Development, Application and Prospect of Comprehensive Logging Technology in Geothermal Drilling

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Abstract. With the continuous acceleration of the exploration and development progress of geothermal (hot dry rock) resources, the workload of geothermal resource investigation and drilling has increased sharply, but the research and application of comprehensive logging technology is relatively lagging behind in China. This article analyses the response relationship of various logging data to geothermal geological conditions item by item, introduces the development and application status of logging technology at home and abroad, and takes HR-1 well as an example to give a brief introduction and analysis of the comprehensive logging technology. Theory and practice have proved that the comprehensive logging can provide an important reference and scientific basis for the evaluation of the potential of geothermal reserves. The development and application status of the geothermal logging technology in China can no longer meet the needs of geothermal resource exploration and development. It is imperative to carry out in-depth research on geothermal logging technology and further increase its application.

1 Introduction

Geothermal resources are a kind of renewable, carbon-free clean energy. With the rapid development of the economy, facing the urgent need of dual-carbon goals, the development needs of China on geothermal resources are increasing rapidly. The exploration process of geothermal resources mainly includes the stages of geophysical exploration, geochemical exploration, drilling investigation and evaluation. The geophysics, geochemistry and other exploration methods are important for delineating the key target areas, but drilling is the only method to accurately obtain the geological parameters of deep geothermal formations. In recent years, a large amount of funds has been invested in the exploration of high-temperature geothermal resources in China, a number of key target areas for high-temperature geothermal and hot dry rocks are delineated, and a number of geothermal resource survey and drilling projects are organized and implemented. The core samples and logging data obtained through geothermal drilling are important basis for comprehensive evaluation of thermal reservoir characteristics and reservoir modelling analysis [1,2]. However, because geothermal logging has not been paid enough attention, the analysis of logging data in the drilling process is not timely enough, resulting in the lack of a large number of important data, which has a very negative impact on the accuracy of geothermal resource evaluation.

2 The response of logging data to geothermal geological conditions

Logging technology is widely used in oil and gas drilling projects, which is very important for discovering reservoirs and arranging drilling plans. And it is of great significance to reservoir research and evaluation. In geothermal drilling, logging technology also plays an important role in the investigation and potential evaluation of geothermal resources [3].

The logging data can be used to effectively judge the lithology, stratification, fracture development, geothermal gradient, water and gas characteristics and other important information of the formation [4]. Timely and accurate analysis of the logging data can be used to effectively discover and identify reservoirs, provide guidance for the follow-up drilling plan, improve the accuracy and efficiency of the geothermal reservoir evaluation.

In addition, the interpretation of completion logging data often requires a large amount of regional drilling data as a reference, while the previous geothermal drilling data is usually very scarce, which makes the accuracy and reliability of the interpretation of completion logging is difficult to guarantee. Analysing

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completion logging data in combination with comprehensive logging data can further improve the accuracy and reliability of the research and evaluation result of geothermal reservoir.

In addition to the significance for geothermal reservoir evaluation, comprehensive logging data also has a strong guiding significance for drilling project. By analysing comprehensive logging data, the lithology and temperature changes of formation can be discovered in real time, which can provide a basis for the subsequent drilling, well completion, testing and other plans. By recording the flowrate of drilling fluid inlets and outlets, it is possible to accurately locate water inrush or mud loss formations, which is also an important reference for complex formation treatment and cementing operation. through logging data, formation pressure can be analysed, so as to prevent blowout accidents in advance. With mud logging data, formation pressure can be analysed in real time, so as to prevent blowout accidents in advance.

2.1 Cutting logging

Cuttings logging mainly includes lithology naming, layering depth, and lithology description. Its main work is to collect rock samples, calculate the depth and describe the lithology [5]. Through the cuttings, the stratigraphic sequence, buried depth, thickness, and lithological characteristics of the formations can be accurately identified, the structural deformation of the formation can be found, and the geophysical survey results can be verified and revised to guide subsequent drilling operations, which can provide greater probability for reservoir identification and discovery.

2.2 Mud logging

The main data of drilling mud includes drilling mud properties, blowout, kick, lost circulation, and inlet and outlet temperature. The mud parameter includes density, viscosity, loss, sand content, and static shear force. The changes and anomalies of drilling fluid parameters have important guiding significance for deep formation hydrogeological research.

(1) Affected by the rock and fluid in the formation, the properties of the drilling mud will change; therefore, the lithology of the formation and the characteristics of the fluid contained in the formation can be judged by the changes in the properties of the drilling mud. The lithology, pressure, fluid content of formation are important data for the evaluation and research of geothermal reservoir. It is essential for the accuracy of the research of geothermal reservoir to detect and analyse the changes in drilling mud properties in real time.

