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Geothermal Well Drilling and Deep Fault

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Abstract. Hydrothermal geothermal resources rely on geological structure condition. Deep fault owns important function in geothermal system. It is specially for high temperature geothermal field which located in volcano and recent magma area. Such fractured reservoir depends on the distribution of deep fault. The purpose of geothermal well drilling is to gain thermal energy and fluid as much as possible. High quality geothermal well starts from well drilling design. Such design should select your target fault and decide a certain depth to encounter the fault. When implementation of the drilling it is very important to take care if the drilling touching fault. Over-drilling after penetrating fault will lead reversed result. Many examples have explained such stories.

Keywords: geothermal drilling, deep fault, designed target fault, drilling process tracking

1. High Quality Geothermal Well Relies on Deep Fault

Everyone hopes a drilled geothermal well to gain higher temperature and fluid yield. High quality geothermal well relies on deep fault as important geothermal geological condition. Numerous exploration and production well drilling practice has proven such principle.

There is no same yield for deferent wells even drilled in same stratiform reservoir. High quality geothermal well was usually drilled close by fault zone. Fault zone is able to increase fractures and connectivity in sandstone reservoir, to induce karst development and extension. These will lead enhanced permeability in reservoir. It will favor of hydrothermal convection. It will make such geothermal well with best yield in the same reservoir.

Fractured banding reservoir relies on fault zone more strictly to form channel and storage space which in favor of fluid movement. The fault's penetrated degree by geothermal well drilling will directly make the well quality good or bad. High quality geothermal well yields high temperature and flow rate, while bad quality geothermal well means fail or scrap. High temperature geothermal field located in volcanic and magmatic rock area is fractured banding reservoir basically. Its well completion quality relies on relationship with deep fault.

2. Geothermal Feasibility Drilling Design Should Select Target Fault

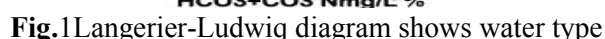
We drilled a successful geothermal well in Muken development zone, Heshan, Guangdong province by invitation service of local developer. The well with depth 1,617 m yields 450 m³/d of thermal water at 51°C of temperature. The drilling site located in central Guangdong province at southwest of Guangzhou city. This over 3,000 km² range distributed large granite intrusion. There is no hot spring manifestation either geothermal well in the region, because no aquifer as potential geothermal



In order to complete developer's entrustment, we carried out prefeasibility and feasibility studies progressively.

Consequent feasibility study carried out detailed geological survey. It found out strata distribution and geological structure. The Kaiping-Hecheng fault is a paralleled fault with the regional Enping-Xinfeng deep fault. It passes through working area and can be as target fault. The result satisfied our basic target.

Total 21 locations of surface water and groundwater were investigated. 15 water samples were collected and sent for chemical detection. Various water types were plotted in Langelier-Ludwig diagram as Fig.2. Some samples showed typical cold water located at right-down corner. However, many samples showed a transitional type which with more components such as SO_4 , Cl and Na usually from geothermal fluid (Fig.1). This indicates that these samples were affected by deep geothermal leaking. The water types of Xinxing hot spring ($\text{HCO}_3\text{-Na}$) and Enping Hot spring ($\text{HCO}_3\text{-SO}_4\text{-Na}$) were plotted also in the diagram. They located at the right-up corner of the diagram. Thus, the transitional types should be mixed origin by cold water with geothermal water in certain proportion. Silica and Fluorine are typical geothermal components usually. The content in groundwater is higher than in surface water in the working area. K-Mg geothermometer and SiO_2 geothermometer were calculated. The ground temperature should be in $40\text{-}50^\circ\text{C}$. It also showed that groundwater is higher than in surface water. This means also deep components have an upward activity.



CSAMT survey was carried out as main geophysical survey. Total 4 profiles were detected. The point's interval is 50m. Total profile's length is 8,000m, detected depth 3,000m. An evident indication of fault showed at the eastern part of CSAMT-4 profile (Fig.2). It should be the Kaiping-Hecheng

fault. Unfortunately, this fault didn't show obvious image at other 3 profiles. It seems that the fault performed sometime strong and sometime weak.

