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Henry J. Ramey, Jr., Paul Kruger, Frank G. Miller,
Roland N. Horne, William E. Brigham,
and John R. Counsil
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FRACTURE DETECTION: INTERPRETATION OF WELL LOGS TO SELECT PACKER SEATS AND LOCATE INJECTION INTERVALS

D. S. Dreesen, K. L. Burns, P. Chavez, Z. V. Dash, S. Kelkar, J. Kolar, and S. S. Levy

Earth and Space Sciences Division
Los Alamos National Laboratory
Los Alamos, New Mexico 87544

ABSTRACT

A wireline and mud logging program has been conducted in conjunction with redrilling operations in well EE-3 at the Fenton Hill Hot Dry Rock (HDR) site near Valles Caldera, New Mexico. The trajectory for the new bore, EE-3A, penetrated a fractured zone stimulated from adjacent well EE-2 and thereby established hydraulic communication. To test and stimulate selected zones in EE-3A inflatable open hole packers designed for high temperature service were used. Proper identification and selection of packer seats was crucial to the success of the project. The logging program successfully identified five competent packer seats in six attempts. Wireline temperature, caliper, sonic televiewer and natural gamma ray logs were used in conjunction with mud logs, drill cuttings and drilling parameter data to locate fractures, out-of-gage hole, temperature anomalies and mineralized zones which were avoided in selection of the packer seats.

INTRODUCTION

The Los Alamos National Laboratory has been engaged for the past decade in developing technology for energy extraction from hot dry rock reservoirs. As a part of the development of a second, deeper, hotter reservoir (Phase II), field experiments are in progress at the HDR test site. The primary objective of the field operations has been to achieve hydraulic communication between wells EE-2 and EE-3 at depths ranging from 11,500-13,200 feet. Thus cold water can be injected down one well and hot water produced at the other well. The rock mass surrounding the two wells was stimulated with the injection of large volumes of water. Subsurface microseismic detectors were used to map the micro-earthquakes during and after the massive injections (House et al., 1985). After failing to establish a connection, EE-3 was sidetracked and redrilled (EE-3A) on a lower trajectory to intersect a high density region in the cloud of microseismic events surrounding EE-2 resulting from the largest injection which used five million gallons of fresh water. The 8-1/2 inch wellbore was drilled from 9,300 to 13,180 feet encountering temperatures in excess of 260°C.

A number of reservoir stimulation tests were conducted at various depths during redrilling operations. Due to the existence of a low pressure region at 10,250 feet, the lower intervals had to be isolated from this zone and open hole packers were selected as the only practical method to effectively stimulate and interrogate the wellbore. This was accomplished with the use of a recently improved, open hole, inflatable packer (Dreesen et al., 1985 and 1986). The high initial temperature, large thermal cycles, high differential pressures and abrasive open hole environment created an extremely challenging environment for open hole packer operations. Packer seats had to be selected to avoid enlarged, fractured, incompetent or mechanically weak borehole. A reliable logging program was essential for successful packer operations and the reservoir development and testing program.

LOGGING PROGRAM

The logging program included in the EE-3A drilling plan sought to identify and locate effective packer seats. Most of the wellbore was assumed to be unsuitable due to one or more of the following conditions: oversized, irregular broken out or washed out bore, open fractures intersecting the bore, mineral filled fractures and jointed or weak rock more susceptible to fracturing than the targeted injection zone (Hickman et al., 1985; Warren, 1981). Potential packer seats were located by using mud logs, temperature logs and caliper logs. Open hole and through-drill-pipe gamma ray/collar locator logs were used to correlate drill pipe and open hole wireline depths. The USGS high temperature televiewer was run to investigate caliper log data of unusual character. Figure 1 presents a composite correlation of the various logs used over one region of interest. Table 1 summarizes the stimulation tests and packer seats by packer run.

