The Application of the Acoustic Televiewer to the Characterization of Hydraulic Fractures in Geothermal Wells

by

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Abstract

Two wells in the Raft River, Idaho, geothermal reservoir were hydraulically fractured in an attempt to increase productivity. The U.S. Geological Survey made geophysical logs of these wells both before and after fracturing. A high temperature version of the acoustic televiewer was the most useful tool for obtaining data on the location, orientation, and character of the fractures produced.

In RR-4 (Raft River Well 4), a hydraulic fracture was logged with the televiewer from a depth of 4,682.5 to 4,873.9 feet, a total of 191.4 feet. This fracture was largely due to the propping and possible extending of a previously logged fracture which is thought to have been accidentally induced during drilling or testing. The fracture is essentially vertical, strikes an average of N72°E, and has an average apparent maximum width of 0.4 inch. The fracture is complex, branching, or en echelon, and in one place curves to parallel a natural fracture.

In RR-5 (Raft River Well 5), a new hydraulic fracture was logged from a depth of 4,562 feet to approximately 4,705 feet, a vertical extent of approximately 143 feet. There is no evidence that this fracture follows a pre-existing break except for intervals where the orientation is affected by natural fractures. The hydraulic fracture is nearly vertical, strikes an average of N29°E, and has an average apparent maximum width of 0.6 inch. The character of this fracture is apparently affected by a change in lithology.

The influence of natural fractures and lithology on these two hydraulically induced fractures suggests that propagation away from a well may be significantly affected by these two parameters. Consideration should be given to such effects in future fracturing. Recommendations are presented to improve the logging program for future hydraulic well stimulation efforts.

Introduction

The U.S. Geological Survey has a research program on borehole geophysics as applied to geohydrology. One of the main thrusts of this program for the past 9 years has been the development of logging equipment and log interpretation techniques for geothermal wells. The Survey has been involved in studies of the hydrology, geology, and geophysics of the Raft River geothermal reservoir since the first shallow test holes were drilled in 1974. Experimental geophysical well logging has been carried out by the Survey in many of the test holes and wells (Keys, 1979), and the logging described in this report is a continuation of that effort. It is also a logical extension of state-of-stress studies where hydraulic fracturing was carried out by the Survey (Wolff and others, 1974; and Keys and others, 1979). The logs used in this study were made by high-temperature logging equipment developed as part of the research program on borehole geophysics. Four of these probes have been tested and operated in wells at temperatures of 250° to 260°C, and others at temperatures of 200°C.

The hydraulic fracturing of RR-4 and RR-5 (Raft River Wells 4 and 5) was carried out by Republic Geothermal, Inc., under contract to the Department of Energy (DOE). The wells were selected for stimulation because of their inadequate yield. Development of the Raft River geothermal field is implemented by EG&G, Idaho, Inc., under the supervision of the Idaho National Engineering Laboratory of DOE (Fig. 1).

The purpose of this report is to describe the use of geophysical logs to obtain pre- and post-hydraulic fracture data in geothermal wells. The acoustic televiewer is the most useful device for obtaining these data, and improvements were made to both equipment and interpretive techniques in order to better characterize the fractures.

Two papers presented at the Geothermal Reservoir Stimulation Symposium provide background information essential to this report. R. V. Verity of Republic Geothermal described the planning and execution of hydraulic stimulation in RR-4 and RR-5 (1980). C. W. Morris of Republic Geothermal provided an evaluation of the results of treatment (1980).

Fracture Characterization Using Acoustic Televiewer Logs

The acoustic televiewer was invented and patented by Mobil Oil Co. (Zemanek and others, 1969). A 1.3 megahertz transducer is rotated at three revolutions per second. The sweep on an oscilloscope is triggered on magnetic north, and the amplitude of the signal reflected from the wall of the borehole is used to modulate the intensity of the trace. The resulting log shows fractures as dark traces of low reflectivity, whose orientation can be calculated. The U.S. Geological Survey and Simplec Manufacturing, Inc. have cooperated to develop the first high temperature version of this useful probe. It has been used at borehole temperatures of 261°C. A system for recording the televiewer signal on magnetic tape was put into use for the first time on RR-5. Playback of these data provided the opportunity to improve the quality of the televiewer logs (Fig. 2).

