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CHEMICAL LOGGING OF
GEOTHERMAL WELLS

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INTRODUCTION

The growth of the geothermal industry has created a need for techniques to be used during drilling operations that will assist in the determination of well depth, casing location, and well development. Important contributions to these needs are the geophysical logging, lithologic logging, and core drilling techniques developed by the petroleum industry. Other exploration and reservoir evaluation techniques were developed by the petroleum industry, universities, and governmental agencies. However, very little development was specific to geothermal well drilling and exploration. The chemical logging method described in this report was developed for geothermal application. It is a technique that is carried out during the drilling operation.

Chemical logging began as a "need to know" situation during the drilling of well RRGE-3 at the Raft River Geothermal Site in southcentral Idaho. Samples of the drill fluid were collected for chemical analysis at certain times during the drilling operation. Analysis was performed to determine the concentration of chemical geothermometers and other indications of geothermal water. The results of the test were significant enough to plan a more complete test on the next well-drilling operation scheduled at the Raft River Geothermal Site. This report describes the chemical logging study of three geothermal wells. The sampling of the drill return fluid for the determination of certain borehole conditions is not unique. Lithologic logging is routine for most major drilling operations. Drill water, inlet and outlet temperatures, pH, flow rates, and certain gasses are the parameters most often measured on the drill fluid. The most important phase of the operation is the geological evaluation of the drill cuttings to study the borehole lithology. Elders, Hoagland, and McDowell [1] used drill cuttings to determine the hydrothermal alterations in the borehole

geology; with this information, they would predict the observed temperature of the completed geothermal well. These applications could be considered geochemical logging. However, in both of these cases, the drill cuttings were analyzed; not the drill water. Chemical logs are prepared by analyzing the drill return fluid and graphically plotting the concentrations of the analyzed chemical species to the drill depth. It is an empirical technique for which few theoretical studies have been made at this time.

Changes in the chemical composition of the drill fluid result from dilution by the drill mud and the water-bearing strata penetrated by the drill string. Figure 1 is a cross-sectional view of a drill string that has penetrated several water-bearing strata. Drilling fluid is pumped through the drillstem and bit. The fluid then returns to the surface between the drillstem and the wall of the borehole carrying the drill cuttings with it. Should water-bearing stratum be penetrated, it contributes water to the drilling fluid. This dilutes the drilling fluid and causes variation in its chemical composition. Generally, after the drill string passes through the water-bearing stratum, the drilling mud or sediments in the drill water form a mud cake on the walls of the borehole. However, if the flow from the stratum is too great and mud cake does not seal it, the incoming water will change the chemical composition background of the drilling fluid. The determination of the change in chemical composition of the diluted drill fluid and its separation from the chemical background contributed by the drill fluid, drill mud, and other aquifer leakage is the essence of the chemical log.

The ratios of chemical species found to be useful in geochemical evaluations by other researchers¹ [3] were used to develop chemical logs. Presently these logs are being correlated to the geophysical logs. The correlations

have already revealed that the ratio of the concentrations of calcium and bicarbonate ions can be used as a relative temperature indicator.

Other applications of chemical logs are being studied. Correlation between the logs of the ratios of chemical species and the geophysical logs are being evaluated. It is evident that chemical logging can be a useful tool in the drilling of geothermal wells and the exploration of geothermal resources.

EXPERIMENTAL PROCEDURE

The sampling procedure used in this study required that the samples be collected from the drill return fluid at specified intervals of change in drill string depth. The drill fluid is pumped from the mud pit through the drill string and returns up the borehole between the borehole walls and the drill stem. As it returns to the drill pit, it carries the drill cuttings out of the borehole. Drill fluid samples are collected at the point where the drill return fluid flows into the mud pit. For this study, samples of the drill fluid returns were collected at 15-120 m intervals of drilling depth. Samples of 4-5 l were collected during the period of the drilling operation when drilling mud was used to assure an adequate sample. Once the borehole was cased and only water was being used for a circulating medium, one-liter samples were collected. The drilling mud and other residues were separated from the water sample by centrifuging and filtering. In most cases, the centrifuge would not settle the gelatinous mud suspension. Filtering with a coarse filter was the method most often used. The samples were analyzed for conductivity, pH, alkalinity, Cl^- , F^- , Ca^{++} , and SiO_2 by the procedures described by Brown, Skougstad, and Fishman [3].