Mud Logging and Geological Interpretation: Drill cuttings were collected and examined at the wellsite by commercial mud loggers. A complete geothermal drilling data log including drill pipe depth, drill rate (Figure 1a), lithology, flowline temperatures, gas content and supporting drilling data were also collected and presented on a ten feet per sample display. Mineral identification and fracture examination by binocular and petrographic microscope, x-ray diffraction, and electron microprobe analysis were performed. Results were used to prepare a lithologic log (Figure 1b) showing the approximate location of geologic unit boundaries, dikes and mineral filled fractures. Gross gamma measurements of cutting samples were made (Figure 1c) in a region of particular interest to compare drilling pipe depths with wireline gamma ray depths (Figure 1d).

Wireline Logging and Procedures: A 7-conductor, tetrafluoroethylene (TFE) teflon insulated logging cable and cable head rated for continuous service at 320°C were used to run the Los Alamos project logging sondes (Dennis et al., 1985) and the USGS high temperature televiewer. Pressure control equipment for the high temperature logging cable was limited to 1000 psig. A casing collar locator was run in conjunction with other sondes for depth calibration.

A commercial "slim hole" gamma ray/collar locator provided a through-drill-pipe log in a drill string cooled with low flow rate circulation.

Temperature Logging: The temperature sonde uses a thermistor probe with high accuracy and resolution. It is readily fielded, reliable and more easily replaced than other sondes. Therefore it was run prior to running other logging sondes. Cable tension and tool turnaround were monitored carefully to assure hole conditions were suitable for the caliper logging to follow. Surveys were run at 60 to 150 ft/min both into and out of the well. Depths were corrected for thermal lag time and cable stretch (turnaround).

Temperature surveys were run in well EE-3A preceding and following each packer experiment. Anomalies and variations from the background temperature gradient were used to infer fracture inlets/outlets within $\pm$10 feet (Figure 1g, Figure 2). More precise location of fractures was often precluded by the high pressures that prevented logging during injection or early shut-in. The packer configuration prevented logging below it. Venting and circulation of the well was required prior to removal and this resulted in a smearing of fluid entrances and made it difficult to determine the fracture locations.

Caliper Logging: The Los Alamos caliper tool is a 3-independent-arm tool configured to measure hole diameters from 5 to 14 inches. Mechanical linkage, magnetic couplings and high temperature, rotary potentiometers are used to convert borehole radius to an electronically measured output. The sonde was run with the arms retracted. They were extended to log out over the interval of interest and then retracted for removal. Logging speeds varied from 5 to 40 ft/min. Pre-log and post-log calibrations were made to calculate corrections for the caliper pad wear which was significant on runs of over 200 feet. The tool was run with two bow centralizers straddling the measuring arms. A slip and stick movement of the tool was indicated by caliper log quality below 12,600 feet.

Accurate caliper logs were required to select packer seats (Figure 1f). Over-extension of the high temperature design inflatable packer element (in the range of 9.5 inch diameter) made the element susceptible to rupture. Washouts, breakouts or ledges which could easily go undetected using a single or dual arm caliper can also rupture the element. After the packer ruptured during initial inflation on run five (Table 1) a repeat caliper log showed that an inoperative arm on the previous log had, in fact, tracked through a washed out fracture with no significant response by the other two arms (Figure 3). A new packer seat was selected 30 feet above the previous packer depth and a successful injection of 1-1/2 million gallons was completed with no evidence of a packer leak.

Televiewer logging: The motor in the logging sonde would not operate in the primary interval of interest below 12,400 feet, but was operational above 12,200 feet so logs were run over several alternate depth intervals. A logging speed of 5 ft/min provides the most detailed image. However stick-slip motion of the sonde at low logging speeds resulted in imagery that was totally incoherent at 5 ft/min and only partially coherent at 10 ft/min. A logging speed of 20 ft/min was used. The best logs were obtained in the depth interval between 11,200 and 12,000 feet, where hole inclination (from the vertical) was about 10 degrees. Below that interval, wire-line drag aggravated the stick-slip motion. Above that interval, the inclination was as high as 20 degrees and image quality deteriorated due to poor centralization of the tool and an increase in stick-slip motion. The results emphasize the need for improved centralizing assemblies for imaging tools.