It would appear that the width of a hydraulic fracture may be measured directly from an acoustic televiewer log, but relative width may only be inferred with significant qualifications. Therefore, the maximum apparent widths listed in Tables 1 and 2 should be used with caution. The televiewer log only detects changes in acoustic reflectivity at the face of the borehole. If the edge or angle of intersection of fracture and borehole wall is broken out, this surface will not reflect high frequency energy back to the transducer, and the apparent width of the fracture will increase. The most accurate measurement of fracture width can therefore be made where the angle of intersection with the borehole is approximately 90°. This occurs only where a vertical fracture passes through the center of the borehole. As the fracture approaches a tangential relationship with the borehole, the angles of intersection become more obtuse and acute, and the likelihood of the acute edge breaking off is increased (Fig. 3). Furthermore, there is an apparent geometric widening and the obtuse angle does not provide a sharp contact on the log. Figure 3 shows an interval of RR-5 from 4,635 to 4,640 feet that clearly demonstrates this problem. The drawings in Figure 3 show how this portion of the fracture might look in vertical view. Therefore, for the reasons described above, the fractures are likely to be narrower than measurements made from acoustic televiewer logs. The width measurements listed in Tables 1 and 2 were made with an optical micrometer and corrected for scale.

The output from an acoustic televiewer probe can also be used to record acoustic caliper logs. The transit time of the acoustic pulse is recorded rather than amplitude of reflected signal. This approach should provide an extremely high resolution log of hole diameter. Furthermore, the signal can be sampled in four directions, NESW, to produce four oriented caliper logs. Recording the probe output on magnetic tape permits acoustic caliper logs to be plotted after returning to the office. Examples of these logs are shown in the section on RR-5.

All orientations are with respect to magnetic north, and all depths are measured along the inclined borehole from ground level. Corrections of strike and dip for true north, hole inclination, and magnetic declination remain to be done in the computer for the hundreds of natural fractures logged with the televiewer at Raft River. These corrections will then yield the true vertical and horizontal positions and orientations so that a three-dimensional fracture model of the reservoir can be constructed.

Selection of Intervals to be Fractured

Data from U.S. Geological Survey logs were made available to DOE and EG&G for the selection of intervals to be fractured in RR-4 and RR-5. Geophysical well logs were utilized to a degree in the selection of the depth intervals to be isolated for pressurization. Gamma, neutron, and resistivity logs distinguish Precambrian schist and quartzite from overlying Tertiary sediments and underlying Precambrian quartz monzonite (Keys, 1979). The depth intervals to be fractured were selected in the metamorphic rock sequence above the quartz monzonite for several reasons. Steep natural fractures that produce significant quantities of hot water occur within this interval in other wells. Acoustic televiewer logs indicate that fewer open fractures are present in the quartz monzonite. Production water of highest possible temperature was desired, which suggested deep rather than shallow fracturing. Logs indicated the presence of open fractures within the intervals selected; however, the low specific yields suggested that these fractures were either not interconnected or they had somehow been plugged. It was definitely important, however, to set the liner below the large open fracture recognized on the televiewer log at a depth of 4,540 to 4,550 feet in RR-5. Nuclear and resistivity logs indicated the presence of both quartzite and schist in the intervals to be fractured. This provided the opportunity to study the behavior of hydraulic fractures in both rock types.

With the advent of the acoustic televiewer it became possible to detect hydraulic fractures accidentally induced by overpressure during drilling (Zemanek and others, 1969). It has also been shown that fracturing is possible at wellbore-face pressures considerably less than the overburden pressure which can be assumed to be 1.0 $lb/in^2/ft$ of depth (Wolff and others, 1975). Some measurements of least principal stress were approximately one-half the assumed overburden pressure. A column of water will produce approximately 0.5 $lb/in^2/ft$ of depth so a column of heavy drilling mud, cement, or pumping or injection pressures may be sufficient to break the rock. Once it is broken, the fracture will continue to propagate at somewhat lower pressures. Televiewer logs indicate that accidentally induced hydraulic fractures may be more common in oil wells than previously supposed (Zemanek and others, 1970). Drilling induced hydraulic fractures have the same character on televiewer logs as those produced by intentional overpressure. The most diagnostic characteristics of hydraulic fractures are: vertical or follow wellbore for many feet, irregular or branching trace, and variable width.