RESULTS, CHEMICAL LOGS

Before describing the results of the chemical logging study, types of aquifers and the chemical composition of aquifer fluids will be defined. The deep geothermal aquifer system at the Raft River geothermal site is a fracture and fault-dominated system. The fresh-water and shallow geothermal aquifers are permeable systems. Also in the Raft River valley, as in other geothermal areas, there are fresh-water aquifers affected by geothermal water intrusion. Table 1 shows the effect of these variables on the chemical composition of the drilling fluid. Geothermal water was used for drilling fluid in this example because most of the geothermal wells at the Raft River Geothermal Site were drilled with geothermal water as the drilling fluid.

The general effects to the drilling fluid when the drill mud is added is a decrease in the concentrations of most of the analyzed chemical species. Increases in alkalinity and pH result from adding drilling mud to the drilling fluid. Chemical composition changes from geothermal water intrusion are not definable except for the increase in Ca-HCO_3 ratio and decrease in alkalinity. Fresh-water intrusion into the drill water would generally increase hardness and alkalinity and decrease F^- , Cl^- , conductivity, and the calcium-bicarbonate ratio. A geothermal and fresh-water mixture intrusion into the drill water would result in increases in the calcium-bicarbonate ratio. The changes in the other chemical species would not be definable. Table 1 can be used as a guideline for the interpretation of the chemical logs.

A chemical log can be prepared by plotting graphically the concentrations of the analyzed chemical species to the drill string depth. The resulting log is a profile of the chemical change taking place in the drill fluid during the drilling operation. This information is very useful in evaluating the water-bearing stratum penetrated by the drill string. Figure 2 is an example of this type of log. Evaluation of this log shows the influence on the chemical

composition of the drill fluid by a fresh-water aquifer. At 488 m of depth there are sharp increases in the alkalinity and hardness and sharp decreases in the F^- and SiO_2 concentrations. This would be a typical change in chemical composition when fresh water dilutes the drilling water. However, the increase in chloride ion concentration and conductivity would indicate the fresh-water aquifer had geothermal water intrusion. The production zone of a geothermal aquifer was penetrated at 1280 m. Due to the drill fluid being geothermal water similar to that in the aquifer, only small changes were observed in the drill fluid chemical composition. There was a small increase in SiO_2 concentration and a small decrease in conductivity. The decrease in alkalinity concentration was the only large change detected at this depth. However, these and many other interpretations could be made from this type of chemical log. Concentration changes in geothermometers such as SiO_2 can be used to determine relative aquifer temperatures. Conductivity can be used as an indicator of water quality. All of these parameters could be determined during the well drilling operation.

RESULTS, CALCIUM/ HCO_3 CHEMICAL LOGS

Chemical logs of the ratios of the analyzed chemical species were evaluated. Chemical ratios used to indicate hydrothermal alteration and geothermometers were studied. From these studies, it was revealed that by taking the ratios of the concentrations of the calcium and bicarbonate ions and plotting them graphically to depth that the resulting chemical log was similar to the temperature log of a geothermal well. The study also showed that as the drill approached the geothermal aquifer, the calcium-bicarbonate ratio increased causing the resulting log to be displaced uphole to the temperature log. This displacement appeared to be due to the leakage of diffusion of the hot water from the aquifer. The uphole displacement varied between 25-120 m for the wells tested. It appears to be a function of the permeability of the material above the geothermal aquifer. This

characteristic of the calcium-bicarbonate ratio for anticipating when the drill is approaching a geothermal aquifer, combined with the information on the permeability of stratum already penetrated furnished by the mud logger, could be useful in determining the depth of the well casing.

