan, cost reduction of drilling has been requested as one of the most important tasks.

However, constraining such requirements, we are obliged to carry out directional drilling under the following conditions, which limit effective drilling:

- Underground conditions: Hard fractured formation, sometimes abrasive formation, lost circulation zones, high temperature conditions.
- Surface conditions: National parks, mountainous areas, steep topography, very limited surface space for drilling rigs.

In order to improve drilling efficiency under such situations, NEDO started the development of a high temperature MWD system, and a drilling support system for geothermal wells in 1991. The drilling support system consists of the directional control support system, and well evaluation support system.

As one part of the directional control support system, a well trajectory prediction system has been developed and tested (Ujo *et al.*, 1997). Main functions of this trajectory prediction system are: well trajectory prediction while drilling in rotary and DHM drilling, design of adequate BHA drilling parameters, and evaluation of the geological effect on well trajectory.

MWD must result in effective directional drilling. However, effective directional drilling with MWD operation should be based on proper directional well trajectory planning, and adequate BHA and drilling parameter design. Regarding geological effect for well trajectory, as the effect in geothermal wells is much stronger than for oil wells, the study and improvement for this problem must be considered.

Based upon this goal, we have developed, tested and improved the system to predict well trajectory of rotary drilling, conventional DHM and steerable DHM motor drilling in geothermal wells, which can be operated not only for the NEDO high temperature MWD system but also for conventional directional drilling with MWD or steering tools.

2. WELL TRAJECTORY PREDICTION SYSTEM, A CASE STUDY AND IMPROVEMENT

2.1 Outline of the System

As part of the drilling support system, a well trajectory prediction system has been developed considering field data and experiences of geothermal directional drilling in Japan (refer to Fig. 1). This system was designed for adequate directional control operations in order to realize improvement of drilling efficiency. For such purposes it has the functions of well trajectory prediction, and design of BHA and drilling parameters for conventional DHM drilling, rotary drilling and steerable DHM drilling.

Program for DHM Drilling
A static BHA model program for DHM drilling has been developed based on the equations of equilibrium for BHA to calculate the force acting on bit (Jogi *et al.*, 1988). These equations of equilibrium for BHA have the following form:

$$EIy^{iv} = Tx^{iii} - Wy^{ii} - w_q\, w_1 z \sin b$$
$$EIx^{iv} = -Ty^{iii} - Wx^{ii} + w_1 \sin b \qquad (1)$$
$$GJw_q = T = \left[1 - 2\left(\frac{EI}{GJ}\right)\right]Ta$$

where, *EI* is the bending stiffness; *GJ* is the torsional stiffness; *Ta* is torque on the bit (TOB); *W* is weight on bit (WOB); w_1 is effective weight per inch of BHA including buoyancy due to drill mud; b is angle of inclination; and w_q is the angle of twist per unit length. The proper boundary conditions for the above equations are omitted.

Also, a drilling ahead criterion for calculating the wellpath is developed based upon Ho's definition (Ho, 1987) (refer to Fig. 2). The angle change between well trajectory and drill path is written as:

$$\tan q_1^{(b)} = i_b \frac{F_L^{(b)}}{F_a^{(b)}}$$
$$g = q_{bt} + \tan^{-1}\left[i_b \frac{F_L^{(b)}}{F_{a}^{(b)}} \right] \qquad (2)$$

where, g is the angle of drill ahead change (angle between well trajectory and drill ahead); q_{bt} is the angle between bit axis and well trajectory; i_b is bit anisotropy; $F_a^{(b)}$ is force on bit along the bit direction; $F_L^{(b)}$ is force on bit; force on bit perpendicular to the bit access direction.

<u>Program for Rotary Drilling</u>

If the rotary speed of drilling does not reach the resonant RPM of the drill string, the above-mentioned theory for static BHA model can be applied for a rotary drilling. However, if the rotary speed of BHA reaches the resonant RPM of drill string, lateral motion of drill collar would occur and it becomes impossible to apply static BHA model. And, in this case, drilling itself becomes more hazardous and downhole tool problems would occur.