Information from acoustic televiewer logs suggested that an accidentally induced hydraulic fracture might already be present in the interval selected in RR-4. Possibly these data should have received more consideration in the selection of an interval to be fractured. A newly induced hydraulic fracture in a different interval would probably have had the same orientation, however. It would be interesting to examine records of operations in RR-4 to determine how this fracture might have been produced.

Raft River Well 4

In written communication to the Department of Energy dated June 1, 1979, the author noted the presence of complex vertical fractures that appeared to be hydraulically induced in RR-4. These fractures appear on the U.S. Geological Survey televiewer log made in March 1979. It is not known at what stage during drilling, reaming, and testing that overpressure may have occurred, but similar fractures that appear to be hydraulically induced have been seen on televiewer logs of other geothermal wells at Raft River, Idaho, and Roosevelt Hot Springs, Utah (Keys, 1979). The acoustic caliper log indicates that the RR-4 wellbore is not round in much of the interval isolated for hydraulic fracturing. Combined with the deviated hole, this accounts for the poor quality of the televiewer log because the probe must be centered for best results. This problem is particularly severe from the bottom of the liner to a depth of 4,743.5 feet, and accounts for some of the difficulty in locating the fracture on both sides of the hole.

Acoustic televiewer, acoustic caliper, and mechanical caliper logs of RR-4 made prior to hydraulic fracturing substantiate the presence of the vertical fractures to the west (Fig. 4), and indicate that these fractures have a depth of several inches. Although it is possible that these pre-existing fractures are natural in origin, the irregularity of branching and relatively consistent strike over such a great depth interval suggest they are hydraulically induced.

The pre-existing hydraulic fracture system can be traced from the bottom of the liner at 4,682.5 to 4,873.9 feet. The earlier fracture is only visible on the March televiewer logs in the west quadrant of the hole, but this may be due to better acoustic reflection in that direction. The post-fracturing logs made in August indicate widening or propping of the fracture to the west, and a detectable fracture in most intervals to the east. Fractures are propped open by the injection of large quantities of sand after the rock is broken hydraulically. The propped fracture follows branches or en echelon traces of the previous fracture, particularly well demonstrated in the interval 4,769 to 4,780 feet (Fig. 5). The hydraulically widened and propped fracture is detectable on the August 1979 acoustic televiewer log from the bottom of the liner at 4,682.5 feet to the top of sand fill up in the hole at 4,873.9 feet. The presence of vertical fractures to a depth of approximately 4,980 feet on the March televiewer log suggests that the widened fracture may extend to at least the sand level that existed prior to pressurization. Thus, the fracture that was expanded and probably extended during intentional hydraulic fracturing is semi-continuous for at least 191.4 feet along the axis of the well. The well deviates 10.5° from the vertical in the direction N80°E (Miller and Prestwich, 1979). The hydraulic fracture logged in March appears to extend above the bottom of the liner to a depth of approximately 4,664 feet. This is just below a major open fracture in the schist which has a low angle dip to the southeast. Thus, it appears that the most significant part of the hydraulically-induced fracture may have been limited in upward extent by a natural fracture. Table 1 is a compilation of data and descriptions of the propped hydraulic fracture in RR-4.

The average strike of the nearly vertical hydraulic fracture is N72°E which has been corrected to true north and is shown as a line through RR-4 in Figure 1. Most of the natural fractures in Well RR-4 dip from 12° to 50° to the southwest and strike averages N45°W. At least one fracture in the pressurized zone is thought to be natural; at 4,820 to 4,822 feet a fracture dips 75° to the north and strikes N60°E (Fig. 6). It is possible that some of the other pre-existing vertical fractures in the pressurized interval are natural, but that seems unlikely because they follow the well for such a great distance, have the irregular character of hydraulic fractures, and are subparallel and similar to the intentionally produced hydraulic fracture in Well RR-5. Furthermore, there are vertical fractures in Well RR-2 below 5,000 feet that strike northeast, and have an appearance similar to unpropped hydrofractures.