Studies of the texture of the imagery indicate that coherent images were obtained for about 95 percent of the logged intervals. Incoherent imagery is characterized by a texture termed "shading" as illustrated by Clark (1981). The 5 percent of incoherent imagery, from comparison with caliper logs, probably corresponds with zones of multiple, open fractures. It is, in fact, reasonable to interpret all the incoherent portions of the imagery as open fracture zones. This means that the televiewer yielded, preferentially, coherent imagery for non-fractured parts of the wellbore. While this result is disappointing for studies of the hydraulic apertures, it was turned to advantage in selecting locations for packer seats.

Two types of geological features were extracted from imagery (Figure 1h and 1i). The first is the discrete, dark, linear feature which, as is well-known, corresponds to fractures or joints. The textural appearance is probably due to wave-guide absorption (Burns, 1986). The second is a diffuse, or dispersed feature with two possible causes. It may be due to foliation or to fractures of aperture less than the sonic wavelength. The two types are shown separately on the accompanying figures. Whatever the geological cause of the second type, it was found that it is clear and distinctive in smooth regions of the wellbore, as indicated by the caliper log, and obscured or invisible in rough sections.

There were therefore two criteria for finding smooth, sound, unfractured portions of the wellbore from televiewer logs which were supported by caliper results: the lack of incoherent "shading" and the visibility of diffuse features. These were felt to give a reliable diagnosis of hole condition and were a major consideration in choosing the final packer seat.

Open Hole Gamma Ray Logging: A geiger detector gamma ray sonde was run in the open hole of EE-3A to tie the natural gamma ray depth signature to project wireline depths. The commercial design electronics for the tool are thermally protected in a dewar housing with a cerrobend heat sink. The tool operates at temperatures of 300°C for more than 6 hours. The gamma ray signature obtained was readily correlated with signatures obtained with the commercial through-drill-pipe log. Most logs were run at 60 to 80 ft/min. Logging speeds as low as 40 ft/min were required to obtain a good repeat signature with the dewared tool.

Gamma Ray/Collar Locator Correlation Log: A commercial high temperature gamma ray / collar locator log was run through drill pipe. It was determined that a packer rupture occurred as a result of setting the packer in enlarged hole. There were two possible explanations for positioning the packer at an improper depth: (1) The depth correlation between the caliper log and drill pipe was incorrect. Open hole and through-drill-pipe gamma ray logs confirm that the packer had been set at the proper depth. Tag bottom depths had been successfully used to correct wireline depth to drill pipe depth. (2) The caliper arm pads failed to track through a washout. This in fact occurred as is discussed under caliper logging.

RESULTS OF THE LOGGING PROGRAM

The logging program provided input to the successful packer operations and also added significantly to the reservoir description process complementing injection and tracer data. Results that contributed to the reservoir description included depth correlation of drilling data with wireline data, location of active fractures, mineral filled fractures and foliations and formation changes.

Depth Correlation: Table 2 shows correlations between wireline and drill pipe depths. Depth measurements made on various runs using the same wireline varied less than four feet. Depths measured using different wirelines varied as much as 20 feet. When working within 600 feet of the bottom of the hole, tag bottom depths were used successfully to make the drill pipe / wireline depth correction.

A logging run was required for each sonde run since multiplexing equipment for the Los Alamos open hole logging tools (now under development) was not available. Where accurate packer depths were required, an open hole gamma ray log was run on the wireline currently in use to correlate with a through-drill-pipe gamma ray log.

There was also concern that drill pipe depth discrepancies may have occurred. Gamma ray measurements were made on the drill cuttings over an interval of specific concern in selecting the packer seat for run 7, to assure that the mud log depths at the packer seat were on depth with the through-drill-pipe gamma ray log being used to position the packer. The resulting measurements led to an alternate correlation presented in Figure 1a, b and c (dashed line).

Active Fractures: Active fractures were located using pre- and post-injection temperature logs. Full interpretation of post-injection logs required modeling or simulation using a wellbore heat transfer code in order to calculate the flow split. However the raw log data were adequate to detect fractures and select packer seats. Temperature logs of the EE-3A wellbore are shown on Figures 1g and 2. The major active fractures inferred using these and other logs are also depicted in Figure 2. Oriented cores were obtained but there is considerable evidence that the orientations were not representative of most of the wellbore. Where log quality is adequate the televiewer log provides the best information on fracture orientation.