To avoid such limitations and problems, we developed the program to find resonant RPM during rotary drilling based on Yew's equations (Yew and Zhang, 1994) as below:

$$wres = \frac{1}{2m}\left[\sqrt{-m^2 + 4m\left(EIn_i^4 + Tn_i^3 - Wn_i^2\right)}\right] \qquad (3)$$

where:

$$n_i = \frac{p}{L} - \frac{T}{4EI}$$

wres is the resonant RPM; *EI* is the bending stiffness; *m* is the unit weight of drill collar; *m* is mud viscosity; *T* is torque on bit; *W* is weight on bit; and *L* is length of drill collar.

2.2 Case Study and Improvement of the System

Tests and parameter studies of the system were carried out for effects of bent sub angle, tool face angle, drilling parameter, BHA configuration and resonant RPM (Nakashima *et al.*, 1995).

After the above studies several case studies have been carried out using actual directional drilling data in Japanese geothermal fields.

<u>Case Study for DHM Drilling</u>

Figure 3 is an example of comparison of the simulated well trajectory by the prediction system and observed actual well trajectory in geothermal drilling with DHM and bent sub; which shows good agreement. The simulated well trajectory by the prediction system was calculated by inputting actual BHA, drilling parameter, tool face orientation of bent sub that were recorded in geothermal drilling. In other cases, the simulated and actual well trajectories also show mostly good agreement. Therefore, it is expected that the well trajectory prediction system will be able to improve efficiency of directional drilling with DHM at least, as the system achieves more adequate selection of BHA, drilling parameter and tool face orientation.

<u>Case Study for Rotary Drilling and Improvement</u>

We have done several case studies for rotary drilling using directional drilling data in different geothermal areas in Japan. At the first stage, we used the fixed bit anisotropy (*ib*) assumed by bit test data, and in most cases the agreement between the simulated and actual well trajectories are not as good as DHM drilling. Especially in some cases which have complicated or strong geological tendency, distinct differences between the simulated and actual well trajectories were observed (refer to Fig. 4).

Through these case studies, we have concluded it is necessary to consider both bit and rock anisotropy for applying the prediction system for rotary drilling. We have therefore introduced the definition for direction of drilling with anisotropy index of both rock and bit (Ho, 1987) into the program as follows.

Direction of drilling with anisotropy index of rock and bit (Ho, 1987):

$$r_n \vec{e_r} = Ir\left[Ib\vec{e_f} + (1 - Ib)\cos q_{af}\vec{e_a}\right] + Ib(1 - Ir)\, r_n \cos q_{rd}\vec{e_d} \qquad (4)$$

where:

$\vec{e_r}$ is the unit vector along the drilling direction; $\vec{e_f}$ is the unit vector along the resultant bit force on the formation; $\vec{e_a}$ is unit vector along the bit direction; $\vec{e_d}$ is unit vector normal to formation bedding; r_n is coefficient; q_{af} is angle between vectors $\vec{e_a}$ and $\vec{e_f}$; and q_{rd} is angle between vectors $\vec{e_f}$ and $\vec{e_d}$.

With:

$$Ir \text{ (anisotropy index of rock)} = \frac{\text{drilling rate parallel to bedding}}{\text{drilling rate normal to bedding}}, \text{ and}$$

$$Ib \text{ (anisotropy index of bit)} = \frac{\text{drilling rate in bit's lateral direction}}{\text{drilling rate in bit's axial direction}}.$$

Although it is expected that this theory improved the accuracy of the simulation of well trajectory prediction, there has been a limitation to the application because it is not possible to acquire actual downhole anisotropy index of rock and bit for input to the system before drilling. Based on this situation, we have developed the new program to calculate anisotropy index of rock and bit reflecting downhole condition by inversion technique and Ho's definition using actual drilling data, and tested to apply these indexes to the prediction of other wells. The actual well trajectory (survey data) is the result reflected by BHA configuration and drilling parameter relating to BHA equilibrium equations, and definitions for direction of drilling with anisotropy index (bit and rock). By applying inversion (method of least squares) with the above equations and actual data, we tried to calculate anisotropy index. Figure 5 shows our concept of calculation and application of anisotropy index for drilling of new well. We consider that anisotropy index calculated with prior well data will be able to improve the well trajectory prediction of a new well, if the distance between old and new wells is close and geological tendency is expected to be similar.

