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Measurement of Dynamic Reservoir Conditions, Volume I

Final Report

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December 1986

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For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
USS Division of USX Corporation
Steel and Related Resources Research
USS Technical Center
Monroeville, Pennsylvania

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ABSTRACT

A joint venture between the U. S. Department of Energy, the USX Corporation (formerly the United States Steel Corporation), and the Gas Research Institute was initiated to evaluate the geologic and reservoir parameters which affect the stimulation and production of coalbed methane. To accomplish this, a single-zone coalbed methane well was completed into the Mary Lee and Blue Creek coal seams in the Warrior basin of Alabama. Following the succesful drilling and coring of the well, extensive reservoir testing resulted in a measured coal seam permeability of 1 millidarcy and a skin factor of -4 to +1. In-situ state-of-stress tests in the Blue Creek coal seam indicated a vertical primary closure and a secondary horizontal closure. Coal and rock core samples were collected from the well and evaluated for flow and mechanical properties. These tests resulted in reservoir and mechanical values consistent with well-test data and underground fracture observation. Geologic studies established the geometry of the target reservoir and the surrounding strata. Unstimulated production tests were performed to establish baseline production parameters for both the Mary Lee and Blue Creek coal seams. Utilizing the collected data from the various test programs, a state-of-the-art hydraulic stimulation was designed and implemented. Detailed monitoring of selective variables during the stimulation permitted an initial evaluation of the success of the stimulation. Following stimulation, production testing evaluated the impact of the hydraulic stimulation on gas and water production. Underground observation of the induced hydraulic fracture revealed fracture containment in the target coal seam with a vertical and horizontal component. Utilizing a fracture-simulation model and the stimulation-pressure record, a combined vertical and horizontal fracture was created that closely matched the observed in-situ fracture.

INTRODUCTION

Project Background

Beginning in 1975, the United States Steel Corporation[1] (USS) and the U. S. Bureau of Mines (BOM) began a program to demonstrate the viability of degasifying coalbeds using vertical wells in advance of mining. The USS Oak Grove Mine, near Birmingham, Alabama, and within the Warrior Basin was selected as the test site. One of the early results of this program was the relationship between the rate of methane and water production from a vertical well and the proximity of the well to underground mine workings[2].

The U. S. Department of Energy (DOE) and USS initiated a study in 1979 to further define the coalbed reservoir and the dynamic movement of gas and water through the reservoir (Contract No. DE-AC21-79ET-14204). This project, as in the earlier BOM projects, was oriented to the effect of mining on the coalbed reservoir. Results of this study indicated that mining does cause changes in the coalbed hydrostatic pressure, water saturation, and methane desorption and migration in adjacent unmined coalbed areas[3]. These changes occur primarily as a function of the proximity of a mine face to the coalbed study area and the length of time the mine face was near the coalbed study area. In the case of the Blue Creek coalbed (studied in this project), it was shown that the coalbed area affected by the mine face was more time dependent than distance dependent. An advancing mine face affects only a small area of the coalbed ahead of the face, whereas if the mine face remains stationary, the coalbed area affected by the face increases slowly with time[4].

In addition to studying the effect of mining on the coalbed reservoir, the project also addressed the hydraulic stimulation of vertical wells. An attempt to determine the controlling factors influencing the creation of a hydraulic fracture and the ensuing gas and water production was made. Inconclusive results were obtained, because of numerous, uncontrollable operating variables (mining influence, short production history, and well head gas pressure). However, a very long (>600 feet) induced and propped fracture was observed underground in one of the wells. Also, further tests utilizing a no-proppant stimulation technique were less than satisfactory.

Because of the encouraging results from the previous work at the Oak Grove mine location, a new program was initiated to further test and define the parameters controlling the hydraulic stimulation process. This program began as a joint venture between USS and DOE (Contract No. DE-AC21-82MC-19404). To further expand the scope of the research activities

pertaining to this project, the Gas Research Institute (GRI) became an active partner with USS (Contract No. 5083-214-0778). This project, the subject of this report, had additional interest beyond the degasification of coal seams ahead of mining, which had been the early program objectives at Oak Grove.

In 1980, commercial production of methane from coal seams in the Warrior basin began. Since then, over 20 billion cubic feet of methane has been produced from approximately 275 coalbed wells[5]. The majority of these wells were installed for degasification purposes. However, the commercial viability of producing methane from coal seams has been recently proved. Wells have been installed in the Warrior basin for the sole purpose of commercially producing methane. In addition, the methane resource in the Warrior basin is substantial, currently estimated to be 20 trillion cubic feet[5]. Because of this growing interest in commercially producing methane from coal seams, a number of research and development projects have been initiated to aid in the growth of this new industry. Therefore, the project discussed in this report is oriented toward the commercial production of methane, while recognizing the benefit to mining of predrainage of the methane.