Lithology and Structure: Lithological banding was detected in mud logs, televiewer logs and cores. More detailed lithologic information was obtained by laboratory examination. Comparison of core and televiewer data is continuing to resolve the question of detectability of fabric elements such as cleavage and foliation (diffuse features).

Early in the drilling, a possible correlation between large drill cuttings/high drilling rates and high biotite concentrations (based on wellsite measurements) was observed. Packer seats were selected to avoid regions of large or irregular cuttings, high biotite concentrations, high secondary mineral concentrations and high penetration rates based on the assumption that any of these might be indicative of weak or incompetent rock. Subsequent laboratory study has shown that simple biotite content is not the controlling factor, but may provide some indication of rock strength or competence. All of the packers were set in granodiorite with biotite concentrations of less than 10%.

Mineral-Filled Fractures: Mineral-filled fractures were identified by laboratory examination of the drill cuttings and core where available. The use of high viscosity sepiolite gel drilling fluid removed cuttings up to 0.2 inches long and complete fractures up to 0.08 inches wide were detected. Cuttings containing fracture surfaces broken during drilling were also observed. Several thousand cuttings per sample had to be examined to detect even moderately abundant fractures. From this study, regions with high density of mineral-filled fractures were identified (Figure 1b).

Textural relations within fracture fillings show that many fractures have been repeatedly reactivated in the past and could be activated during packer inflation and reservoir stimulation. Information about mineral-filled fractures was used in selecting the last two packer seats.

Microseismic Earthquake Density Plot: An earthquake density plot was constructed using earthquakes mapped during the 5 million gallon injection into EE-2. The number of earthquakes located within 300 feet (100 meters) of a given measured well depth are compared with the active fractures inferred from temperature logs (Figure 2). There is a correlation between the seismic density and the connecting and non-connecting fractures. Regions of high density surround and in some cases overlap the connecting fracture entrances.

Stimulation Testing Program: The stimulation testing program, summarized in Table 1, achieved two goals: (1) Stimulate the reservoir in the vicinity of the new wellbore (EE-3A) to establish and enhance hydraulic connections with EE-2. (2) Assess injection potential and determine injection pressure/rate relationships for the stimulated intervals. The first two tests below the low pressure region were primarily for the purpose of evaluating packer performance while the subsequent testing had specific reservoir testing objectives (Kelkar et al., 1986). Volumes up to 1-1/2 million gallons of water and test durations up to 100 hours were achieved using the packer system. Hydraulic communication between the two wells was established through several well defined fracture entrances at depths between 11,700 and 12,550 feet.

Packer Results: Packer performance was much better than expected. Out of seven runs two packers ruptured during initial inflation. Leakage around the packer was observed on only two packer runs. Packer damage caused the leak on run 2. A packer seat located between two fractures which were both connected to EE-2 explained the leakage observed during run 7. The ability to select suitable intervals for packer seats and a well planned and systematic approach to the experimental plans played a major role in the successful program.

CONCLUSIONS

The EE-3A logging program was crucial in selection of packer seats for the reservoir testing program. The mud logging program provided wellsite input to focus the caliper logging on regions with good potential packer seats. The three arm caliper log was needed to eliminate sections of bore that were too large for the high temperature packer element. This was confirmed on packer run 5 where the packer element ruptured after it was set using two arm output from the three arm caliper sonde. Temperature logs provided sufficiently accurate location of fractures to select packer seats. The logging program has also contributed to the understanding of reservoir structure which at this point is in good agreement with other reservoir data.

The importance of multiple arm caliper logging and good wireline depth corrections was demonstrated during these operations. High temperature wireline logging has been shown to be a useful investigative tool in granitic rock. A six arm, hot hole caliper, a high temperature multiplexing system and high pressure well control equipment for large diameter hot hole wirelines are needed to make the techniques described commercially viable. A method to eliminate the severe stick-slip movement of the the caliper and televiewer sondes in the inclined, abrasive wellbores at Fenton Hill would make the caliper/televiewer and open hole packers a powerful and complementary wellbore evaluation system.