Figure 6 shows an example of application and the results of the above method. These two wells (WD-1a and WD-1b) were drilled by NEDO in the Kakkonda geothermal area with different rotary BHAs and DHM assembly, respectively. In this study, first we calculated bit and rock anisotropy index of the first well before side track (WD-1a) with inverse program and actual drilling data including BHA configuration and drilling parameters for each section. Then, we carried out the well trajectory prediction of the second well (WD-1b after sidetrack) by prediction system with drilling data of this well (WD-1b) and anisotropy index of the first well (WD-1a). In this study a distinct difference was observed between simulated well trajectory without anisotropy index and actual well trajectory; which was corresponded to complex geological structure. On the other hand, the simulated result with anisotropy index shows good agreement with actual well trajectory as anisotropy indexes of these two wells were similar. We consider it possible to improve the accuracy of well trajectory prediction with the program even in rotary drilling, if we have data from nearby well locations to apply for calculating anisotropy index for a new well. We are scheduled to carry out case studies using other geothermal drilling data to find points to be improved.

3. PRELIMINARY STUDY OF GEOLOGICAL EFFECT IN GEOTHERMAL DRILLING

Many qualitative discussions had been made regarding the well trajectory control problems due to geological effect in directional drilling for many years. We tried to find what happened downhole during directional drilling by using possible simulated numerical data as preliminary study for this subject.

A distinct correlation has been observed between calculated bit anisotropy indexes and geological boundary as confirmed by drilling in WD-1a. Especially, at the following TD (total drilling depth) and geological boundary of WD-1a, bit anisotropy index of more than 0.7 was observed as a distinct correlation:

- TD approx. 2300m: Boundary between Tertiary Formation (Obonai Formation, acidic tuff and andestic tuff) and Old-Granites (intrusive rock)
- TD approx. 2720m: Boundary between Pre-Tertiary Formation (sandstone, acidic tuff and slate) and Old-Granites (intrusive rock)
- TD approx. 2850m: Boundary between Pre-Tertiary Formation (sandstone, acidic tuff and slate) and New-Granites (Quaternary)

Near the above depths (TD), bit anisotropy index: [Drilling rate in bit's lateral direction / Drilling rate in bit's axial direction] indicates larger values compared to other sections. It is considered that force on bit perpendicular to the bit direction becomes much larger at the geological boundary which seems to have large physical difference as relating to intrusive rock, for example, and it makes drilling rate in the bit lateral direction much bigger.

On the other hand, large bit anisotropy index observed below TD approx. 2900m is not related to geological boundary. We assume that this larger value compared with the Tertiary formation might be caused by physical heterogeneity of the New-Granite such as boundary permeability; although further study with logging and other data is necessary.

Regarding other possible geological effect such as bedding and fracture; although data to confirm scale, dip and direction is limited, we are trying to evaluate such effects and relations to rock anisotropy index with data as FMI or BHTV logging.

From the standpoint of directional drilling, information of the geological boundary relating to large bit anisotropy index is very important and should be strongly considered. Next drilling step including BHA (rotary or DHM, hold, build and drop BHA) should be considered based upon not only the drilling plan and situation but also prediction of geological effect.

From the standpoint of well evaluation, there is the possibility for bit and rock anisotropy index to be calculated from directional drilling data to support geological evaluation; although more detailed study is necessary.

4. CONCLUSIONS

The well trajectory prediction system, for both well trajectory prediction and design of BHA system, one of the drilling support systems, has been developed, tested and improved. Regarding DHM drilling, as well trajectory calculated by the original program was consistent with actual data, we considered that the well trajectory prediction system could support the efficient DHM drilling. On the other hand, regarding rotary drilling, as well trajectory had the tendency to be affected by not only force acting on the bit, but also geological effect, the original program without considering geological effect was not adequate for well trajectory prediction. For estimating and rejecting such effects, we developed a new program to calculate bit & rock anisotropy index by inversion method and tested it using actual rotary drilling data. We found it possible to improve the well trajectory prediction by applying this method. Also, strong correlation was observed between bit anisotropy index calculated by the inversion program and geological boundary confirmed by drilling. It is considered that force on bit perpendicular to the bit direction becomes much larger at the geological boundary. Therefore, the information of geological boundary relating to large bit anisotropy index is very important and should be more closely examined for directional drilling.