Project Objective

The joint USS-DOE-GRI project at the Oak Grove Mine concentrated efforts on a single-zone completed vertical coalbed methane well. This well, identified as DHM-7, was designed such that numerous objectives could be achieved within the time frame and cost structure of the two concurrent contracts. These objectives included 1) measurement of pressure and fluid saturation changes which occur in the coalbed and near the mine workings during the unstimulated and stimulated production of the well, 2) determination of coalbed reservoir and stimulation parameters from laboratory measurements and production history matches, 3) measurement of the in-situ state-of-stress within the coal and boundary rock units, 4) measurement of the hydrologic reservoir characteristics of the target coal seams, 5) design of a state-of-the-art hydraulic-stimulation technique for optimum methane production and coal-seam degasification, 6) measurement of the geometry of the induced hydraulic fracture by direct underground observation following mine-through, and 7) rationalization of the mechanisms which controlled a) the geometry of the induced fracture and b) the production from the well.

To achieve these objectives, a test plan was designed that incorporated both the field testing of a single-zone coalbed methane well and the laboratory testing of core samples

and utilization of numeric computer fracture and reservoir models. The field testing occurred at the Oak Grove Mine site (see Project Location below). The laboratory testing took place at numerous industrial and academic research and development laboratories in the United States and are described in various sections of this report.

Project Location

The project site is located in Jefferson County, Alabama, USA, at latitude 33 degrees 26 minutes north and longitude 87 degrees 6 minutes west. The site is located approximately 10 miles west of Birmingham, Alabama. Access to the site from Interstate Highway 59 in Birmingham is provided by paved road to the main surface location of the Oak Grove Mine and by gravel road to the field site, Figure 1.

Alabama has a humid and generally temperate climate. Precipitation averages 52 inches per year and is evenly distributed throughout the year, with the exception of a slight increase occurring from December to March. Average annual temperature is 62 degrees Fahrenheit, with an average minimum of 42 degrees Fahrenheit in January and an average maximum of 80 degrees Fahrenheit in July.

Valley Creek provides drainage for the site area, Figure 2. Differential erosion by Valley Creek has created a highly dissected topography with resistant sandstone forming flats and less resistant shale forming slopes. Strong regional jointing in the surface rock formations creates a rectangular surface drainage pattern (and possibly controls subsurface reservoir flow). Differential erosion of the area is both lithologically and structurally controlled.

Forestry is the major land use within the Oak Grove Mine area. Much of the area is covered by an oak-hickory-pine forest. The dominant species of this forest include bitternut, mockernut, and pitnut hickories, white oak, post oak, northern and southern red oak, and loblolly and shortleaf pine. On ridges, the Virginia pine and scarlet oak are the dominant species. Numerous tracts of land within the mine boundary have been recently timbered.

The USS Mining Company, Inc., a subsidiary of USS, operates the Oak Grove Mine, which underlies the project site. This mine is developed in the Blue Creek coal seam of the Mary Lee coal group, which is approximately 1050 feet below the surface. The thin Mary Lee coal seam, which overlies the Blue Creek coal seam, is not mined at Oak Grove. The Oak Grove Mine is a room- and pillar-type mine utilizing continuous-mining equipment. Complete extraction (pillaring) is practiced at the

mine by removing the pillars of coal once development room and pillar panels have been blocked-out. The mine-block area consists of approximately 10 acres and is bounded on the east and southwest by boundary faults and on the northwest by the Sequatchie anticline. The DHM-7 project site is located in the east-central area of the Oak Grove Mine, Figure 3. The well was located in 1350 feet north of an advancing 5-entry continuous mining section, Figure 4. The surface location was centered over the left entry of the section. Locating the well in the center of the entry permitted up to 9 feet of east-west drilling deviation (0.5 degree) before the mine would miss the well bottom on mine-through. In addition, the well was located 1800 feet southwest of Grid Well 30-5-21, which is part of the 48-well Oak Grove Coal Degasification Field. This location also allowed for the placement of the well in a virgin to near-virgin coalbed area, yet also allowed for the near-term mine-through and observation of the well-bottom area and the determination of area of production influence of the well.

Site Geology

Warrior Basin

The coal-bearing strata of the Warrior Basin are in the Pottsville formation of Lower Pennsylvanian (Namurian-Westphalian) age and consist of sedimentary rocks which are predominately sandstones, siltstones, and shales. Seat earth (underclay), coal, and marine fossil zones make up the proportionally small remainder of the Pottsville strata, but are more laterally correlative than the other three primary lithologies.