In areas and at depths where the least principal stress is less than overburden stress, hydraulically induced fractures can be expected to be vertical. In areas of low topographic relief and at sufficient depth, the maximum compressive stress is vertical, and the least and intermediate stresses are in the horizontal plane. The depth intervals of the wells intentionally fractured at Raft River are 10.5° and 5° from vertical and this fact, along with interruption of fracture propagation by natural fractures and lithology changes, may encourage the production of complex rather than simple planar fractures.

Most hydraulic fractures logged by the U.S. Geological Survey tend to branch, curve, and split rather than propagate as simple planar features geologists are used to seeing in outcrop or in core. Actually, these complex characteristics are typical of some hydraulic fractures (produced by pressurizing drill holes) that have been exposed by mining at the Nevada Test Site (Northrup and others, 1978). The unique opportunity to examine these fractures has proven helpful in the interpretation of televiewer logs. Figure 7 is a photograph of a neat-cement-filled hydraulic fracture exhibiting some of the curving and branching characteristics of the fractures induced at Raft River. The width of this vertical fracture averages 0.1 inch in the sample of tuff illustrated, the same order of magnitude of the hydraulic fractures in RR-4 and RR-5.

Raft River Well 5

A new fracture was intentionally produced by pressurization and propping with sand in RR-5. A 200-foot stimulation interval was isolated by a packer set in a cemented liner and sand-filled hole. The fracture is clearly defined on televiewer logs from the bottom of the liner at 4,562 feet to a major natural fracture system at a depth of approximately 4,690 feet (Fig. 8). A relatively tight extension of the hydraulic fracture is poorly defined below the natural fractures to a depth of approximately 4,705 feet, which gives a vertical length of 143 feet. The hydraulic fracture is approximately parallel to leg B of RR-5 which is deviated 5° to 5-1/4° from vertical in a direction N56° to 59°W (Miller and Prestwich, 1979). Therefore, it is nearly vertical. The average strike is N29°E, but the fracture curves considerably. Figure 9 is a tracing of the fractures described from a taped televiewer log, played back at a compressed scale. The scale ratio tends to exaggerate curvature, but it does show the complexity of the hydraulic fracture. The apparent maximum fracture width from the acoustic televiewer log averaged 0.6 inch. The absolute value of the width is not so meaningful as the relative widths as a function of depth (Table 2). Furthermore, it is likely that the fracture in RR-5 is wider than the fracture in RR-4. If the lithology is similar, which appears likely, then the difference in width may be related to fracturing or propping procedures. Test data show that more than four times as much sand was used in propping procedures. Test data show that more than four times as much sand was used in propping RR-5 than was used in RR-4, which apparently produced a wider fracture. Furthermore, pumping tests are not complete, but it appears that production may be greater from RR-5.

Figure 10 shows an acoustic caliper log of the depth interval of RR-5 from 4,585 to 4,590 feet compared with an acoustic televiewer log. The caliper was calibrated as shown with a 2-inch change in well diameter equal to a 1-inch change on the radius from the transducer.

Note the correspondence between the oriented caliper traces and the televiewer log at the same azimuth. The caliper traces would suggest fracture depths greater than one inch; however, this may be misleading because of the unknown acoustic reflectivity of the epoxy sand used for propping. Figure 11 shows another type of acoustic caliper presentation for the depth interval 4,665 to 4,670 feet. The X axis still represents a single-transducer sweep around the hole, but the Y axis represents changes in hole diameter or transit time. The eccentricity of the probe or well can be seen along with the two fracture traces. This caliper presentation suggests that fracture widths measured from the televiewer log may be too great.

The hydraulic fracture in RR-5 does not always pass through the center of the wellbore. Further, it has a very irregular trace which indicates a varying strike. From a depth of 4,563 to 4,570 feet, the hydraulic fracture is nearly parallel to a pre-existing vertical fracture which is probably natural. There is no strong evidence of a pre-existing hydraulic fracture in RR-5 as was found in RR-4.