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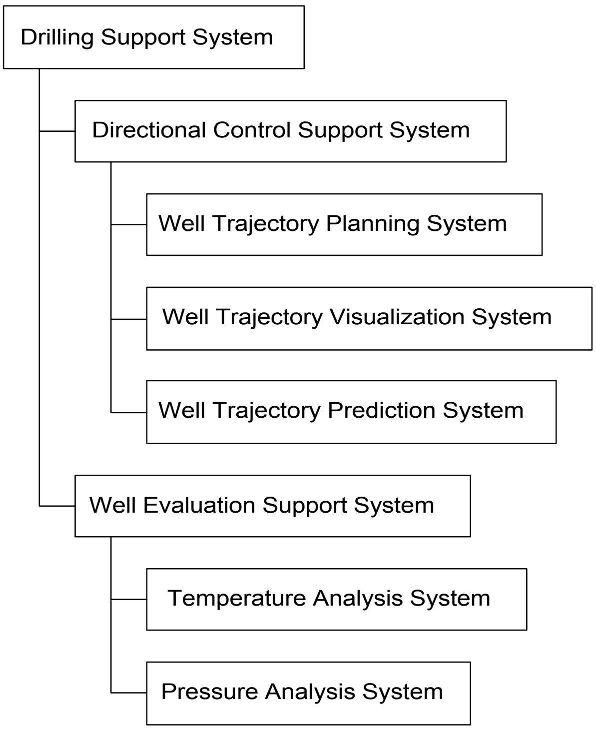

Figure 1: Structure of the drilling support system.

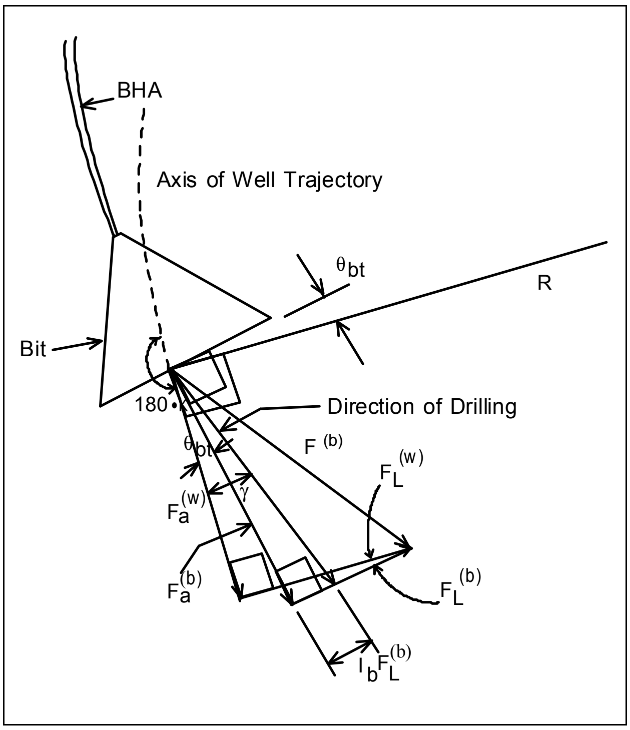

Figure 2: Drill ahead model.

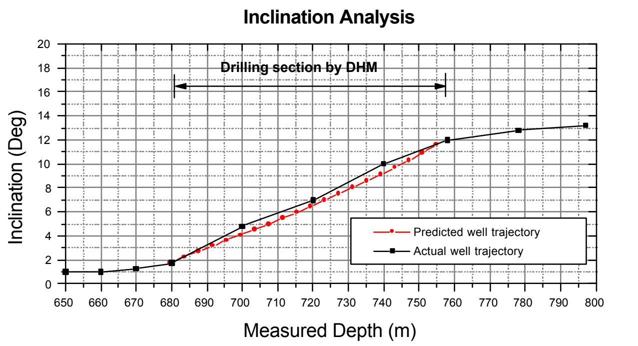

Figure 3: Comparison between predicted and actual well trajectory of geothermal well.