The first program designed specifically for the chemical logging of a well was conducted on well RRG1-6 at the Raft River Geothermal Site. The purpose of the program at this time was to chemically characterize the aquifers penetrated by the drill string. Samples were collected at every 120-m interval of drill string depth to a depth of 911 m and then every 60 m to total depth. When the well was completed, studies were made of the chemical and geophysical logs. Comparison of the calcium to bicarbonate ratio to the temperature log revealed that they were similar. Figure 2 shows the similarities of these logs. Also it shows the displacement of the calcium-bicarbonate log to the temperature log which is about 60 m uphole. This means that the chemical log anticipated the geothermal aquifer 60 m before the drill penetrated it.

The evaluation of the chemical logs on well RRG1-6 indicated a need for further verification. This was accomplished by chemically logging the next well drilled at the Raft River Geothermal Site (RRGP-5). Also, comparison of the chemical logs to the geophysical logs indicated the need for increasing the sampling of intervals to increase the resolution of the chemical log.

The chemical logging procedure for the next well-drilling operation was designed as follows:

- (1) Sampling intervals were to be 120 m until changes were observed in the chemical log, indicating increasing temperature.
- (2) When increasing temperature was detected, the sampling interval was to be 60 m.

- (3) Samples were to be collected whenever the driller detected structural changes during the drilling operation.

The resulting chemical log in which all the chemical species analyzed were plotted is shown in Figure 2. The calcium-bicarbonate chemical log is shown in Figure 3. Evaluation of the calcium-bicarbonate log reveals a sharp increase in temperature at 1220 m of depth. This increase in the calcium to bicarbonate ratio was observed until the drill string reached 1280 m of depth. At this depth, a high flow of hot water was observed. The flow rate was estimated to be approximately 4100 l/m. This caused the original drill water to become so diluted with the water from the aquifer that only small chemical changes would be observed in the chemical logs. The aquifer water from this depth to total depth washed away the chemical profile of the well. The lower part of this borehole was lost when a concrete plug was set at 1051 m depth to install the well casing. After the well was cased and re-entry was made with the drill string, they were unable to drill out the concrete plug. Sidetrack drilling was initiated at the top of the plug. The second leg of the borehole either did not penetrate the high-flow aquifer penetrated in the first leg of the borehole or the fractures were sealed with concrete. Due to this, little geophysical logging was accomplished. The second leg is shown as Leg B in Figure 5. It is notable that the chemical log of Leg B does indicate the penetration of a narrow, hot-water-bearing aquifer which later flowed at about 800 l/m with a maximum temperature of 123°C.

Another variation in the calcium-bicarbonate log pertinent to the fluids definition of the borehole was observed at 488 m of depth. The presence of a fresh-water aquifer at this depth was discussed previously. The increase at this depth of the calcium to bicarbonate ratio could be an indication that this water was influenced by upwelling from a geothermal aquifer.

Figure 5 shows the calcium-bicarbonate chemical log of the next well-drilling operation. This was the redrilling of well RRG1-4 at the Raft River Geothermal Site. The object was to convert an injection well into a production well. The sidetrack drilling started at 565 m depth and the total depth of Leg A was 1650 m. To improve resolution, samples were taken at 15-m intervals with the exception that in areas where the driller detected structural change, this interval was reduced to 8 m. To evaluate the chemical log as a rapid turnaround time tool, the calcium-bicarbonate chemical log was kept current with the drilling progress. The object was to detect any significant temperature changes to determine if the drill string was approaching an aquifer. At the depth of 1520 m the drill string encountered a hard stratum prior to the penetration of a narrow, low-producing, hot-water aquifer. The calcium to bicarbonate ratio began to increase when the drill reached the hard stratum. It continued to increase as the aquifer was penetrated and decreased after the drill passed through the aquifer. The driller noticed the change in drilling rate approximately 10 m before the drill penetrated the aquifer. This situation was repeated at 1580 m in depth. The combined flow of the two aquifers was about 135 l/m, with water temperatures above the boiling point.