(2) The leakage and water outflow of the formation can be reflected by the inlet and outlet flowrate of drilling mud effectively. By measuring the inlet and outlet flowrate, the leakage and water outflow of the formation can be calculated accurately, so as to calculate the water content, pressure and fracture development of the formation. Leakage is the most common downhole complications in geothermal wells. The geothermal reservoir can be accurately judged and located through the temperature change and leakage of the drilling mud circulation. After the reservoir is discovered through logging, the reservoir test and the next operation plan can be discussed and decided in time. Affected by the heat transfer between the upper and lower layers with the drilling mud in the well, it is difficult to accurately locate the top and bottom depths of the reservoir only by completion logging. The method of identifying reservoirs by mud logging is more time-efficient and accurate than completion logging.

(3) Formation thermal anomalies can be detected in time through temperature changes at the inlet and outlet of the drilling mud. The heat transfer between the drilling mud and formation occurs during the mud circulation process, the temperature changes of the drilling mud is an important indicator of the temperature change of the downhole formation. The change of the geothermal gradient can be accurately calculated by the dynamic change of the drilling mud [6-8], which is an important basis for locating the reservoir.

(4) The change in the resistivity of the drilling mud is manifested as an abnormal response of formation. Studies have shown that the hydrochemical characteristics of the fluids in geothermal reservoir have a good correlation with the characteristics of geological structural units and geothermal reservoirs [9]. The content of each ion at a certain point in the geothermal well is a comprehensive reflection of the conditions of the replenishment, streamflow, and seepage of the fluid in the reservoir, and is related to its structural location, fracture nature, lithology, burial depth, temperature and other factors [10].

2.3 ROP logging

The ROP Logging data mainly includes well depth, footage, rate of penetration (ROP), weight on bit (WOB), suspending weight, drill pipe rotation speed, torque, drilling tool assembly, drilling bit, mud flowrate, standpipe pressure, etc. Drilling parameters logging is also called engineering logging [11-13]. Drilling parameters such as WOB and torque characterize the drill ability and integrity of the formation. By comparing the drilling efficiency under the same drilling parameters, the difference in the drill ability of the formation can be distinguished, so as to determine the changes in lithology, structure and other aspects along the depth of the well [3]. At the same time, changes in drilling parameters such as WOB and torque can also effectively reflect the development of the cracks and fractures in formation, which play an important role in the analysis of reserves and productivity of geothermal reservoirs.

The Dc-exponent is usually used to predict the formation pressure in oil and gas drilling. The Dc-exponent of the formation can be calculated by parameters such as WOB, ROP, drill pipe rotation speed, bit diameter, drilling fluid performance, etc., and the change of formation pressure can be derived from the Dc-exponent [14,15]. There are usually very few existing drilling data in the geothermal resource exploration block, and the formation pressure is usually unknown. There is no doubt that formation pressure is very important to ensure drilling safety, and it is one of the important parameters in the evaluation and development of geothermal reservoirs.

2.4 Core logging

Core logging is a process of analysing, testing, and comprehensively researching drilling cores. Cores can provide more accurate geological information than cuttings, including the thermal conductivity, heat generation rate, and geochemical characteristics of rocks in different formations, provide a scientific basis for the geothermal structure and heat source mechanism research of the reservoir. In some important formations, it is necessary to carry out sidewall supplementary coring, to verify the analysis results of the mud logging and completion logging more accurately, and to conduct more accurate and scientific evaluation of the reservoir.

2.5 Gas logging

As one of the important works in the oil and gas drilling process, the gas logging is to collect the gas in the drilling fluid through a degasser and perform component analysis. Its main purpose is to identify and judge oil and gas formations by analysing the gas composition and content in the drilling mud, and to detect the harmful gas composition and content at the same time to ensure drilling safety. In the process of research and evaluation of geothermal reservoirs, the analysis of the composition and content of gas in the formation is equally important for the study of the reservoir characteristics [16].

3 Application of comprehensive mud logging technology

As a necessary work, comprehensive mud logging technology is widely used in oil and gas drilling, and plays an important role in the process of oil and gas resource exploration and evaluation. The importance of comprehensive mud logging for the exploration and evaluation of geothermal reservoirs has been realized by European and American countries a long time ago. In these countries, comprehensive mud logging runs through the entire process of geothermal drilling (or dry hot rock drilling), reservoir reconstruction, enhanced geothermal systems construction, and reservoir development. At present, the domestic research and application of comprehensive mud logging technology in geothermal drilling is still in its infancy, and a complete research, application, and evaluation system based on comprehensive mud logging has not yet been formed.