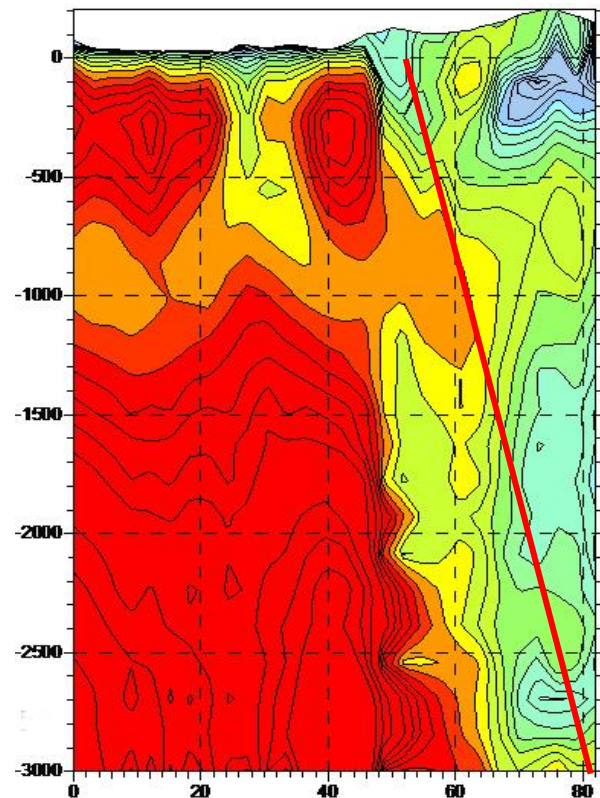


Fig.2 CSAMT-4 profile and interpreted fault

As further verification, Redon and Mercury detections were carried out with point's interval of 10m and total profile's length of 1,520m at the anomaly areas of CSAMT results. Both gases of Redon and Mercury origin from ground fault zone. They are easier to rise along fault and penetrate tight small fracture to reach surface soil. So, it can be used to recognize active fault precisely.

Comprehensive analysis recognized that target fault was passing this development zone. Geophysics interpreted the fault's strike, dip direction and dip angle. Thereupon the best well drilling location was selected. The well drilling was designed to 1,600 m depth. It was expected to touch the target fault at 1,400 m depth. This target fault will own good transmissibility, water content and ideal temperature. This drilling will complete an ideal geothermal well.

Geothermal well drilling faced great challenge. The well was drilled in hard granite body with 216 mm diameter. The drilling was touched target fault at 1,410-1,470 m depth. The drilling penetrated the crushed zone of the target fault. This is the key of success.

3. Drilling Process Should Pay Attention to Predicted Target Fault

During the well drilling process, we have to pay great attention to the predicted target fault. We should tail after if the drilling had entered and had penetrated the fault. There is a certain error for the fault's dip angle by geophysical interpretation. The depth for drilling process touching the fault will have deviation. So, we need tail after the drilling process in order to adjust operation for casing depth and cementing grouting. We also need tail after the penetrated depth of the fault. Initial well drilling design perhaps need adjust in certain degree. When the drilling penetrated target fault for a certain depth we should consider completion of the drilling. Excessive drilling will get reversed result.

We still see the instance described in last paragraph. We used cutting logging, visual inspection and cutting identification by mineral microscope during the drilling process. The important thing is to find sudden loss of circulation fluid timely. Unfortunately, it didn't appear for this drilling. However, the cutting lithological characters changed even in the same granite body, and the drilling footage showed difference. Microscope found also some special cuttings which formed by glued fragments with interspaces. It means the initial granite had been fractured (faulted) and then glued. When drilling in fault zone at range of 1,410-1,470 m it showed very different drilling footage, say daily 10 m record among a daily 1-3 m background. After that the drilling footage recovered into daily 1 m about. It means the drilling has penetrated the fault zone. Therefore, the drilling was finished at 1,617 m depth. Then well flushing and pumping test started over and over again. Finally, the well production exceeded designed target. Relying on drilled fault in granite the well yields 450 m³/d of flow rate with 51°C of temperature at wellhead.

Another example showed that an excessive deep drilling made great reduced yield than initial shallow well. This is a high temperature geothermal well drilled by developer in Xiaoresui geothermal field in Kangding county, Sichuan province.

The developer drilled 10 geothermal wells in the geothermal field until 2013. The highest temperature appears in well ZK201. It is 208°C at well bottom of 267.25m depth. Gushing test got such results: wellhead working pressure 8.5kgf/cm² with working temperature 174°C, total flow rate of steam and water 159t/h. Such yield is suitable for geothermal power generation. Unfortunately, the well casing is short only 65 m with cement grouting. The well depth is also too short as a production well. Geothermal expert suggested to drill a deeper well around 1,000 m depth as production well.