There is a significant change in the apparent character of the fracture and direction of strike at a depth of 4,652.6 feet (Fig. 12). This may be primarily due to a change in lithology. Although the interval fractured has been described on the basis of cuttings as all quartzite with minor amounts of feldspar and muscovite, geophysical logs suggest more significant changes in lithology. The natural gamma log indicates that the quartzite may contain layers of schist, possible biotite. A change in lithology is indicated by several logs at approximately 4,650 feet, which is close to the depth where hole diameter and character of the post-fracturing televiewer log changes. A decrease in radioactivity below this depth suggests an increase in the percentage of quartzite. If this interpretation is correct, then the hydraulic fracture as seen in Figure 12 is better developed in quartzite than in schist.

If measurements of hole deviation are correct, then a northeast-striking, vertical, hydraulic fracture should have intersected leg A of RR-5 in the vicinity of a production zone which was reported to have yielded 1,000 gal/min (Miller and Prestwich, 1979). Unfortunately, this fracture was apparently cemented up so the hydraulic fracture may have intersected cement rather than a producing zone. Cement may have also limited the lateral propagation of the fracture. The hydraulic fracture was also probably limited in vertical propagation between natural fractures at 4,535 to 4,540 feet and 4,690 feet. These major natural fractures are essentially parallel with a dip of 80° with respect to the hole and a strike of N20°W to N40°E. The shallower of these two fractures appeared on gamma-gamma, acoustic velocity, neutron, caliper, and acoustic televiewer logs as a major open fracture zone which should have produced significant amounts of water. Production was minimal and may have been drastically reduced cement invasion.

The average strike of the hydraulic fracture in RR-5 corrected to true north is shown by a line through the well on Figure 1. The average strike of N29°E appears to be significantly different from the

N72°E average strike in RR-4. The averaging technique for such a complex surface may produce an error; however, it is important to note that the hydraulic fractures are subparallel to major faults postulated in the area (Williams and others, 1976). RR-5 is closer to the Bridge Fault which trends slightly east of north, and RR-4 is closer to the Narrows structure which trends east-northeast. In many areas, hydraulic fractures have been found to parallel major structures (Wolff and others, 1974). If this is the case at Raft River, then hydraulic fractures may parallel rather than intersect major structures that are probably conduits for the movement of hot water.

Recommendations

As a result of this study, a number of suggestions can be made to improve the cost benefit ratio for utilizing borehole geophysics in hydraulic fracturing programs. Well logging can be more beneficial to planning a hydrofracture and understanding the results.

Better results from logging and fracturing in general might be obtained if the interval of the well selected was near vertical rather than deviated. The televiewer can be better centered in a vertical hole; but even more important, the hole is more likely to be perpendicular to the direction of least principal stress. This may tend to produce a fracture with a more uniform trace that does not change direction away from the well. Under these conditions measurements of fracture orientation in the well are more likely to be related to average orientation. The pre-fracture logs should be considered carefully from the standpoint of existing fractures or lithologic contacts that may affect the extent and direction of propagation of a hydraulic fracture. Further, favored directions of natural fractures may be followed by induced fractures; that is, the stress field may have the same orientation at the time of hydraulic fracturing as it did when natural fractures were produced. These factors may tend to influence fracture propagation parallel to a producing structure rather than towards it.

After the depth interval to be fractured has been selected but before pressurizing, a complete suite of porosity sensing logs should be run on a high resolution scale. These can then be compared to the same kind of post-fracture logs in an attempt to detect changes in porosity. Resistivity devices, such as micro-guard and dipmeter, might be particularly useful. Before and after acoustic waveform logs would improve the understanding of the response of these logs to vertical fractures. A pre-fracture rerun with the televiewer should be made with maximum attention to log resolution.

Post-fracture logging would be greatly enhanced by assuring that the well is clean and free of sand to the bottom. Successive depth measurements may be necessary to determine that no propping agent or other material is entering to fill the well. Under these conditions, it should be possible to determine the lower limit of crack propagation. It would be extremely useful if the well could be made available for temperature and flowmeter logs during post-fracture testing. It is very important to determine which part of a fracture is producing and possibly why. An attempt should be made to determine if the apparent fracture width on a televiewer log is related to productivity as our preliminary data suggest.

It has been reported that RR-5 is continuing to produce propping sand. If the pump is pulled to clean out the hole then a third televiewer log should be run in order to determine if intervals of sand loss can be detected and what effect this has on apparent fracture width.

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