3.1 The application of comprehensive mud logging in geothermal exploration abroad

Comprehensive mud logging has been used in geothermal drilling for a long time in European and American countries. In the early days, Italy proposed the method of geochemical logging, which is essentially to study the changes in the chemical composition of the drilling mud during the drilling process to determine the possible thermal reservoir. Practical application results show that this method is very effective [17]. The combined analysis of mud logging and completion logging data was applied in the Soultz and Rittershoffen geothermal fields in France, which provided scientific basis and guidance for the later construction of artificial reservoir reconstruction [18,19]. Iceland is currently the country with the highest degree of geothermal development and utilization. Comprehensive mud logging technology has played an important role in the exploration and development of Iceland's geothermal resources [20, 21].

The USA has applied comprehensive mud logging technology very early in hot dry rock development, and the selection of logging technology and equipment is one of the important works of geothermal drilling engineering design [22]. In addition to ground logging equipment, downhole geological logging while drilling tools are also used in the geothermal drilling process [1, 20]. The parameters recorded by the logging equipment mainly include drilling depth, drilling time, drilling pressure, drill pipe rotation speed, torque, inlet and outlet mud flowrate, inlet and outlet mud temperature, H_2S gas content, standpipe pressure, annulus pressure, mud loss, drilling fluid parameters, etc. The temperature resistance ability of downhole logging while drilling tools can reach above 150℃, and the acquired parameters mainly include the temperature, pressure, flowrate, fracture distribution of the reservoir, and the radioactivity and electrical properties of the rock [1, 22, 23]. Taking the Geysers geothermal field in California as an example, the gamma data collected by the downhole logging tool played an important role in the research and evaluation of the volcanic fracture [24].

Similarly in the Fenton Hill geothermal field, comprehensive mud logging technology was applied during the processes of drilling, fracturing test, connection test, water injection test, and production test, which provided a good support for the development of geothermal resources. During the drilling process of Well GT-2, the loss analysis based on logging data provided a sufficient basis for judging and locating the lost section, and provided effective guidance for cement plugging operations. Before the hydraulic fracturing test of the GT-2 well, the selection of the 6 fractured sections was entirely based on the analysis of the comprehensive mud logging and completion logging data. During the connection test between Well GT-2 and Well EE-1, logging technology was used to monitor and analyse the injection flowrate of Well GT-2 and the return flowrate of Well EE-1. During the connection test between Well EE-3A and Well EE-2A, the chemical logging of drilling mud was also used to monitor and analyse the whole process. During the water injection test of Well EE-3A, the injection time, pressure, and flowrate were recorded by the logging equipment, and the working status and time of the downhole packer were judged through related data. Continuous steady-state observation of production data was carried out during 1992-1995, the data such as pressure, flowrate, temperature of injection and production well were completely recorded, which has provided important contributions for scientists to carry out research on geothermal energy mining technology [25].

3.2 Application of logging technology in Chinese geothermal development

With the continuous acceleration of the exploration and development of geothermal resources, the invest in geothermal drilling is increasing year by year, and the recognition of the comprehensive mud logging in Chinese geothermal resources exploration has gradually increased.

In 2014, the former Ministry of Land and Resources promulgated the "Technical Regulations for Geothermal Drilling" and Tianjin City issued the "Regulations for Mid-low Temperature Geothermal Drilling"[11, 12]. The technical regulations set clear requirements for logging work. On November 4, 2019, the National Energy Administration issued the "Geothermal Logging Technical Specifications", which will be implemented on May 1, 2020. The issuance and implementation of this specification is a milestone in the application and development of geothermal logging technology. In addition to the definition of the logging items and series, the specification also explains the work content and requirements of each logging item [13].

However, in most of the current geothermal drilling projects, the logging work still stays at the cuttings logging and simple hydrological observation level [3, 24]. Although the specification has been implemented in 2020, there has not yet been a fully equipped geothermal logging equipment and technical system, and there is no way to talk about geothermal reservoir evaluation methods based on the comprehensive mud logging technology. In the current geothermal drilling regulations, there are still the problems of inconsistent parameters and requirements for logging work, which also fully shows that the recognition of the comprehensive mud logging has not been unified, and the attention of it is far from enough.

Although the specification has clarified the geothermal logging items and technical requirements, due to the technology and cost factors, the application cases of comprehensive mud logging in actual geothermal drilling project are extremely rare; even if a drilling project is equipped with logging equipment, there is still a lack of systematic analysis methods to interpret the logging data in real time and efficiently, which severely restrict the development of geothermal logging and reservoir evaluation technology.

4 Application case of geothermal logging technology

Well HR-1 is a geothermal exploration well deployed by the China Geological Survey in Guangdong Province. A comprehensive logging system was applied Well HR-1, which mainly included cuttings logging, core logging, ROP logging, drilling mud logging, production test logging. It provided important data and scientific basis for the drilling and reservoir evaluation.