Geothermal Council of China Energy Society (GCES) proposed the developer a further geothermal geological survey around the geothermal field. Because of initial AMT geophysical survey didn't reach deeper depth and the profile extended along fault anomaly, it made no possibility to control main fault zone. So advanced CSAMT (controllable source audio magneto-telluric) geophysical survey was proposed to carry out reaching 3,000 m depth. Then a conceptual model can be established for the geothermal field. This will guide future geothermal development.

The developer complied our proposal. Geophysical team carried out 7 profiles of CSAMT survey. The best well site was selected in north 700 m of ZK201 at western bank of river for 1,000 m deep drilling. Secondly it can be located in western bank of river of ZK201 for 1,000 m deep drilling. Local topography is very difficult for drilling implementation across the river. The developer delayed the deep well drilling until 2016 and didn't move the well site into western bank. The new well ZK206 was drilled still in eastern bank of river separating several meters from ZK201. New well ZK206 completed in 2,000 m depth. Twice rushing tests were carried out at well depths of 1,480 m and 2,000 m respectively. Electric well logging was carried out finally. But it reached a depth of 1,662 m only.

The developer gave us the rushing tests and logging data and requested us for analysis. However, the results showed that an excessive deepened drilling made a reversed result with predicted target.

The comparison of rushing test results for ZK201 and ZK206 showed as table 1.

Table 1 comparison of rushing test results of high temperature wells in Xiaoresui geothermal field

Item	Well ZK201	ZK206 at 1,480m	ZK206 at 2,000m
Measured temperature, °C	174	190	142
Saturated pressure, bar	8.7	12.5	3.85
Measured pressure, bar	8.5kg/cm ² =8.3 bar	8kg/cm ² =7.8 bar	2kg/cm ² =1.85 bar
Saturated -measured, bar	0.4	4.7	2.0
Unsaturated ratio, %	4.6%	37.6%	51.9%

Further calculation could get the comparison of enthalpy of geothermal fluid as table 2.

Table 2 Comparison of enthalpy of geothermal fluid from high temperature well

Situation	Well ZK201	ZK206 at 1,480m	ZK206 at 2,000m
Measured temperature, °C	174	190	142
Measured pressure, bar	8.5kg/cm ² =8.3 bar	8kg/cm ² =7.8 bar	2kg/cm ² =1.85 bar
Saturated temperature, °C	172.1	168.7	117.8
Enthalpy of water (hf), kJ/kg	728	716	495
Enthalpy of steam (hfg), kJ/kg	2043	2054	2208
Assumed steam fraction, %	10	10	10
Enthalpy of total fluid, kJ/kg	932.3	921.4	715.8
Relative compare of enthalpy	100%	98.8%	76.8%

Thermodynamic data from above two tables explains following implications.

1. The thermodynamic result of well ZK206 at 1,480 m depth is inferior than initial ZK201. The thermodynamic result of well ZK206 at 2,000 m depth is inferior than ZK206 at 1,480 m depth. The measured pressure is less than saturated pressure which corresponding to measured temperature. It showed an unsaturated ratio. The increased unsaturated ratio represents a decreased thermodynamic function.
2. initial ZK201 has highest enthalpy. Well ZK206 at 1,480 m depth has decreased enthalpy than ZK201. Well ZK206 at 2,000 m depth has decreased enthalpy than ZK206 at 1,480 m depth. It is about 76.8% of initial ZK201 only.
3. Above data explained that excessive deepened drilling has penetrated target fault. We have expounded in previous development strategy report that the main fault dips towards west. Existing well drilled at eastern side of the fault. Deeper drilling will lead the fault zone to be penetrated. The well will deviate with the fault, the deeper the more deviation. It will be necessity for yield falloff.

By consequent electric well logging such concept was verified again. The well casing of ZK206 was down to 200 m depth. The electric well logging measured a range between 200 m and 2,000 m. But actually, the logging reached a depth 1,662 m only. The comprehensive logging item includes temperature and pressure, and further more for resistivity, self potential, γ radioactivity, interval transit time etc. The logging was carried out twice for upwards and downward respectively. And the logging was carried out for static and dynamic situations respectively.

The temperature and pressure logging showed following features.