These rocks were deposited in repeated sedimentary cycles, each of which contains the important coal beds of the Warrior Basin. Subdivisions of the Pottsville strata in the Warrior Basin are based on the major coal groups. Ascending a typical sedimentary cycle, they are: (1) a dark shale grading into a siltstone; (2) a bioturbated fine-grained sandstone; (3) a zone containing marine fossils; (4) a marine shale; (5) a siltstone; (6) a massive sandstone with the grain size generally increasing upward; and (7) a coal group including seat earth(s), which is commonly referred to as "underclay" or "fireclay", even when it is predominately sandy, coal seam(s), and nonmarine shale. Variations or "subcycles" of the nonmarine rocks within an individual coal group may occur. However, the depositional cycle between coal groups is remarkably similar, and a marine influence is present among all coal groups.

The Warrior Basin of Alabama and Mississippi is bounded to the north by the Nashville dome, to the southeast by the Appalachian folded and thrust-faulted belt, and to the west and southwest by the Ouachita belt, Figure 5. The Warrior Basin of Alabama is structurally much less deformed than the adjacent Appalachian folded and thrust-faulted belt. However, the basin does contain gentle folds, normal faulting, minor reverse faulting, and jointing.

The Sequatchie anticline is the largest single structural feature of the Warrior Basin in Alabama, Figure 6. It increases in deformational intensity along strike to the northeast, from a weakly asymmetrical anticline 20 miles west of Birmingham, Alabama, to an overthrusted anticline near the intersection of the Tennessee-Alabama-Georgia state lines. Numerous northwest-striking normal faults have been mapped in the Warrior Basin of Alabama, Figure 6. Individual faults have maximum vertical displacements ranging from a few tens of feet up to 400 feet. Strike lengths range up to five miles, with maximum vertical displacement usually occurring near the center of the surface trace of the fault. Reverse or thrust faults are rare in the Warrior Basin of Alabama. Data from the few observed thrust faults indicate that their strikes are generally parallel to the regional structural strike (i.e. northeast-southwest).

Origin of faulting is speculative, but a relationship to the Appalachian orogeny is considered likely for most faults. Surface observations and limited core data indicate that most faulting occurred after sediment lithification but before the deposition of the Upper Cretaceous (Cenomanian) Tuscaloosa formation.

Joints in the Paleozoic rocks of the Warrior Basin are ubiquitous. Regionally, these joints are described as belonging to one of two orthogonal joint systems[6]. The strikes of the joints in these systems are northeast and northwest. In the joint system that occurs roughly southeast of the Sequatchie anticline, the northwest joint set is the predominate set. In the other joint system, the northeast joint set is the predominate set.

DHM-7 Site

The degasification/methane production target in the Oak Grove Degasification Field, where DHM-7 is located, is the Blue Creek coal seam. The Blue Creek coal seam is a member of the Mary Lee coal group and is contained in the Pottsville formation of Lower Pennsylvanian age. This coal group also contains the New Castle, Mary Lee, and Jagger coal seams, Figure 7. The Blue Creek coal seam in the Oak Grove area

averages 5 feet in thickness and is at an average depth of 1100 feet. The overlying Mary Lee coal seam averages 1.5 feet in thickness and is seperated from the Blue Creek coal seam by a highly variable, silty-shale rock parting which averages 7 feet in thickness. The Jagger coal seam is noncontinuous and when present, lies 5 to 15 feet below the Blue Creek coal seam. Specifically at Well DHM-7, the Blue Creek coal seam is 4.50 feet thick, the Mary Lee coal seam is 2.33 feet thick, and the two coal seams are separated by 5.47 feet of silty shale. The top of the Blue Creek coal seam is located 1086.67 feet below the surface.

The Oak Grove Mine is bounded on the east and southwest by north-northwest trending normal faults, Figure 3. These normal faults have maximum normal displacements of 140 and 125 feet, respectively. Small normal faults have been encountered in the mine, with maximum displacement of 7 feet. The beds in the mine area dip to the southeast at a rate of approximately 50 feet per mile. No major geologic features were found in the area of DHM-7 during the underground mapping; however, several small geologic features were observed. A roll in the coal was mapped 150 feet southwest of DHM-7, with a strike of N42E. Also, a small fault was mapped 300 feet south and again 750 feet west of the well, with a strike of N67W, Figure 8. The Blue Creek coal seam in the vicinity of DHM-7 dips to the southeast, Figure 9.

A total of 804 joints were measured on the surface in the area surrounding the Oak Grove Degasification Field, as part of a joint and linear study, Appendix A. A rose diagram of these joint measurements indicates the presence of four distinct joint orientations, Figure 10. The most prominent joint set strikes 295^{0}. This joint set is present throughout the Oak Grove area with varying degrees of intensity. Six joints were mapped underground in the DHM-7 area with an average strike of 291^{0}, Figure 11. The jointing in this area appears to be less intense than in other areas of the mine. In conjunction with the surface joint mapping program, a surface linear study was also conducted. A total of 260 linears have been identified in the Oak Grove Degasification Field study area, Figure 12. These linears were traced from two photographs; a 1982 color infrared photograph and a 1951 black and white photograph. Figure 13 is a rose diagram of the visible linears greater than 500 feet in length. This rose diagram shows the major linear trend in the study area to be 340^{0} to 350^{0}, which is the approximate orientation of the normal faults in the area. Two lesser pronounced linear trends strike 020^{0} to 030^{0} and 280^{0} to 300^{0}.