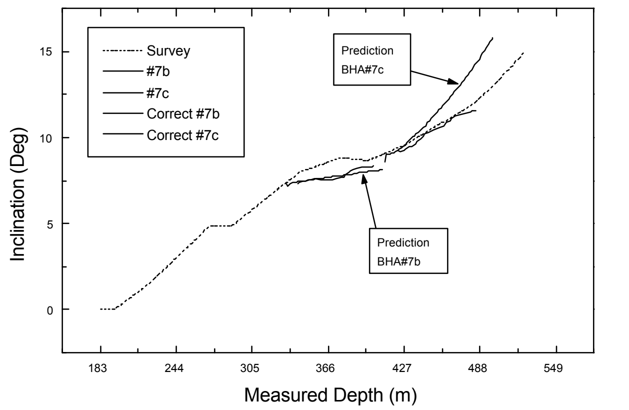

Figure 4: Example of comparison between predicted and actual survey data (first program).

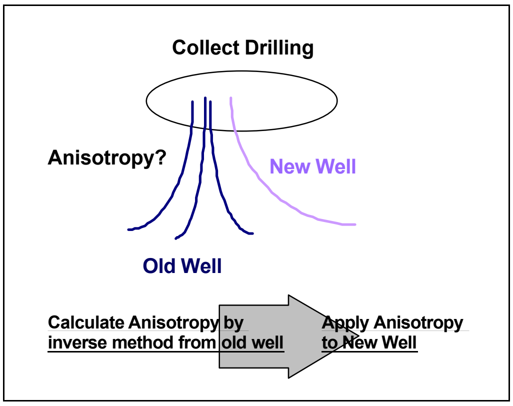

Figure 5: Concept of calculation and application index for new well's drilling.

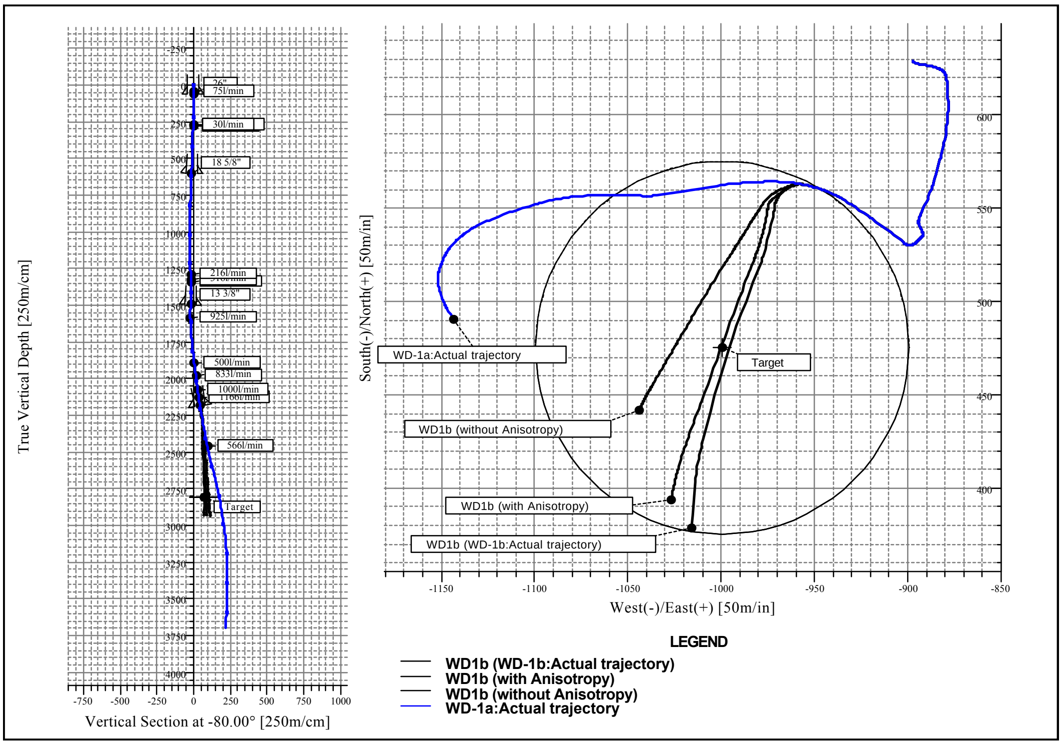

Figure 6: Actual well trajectory of WD-1a, WD-1b, and calculated well trajectory of WD-1b.