1. The static and dynamic temperature curves showed calescence rapid first then gentle, then decrease. This is an upward arc curve. The highest well temperature existed in depth of 1,011.8- 1,016.56 m. The well bottom temperature (1,662 m) has decreased 14.50-14.83°C than the maximum temperature.
2. The static and dynamic pressure curves showed a homogeneous increase. The dynamic pressure has an increased gradient at shallower depth for less than 800 m. when deeper than 800 m the pressure curve is almost a slope line.
3. The static well bottom temperature is 2.6°C higher than dynamic measurement. The static well bottom pressure is 3.14 bar higher than dynamic measurement.
4. The static and dynamic temperature curves have same variation (Fig. 3). They showed the same breakpoint between 800-1,100 m depths. Two big breakpoints are in depths of 1,027 m and 1,082 m respectively. Their temperature decreased 2°C more. In addition, there are two small breakpoints at depths of 870 m and 993 m respectively. Their temperature decreased about 0.5°C. These breakpoints of temperature explained that downhole geology controlled the temperature dropping. It should be the drilling penetrated a fault and entered the lower position.
5. The minimum gradient of dynamic well temperature curve represents a water convection section there. While the maximum gradient of dynamic well temperature curve represents a

conduction section, means waterproof well wall. The minimum gradient is 0.33°C at depth of 800-900 m and 0.28°C at depth of 900-1,000 m respectively. Under such depth the well temperature becomes decrease and show a negative gradient. There are another two small gradients at depths 1,100-1,200 m and 1,300-1,400 m respectively. These 4 locations are aquifer fractures. The main fractures are the shallow section.

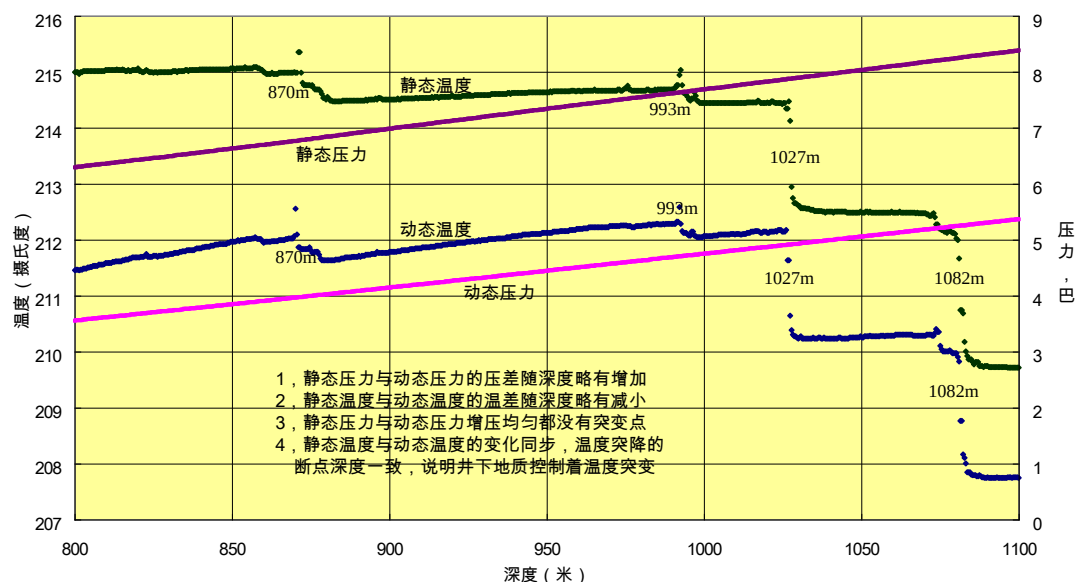


Fig. 3 Dynamic and static temperature and pressure curves in 800-1,100m depth of ZK206

In conclusion, the well ZK206 was deepened into 2,000 m has obviously penetrated target fault and entered lower section. It made temperature decrease and yield decrease.

Well drilling is an irreversible procedure. Whether existing well ZK206 at 2,000 m depth could return to previous function (for example 1,480 m depth)? It is impossible. Because of latter drilling has made that new cuttings jammed into shallow fractures during upward movement of drilling fluid circulation. It is very difficult for recovering by well washing operation.

4. Conclusions

Deep fault has very important function for the origin of hydrothermal type geothermal system. Well drilling design when feasibility study should select a target fault. During the well drilling process should pay attention to the predicted target fault. Be careful if the drilling has reached the target fault and penetrated the target fault. These measures will insure maximum success of geothermal well drilling to yield highest thermal energy and fluid.

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