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TABLE 1. PACKER SEAT SELECTION AND RESERVOIR TEST DATA

RUN	TEST INTERVAL+ (ft.)	BOREHOLE DESCRIPTION* DIAMETER (in)	SECONDARY MINERALS %	BIOTITE %	INJECTION VOLUME (gal)	TIME (hr)	COMMENTS
1	10,829-10,875	8.75	1	3-5	6,000	1.5	Initial packer test, no leakage observed.
2	10,841-11,615	8.75	2	3-5	140,000	10	Packer deflated, moved and leaked.
3	11,537	8.9	2	5-7			Packer damaged during run in and failed to set.
4	11,537-12,203	8.9	2	5-7	420,000	20	Small leak via fracture suspected. Connection to EE-2 established.
5	12,585	9.2**	1	<5			Packer ruptured during initial inflation.
6	12,555-13,180	9.2	1	<5	1.4×10^6	38	No leakage observed.
7	11,976-12,550	9.1	2	<10	1.5×10^6	84	2nd connection to EE-2 established, 1 BPM leak observed. Bypass to upper EE-2 connection formed leak path.

* Diameter based on caliper log. Mineral percentages based on wellsite mud log estimates. Country rock lithology was identified as biotite granodiorite on the mud log.

\+ Initial depth corresponds to packer setting depth.

** Repeat caliper log showed a 4.9 inch radius wash out or break out on one side of bore.

TABLE 2. DEPTH CORRECTIONS FROM COMMERCIAL AND LOS ALAMOS WIRELINE GAMMA RAY LOGS USED FOR RUN 6 AND 7 PACKER SEAT SELECTIONS.

FEATURE	DEPTHS PIPE	THRU DP	OPEN HOLE	DEPTH CORRECTIONS THRU DP LOG	OPEN HOLE LOG
Whipstock	9,391*		9,376		15
GR Spike**	9,584	9,573	9,571	11	13
GR Spike	10,048	10,036	10,040	12	8
GR Spike	10,910	10,896	10,902	14	8
GR Spike	11,761	11,746	11,755	15	6
GR Spike	12,454	12,440	12,453	14	1
GR Spike	13,038	13,021	13,037	17	1
Tag Bottom	13,170	13,155		15	

* Top of whipstock set at 9,380 ft. with previous rig and drill string.