Another geothermal aquifer was penetrated by the drill between 700 and 870 m of depth. The calcium-bicarbonate log increased sharply through this area. This interpretation was notable for two reasons. One was that drilling mud was being used for drilling at this time. So the drill fluid had to be separated from the drilling mud to be analyzed. The background chemical composition of the drill fluid is changed by the presence of the drilling mud. This can be seen in Figure 5 by comparing the calcium to bicarbonate ratio before and after casing. The second reason was the comparison of the chemical

log to the lithologic log. The section of the log where high calcium to bicarbonate ratios were experienced (between 700 and 870 m) corresponds very well to the increase in sandstone shown on the lithologic log. This sandstone stratum was verified to be an aquifer by geophysical logging. The conductivity is also plotted on the log in Figure 5 to show the water quality of the aquifers penetrated by the drill string. These conductivity values were found to compare very well with the conductivity values determined from the flow tests of these aquifers. It is important to note that the resolution and the quality of the chemical log of well RRGP-4A was improved by the closer sampling intervals.

CONCLUSION

The series of chemical logging studies conducted during the drilling operations at the Raft River Geothermal Site were important to the development of the method. The purpose of the study was to develop chemical logs of good resolution that could be useful as a support tool to the drilling operation. It also assisted in the correlation of the various geophysical logs. It defined chemical composition of aquifer fluids and developed chemical profiles of the borehole. The results of these studies showed these goals were realized.

The quality of the chemical logs is defined here as the ability to correlate accurately chemical concentration changes to definite borehole depths. This is the resolution of the log and is dependent on the size of the sampling interval. The 16-m sampling interval used in chemically logging well RRGP-4A was adequate to produce a log of good resolution. However, when comparing specific sections of the chemical log to a continuous geophysical log, the chemical log is difficult to correlate if the comparable section of the geophysical log is small. This problem is being considered and some potential solutions will be studied in future drilling operations.

The ability of the chemical log to furnish support to the drilling operation was evident during the drilling of RRGP-4A. Here the calcium-bicarbonate chemical log was used to determine if the drill string was approaching a geothermal aquifer. Although the production of the well was small, the chemical log did indicate the two small, hot water-bearing stratum prior to penetration by the drill string.

REFERENCES

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2. Ellis, A. J., and Mahon, W. A. J., Chemistry and Geothermal Systems, Academic Press, New York, 1977, pp. 144-152.
3. Brown, Eugene, Skougstad, M. W., and Fishman, M. J., Techniques of Water-Resources Investigations of the USGS, Washington, DC, 1970, Book 5, Chapter A1, Part IV.

TABLE 1--Variables to the chemical composition of geothermal water used for drilling fluid.

Variable	$\frac{[Ca^{++}]}{[HCO_3^-]}$	F ⁻	Cl ⁻	Ca ⁺⁺	SiO ₂	pH	Conduc- tivity	Alka- linity
Drilling Mud	ND	-	-	-	-	+	-	+
Geothermal Water Intrusion	+	+	+	+	+	ND	+	-
Fresh Water Intrusion	-	-	-	+	-	ND	-	+
Geothermal Contaminated Fresh Water Intrusion	+	ND	ND	ND	ND	ND	ND	-

+ Increased concentration of this species in the drill water.
 - Decreased concentration of this species in the drill water.
 ND Not definable.

LIST OF FIGURES

Figure 1. Drilling fluid dilution by a geothermal aquifer.

Figure 2. Chemical log of all analyzed chemical species for well RRGP-5.

Figure 3. $\frac{[Ca^{++}]}{[HCO_3^-]}$ chemical log and temperature log for well RRG1-6.

Figure 4. $\frac{[Ca^{++}]}{[HCO_3^-]}$ chemical log for well RRGP-5.

Figure 5. $\frac{[Ca^{++}]}{[HCO_3^-]}$ chemical log for well RRGP-4A.

FOOTNOTE

1. Harold L. Overton, Senior Staff Engineer, Cer Corporation, Las Vegas, NV, private communication.