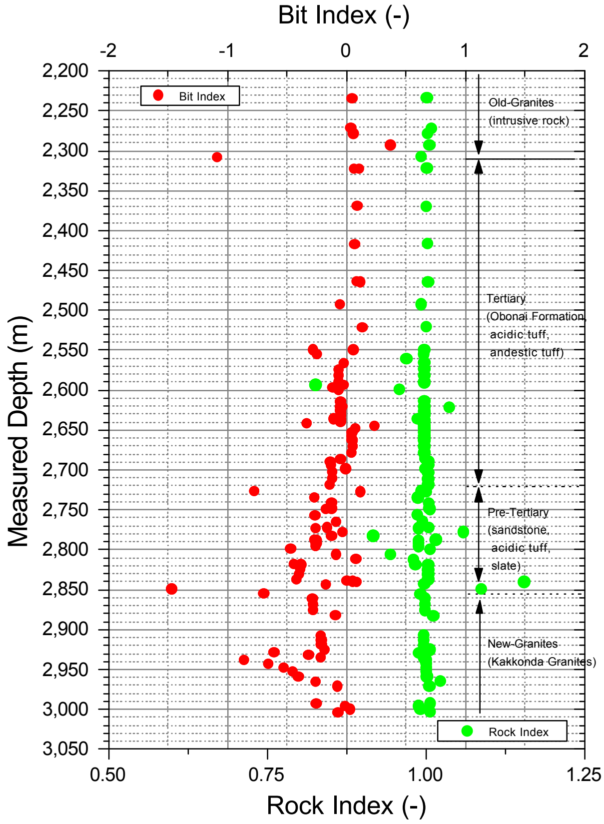

Figure 7: Anisotropy index (bit and rock) and geology of WD-1a.

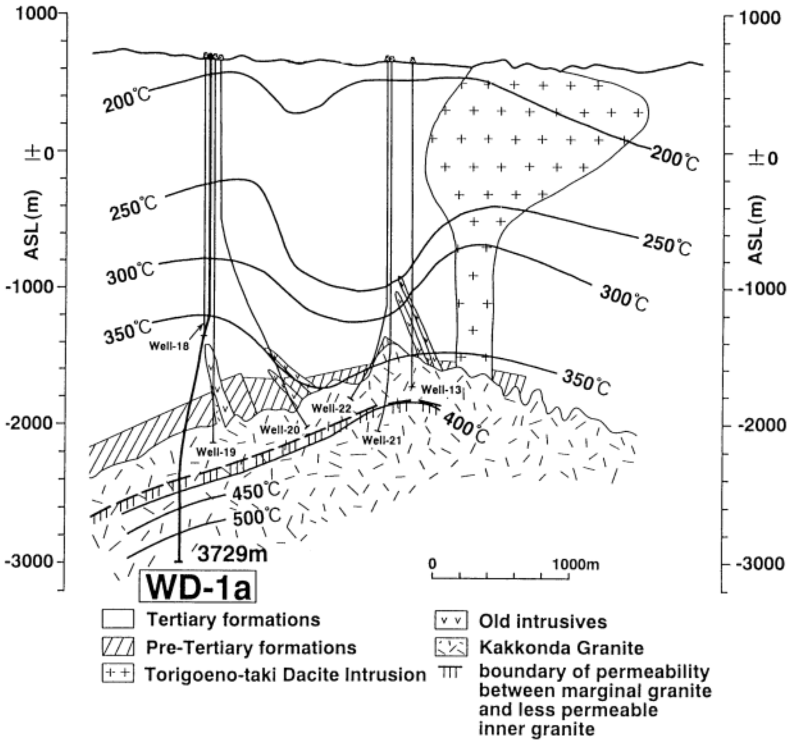

Figure 8: Geothermal model of the Kakkonda field (modified from Kato *et al.*, 1996).