** High gamma ray count over a narrow interval.

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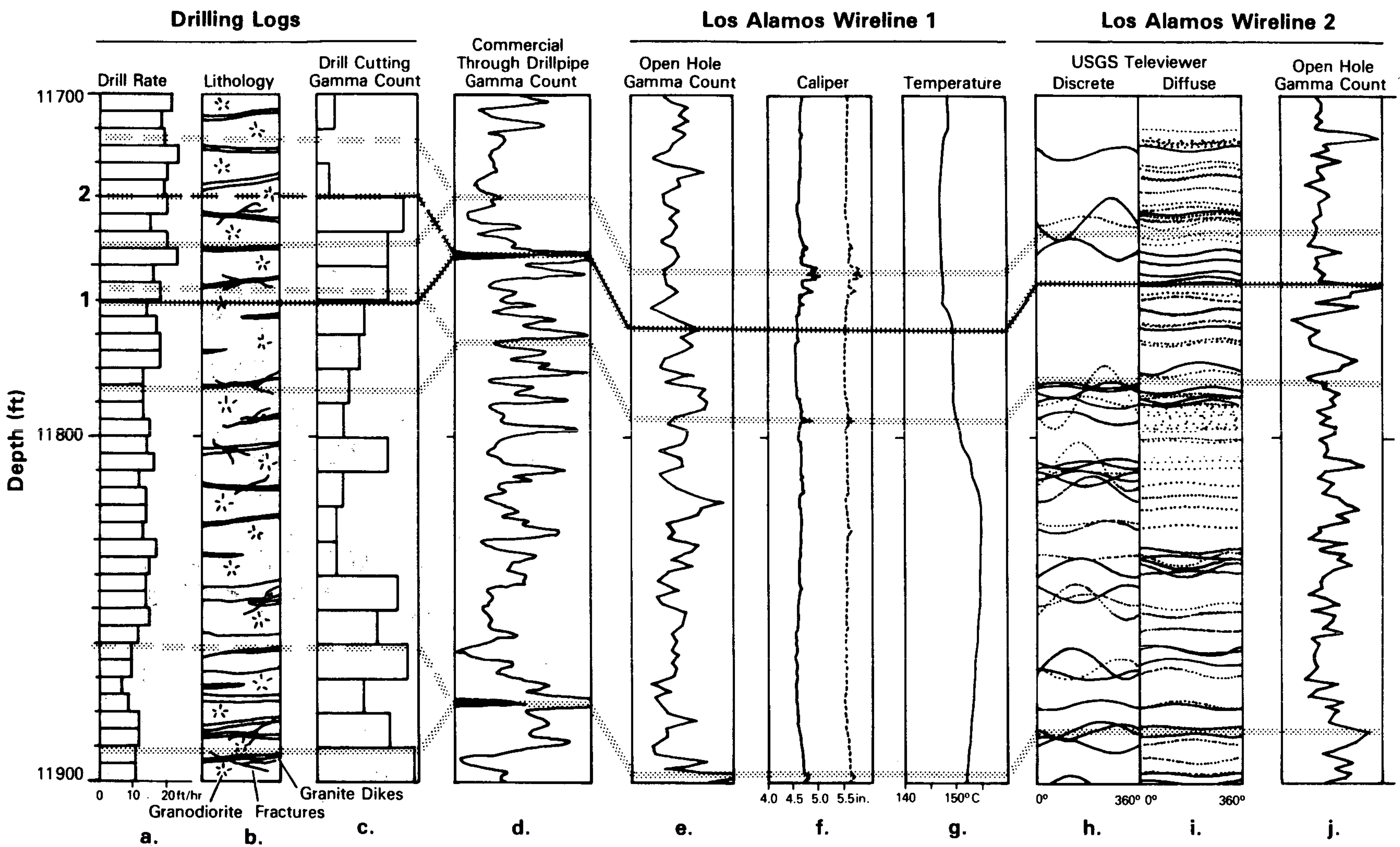

Figure 1. Example of well logs used for selecting packer seats.
1. Correlation based on through-drill-pipe and wire-line gamma ray logs run after drilling was completed.
2. Alternate correlation of drilling logs based on gamma ray counts of drill cuttings.

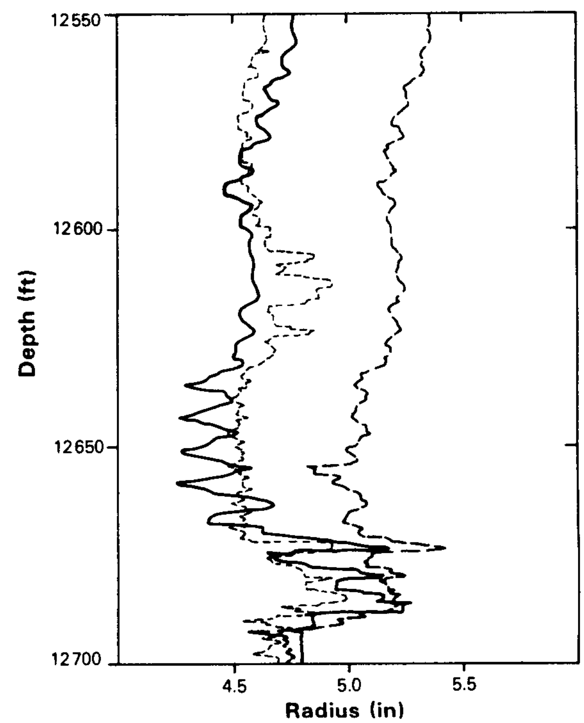

Figure 3. The lightest trace is a 3-arm caliper survey showing a break-out near 12,600 feet. The packer failed in run #5 when set at this depth. The medium trace is an earlier caliper survey with only two arms functioning. The heavy trace is from the same survey using the two functioning arms.