4.1 Cutting logging

During the drilling process of Well HR-1, a total of 588 packs of cuttings were collected. Based on the analysis of cuttings, the formations were accurately divided, and the regional thermal metamorphism sequence from shallow to deep was clearly recognized. At the same time, the well structure and coring plan were optimized according to the changes in the formations. Take the No. 1-6 cuttings obtained from the 2410m-2415m depth as an example (Figure 1). No. 1~3 are monzonitic granites with dense lithology and strong abrasiveness; No. 4-6 cuttings have darker colour and low hardness, which is determined to be alteration hornfels according to mineral analysis, indicating that the lithology of the formation is dominated by altered minerals after the depth of No. 4 cutting.

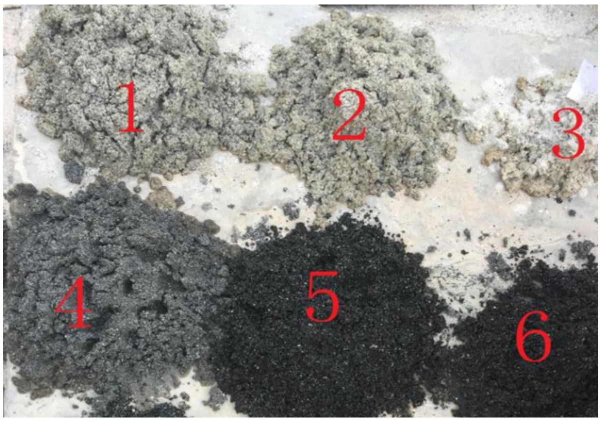

Fig. 1. 2410m-2415m cuttings samples from Well HR-1

4.2 Core logging

The coring plan of Well HR-1 was arranged based on the changes in the lithology of formation. There were 13 coring trips in total. The cores taken are extremely representative, which is of great significance to the study of regional geological structure and geothermal reservoir. For example, when drilling to the depth of 2913m, the ROP is unstable and the drilling tool bouncing is severe. According to the core taken from 2917m-2920m (Figure 2), it can be seen that the formation fractures are developed, and fluid crystalline minerals can be seen on the cores.

Fig. 2. 2917m-2920m cores of Well HR-1

4.3 Mud logging

The Well HR-1 locates the temperature abnormal section and water content formation through the mud logging. And the leakage of drilling mud was recorded in detail and accurately. When drilling to the depth of 2572m, a sudden loss occurred, the leakage rate was 8 cubic meters per hour.

The sealing while drilling was carried out and succeeded after a total of 55 cubic meters of mud was lost. The second severe mud loss occurred at the depth of 2777.12m, the drilling mud lost return. After all possible methods failed, the drilling mud was forced to be changed to water. From the depth of 2777.12m to 3006.9m, a total of 1399.8 cubic meters of drilling mud and 7922.2 cubic meters of water were pumped into the well. This loss accident showed that fractures of the formation from the depth of 2777.12m to 3006.9m are well developed.

4.4 ROP logging

The drilling time of the upper granite formation ss about 50-70min/m, then it suddenly decreases to 13-20min/m when drilled to the depth of 2413m, the WOB and standpipe pressure begins to change significantly, and the temperature of outlet drilling mud gradually increase. According to the completion logging data, the resistivity of the depth of 2413m-2420m is reduced from 1000Ω·m to 140-150Ω·m, and the natural gamma is reduced from 400API to 20-30API. The temperature curve of completion logging shows a positive anomaly. The acoustic travel time increases slightly, which indicates that the bottom layer of the section from the depth of 2413m-2420m is a typical high-temperature altered formation. Analysis of the cuttings logging, mud logging, ROP logging and completion logging data shows that the fractures of the formation in this section are developed, which proves that the formation must be a good water-producing layer.

4.5 Production test

A total of 6 production tests are carried out in Well HR-1, and the temperature, flowrate, and pressure data are recorded real-time (Figure 3), which has provided an important scientific basis for the evaluation, productivity analysis, and economic evaluation of the geothermal reservoir [26].

Fig. 3. Data collection system of thermal storage test of Well Huire-1

5 Conclusions and prospects

Application practices at home and abroad have proved that comprehensive logging technology can provide an important scientific basis for the evaluation and research of geothermal reservoirs.

At present, the research and application of comprehensive logging technology in geothermal exploration is still in its infancy in China, and practitioners still have insufficient awareness of the importance of it. It is urgently needed to further increase the investment in the research and application of geothermal comprehensive logging technology.

With the rapid development of information technology, the technical problems of integrating geophysical prospecting, drilling, comprehensive logging, and completion logging data no longer exist. The concept of integrated exploration and development system has been put forward in the field of oil and gas exploration. The development of an integrated exploration and development system is of great significance, for improving the of the exploration and promoting the development and utilization of geothermal resources.

The development of an integrated exploration and development system is of great significance, which will help to improving the scientificity and efficiency of exploration, and provide an important impetus for the development and utilization of geothermal resources.

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