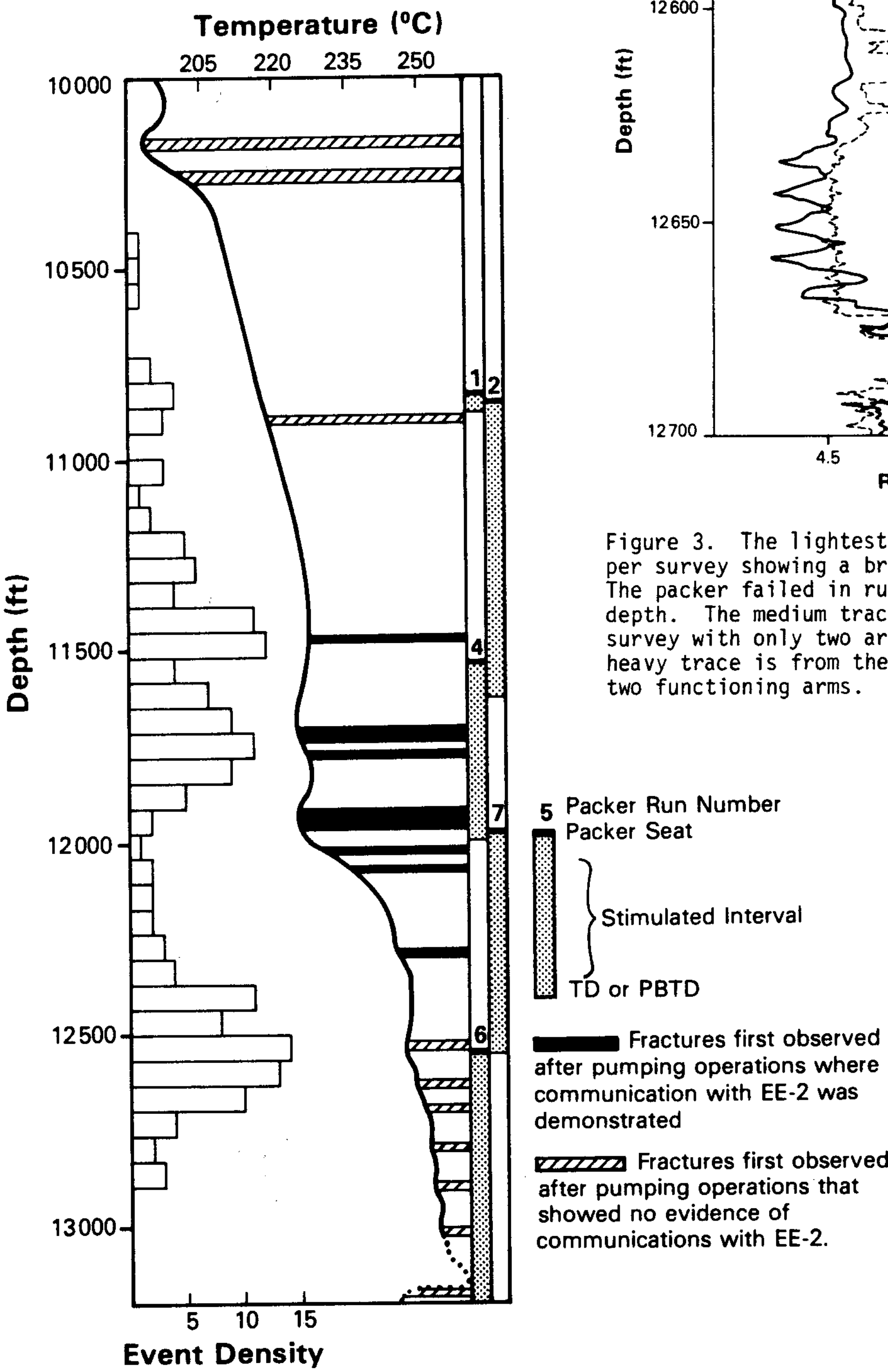

Figure 2. A histogram of microseismic event densities and a typical temperature log compared to fracture entrances detected in stimulation test # 1 to 7.