Site Development

The selection of the location for Well DHM-7 was finalized on December 7, 1982. Surveying of the spud location, site perimeter, and power-line right-of-way began on December 8, 1982 and was completed on December 9, 1982. Site preparation (earth movement) began on December 7, 1982 and was scheduled to be completed by late December 1982. Unusual weather conditions (heavy and constant rainfall) delayed the completion of the site until January 7, 1983. The completed site measured 200 feet x 300 feet and was designed to accommodate the planned drilling, completion, testing, and stimulation hardware. Electric-power installation, which also was delayed because of inclement weather, was completed on March 18, 1983.

DRILLING AND COMPLETION

Drilling

On March 3, 1983, the driller began equipment mobilization in preparation for the start of drilling. Drilling in this portion of the Warrior basin commonly consists of a combination of rotary and rotary-percussion techniques. Rotary-percussion is the preferred method, as high penetration rates are achieved through the consolidated and indurated sediments (sanstones, siltstones, and shales). In addition, this method allows for the well to be maintained underbalanced, which limits formation damage. Circulation medium is typically a water/air mist, sometimes with the addition of a detergent to aid in cutting removal. Rotary drilling is typically used to penetrate the unconsolidated surface formations and to install the open hole intervals below the cased section. Water or a water-based mud is the typical circulation medium.

Drilling began on March 5, 1983 with the installation of a 12-1/4-inch-diameter, 16.58-foot deep hole through the unconsolidated surface material. Rotary drilling with fresh water as the circulation medium was used. Following the installation of the surface casing (see Casing and Cementing), the bit was changed to an 8-1/2-inch-diameter percussion bit for the main section of the well. An air/water mist was used as the circulation medium for this portion of the well. Numerous mechanical problems with the drill rig, the auxiliary compressor, and the drill bits slowed the penetration significantly. The drilling of this section was completed to the planned total depth (TD) of 1056 feet on March 15, 1983. The lithologic log of the formations penetrated, as observed from the collected cuttings, is presented in Table I.

Prior to the installation of the casing and the completion of the well, a section of large-diameter core was recovered (see Coring) from the well and a series of stress tests were performed (see In-Situ State-of-Stress Testing). Once the stress tests were completed, the 7-inch-diameter open-hole section exposed by the coring was reamed. To allow for the placement of the casing and casing hardware, an 8-1/2-inch-diameter rotary bit, with fresh water as the circulation medium, was used to ream the cored interval from 1056 feet to 1116 feet. Reaming began on April 6, 1983 and was completed on April 7, 1983.

Once the well was cased and cemented, the wash-down plug and packer shoe were drilled out utilizing a 6-1/4-inch-diameter rotary bit and fresh water as the circulation medium. This completed the drilling activity on

Well DHM-7. A summary of the drilled intervals is shown in Figure 14.

Coring

As part of the reservoir evaluation program, an extensive suite of rock and coal core tests was planned. To recover sufficient core sample, especially of the target coal seams, a coring program was developed that incorporated the recovery of large-diameter core (6 inches). Core recovery in this area of the Warrior Basin is usually very high, commonly over 95 percent. However, the coal seams are normally not recovered intact, because of the extreme friability of the coal. The large-diameter core was selected because it was believed that the recovered coal core would yield some samples of sufficient size to permit core testing.

The coring rig mobilized on March 16, 1983 and began coring on March 19, 1983. Coring began at the previously completed open hole TD of 1056 feet and continued to the coring TD of 1116 feet, which was reached on March 25, 1983. Coring was by the wireline method with recovered core runs of approximately 10 feet. Details of the intervals cored and the core recovery are listed in Table II. Recovery of the rock units surrounding the coal seams was excellent, over (>99%). However, core recovery of the coal seams was very poor (<40%) and the recovered coal was very badly broken. The highly friable nature of the coal, the weight of the overlying cored rock units resting on the coal core in the core barrel, and the flushing action of he circulating fresh water all contributed to the lack of recovery. A summary of the cored interval is presented in Figure 14. Because of the poor core recovery in the coal seam sections, supplementary blocks of coal from the active mine workings near the location of Well DHM-7 were recovered (see Core Testing).

Recommendations for future large-diameter coring of friable coal formations in the Warrior and other coal basins include 1) reducing the length of the core run from 10 feet to less than 5 feet, 2) limiting the amount of rock resting on top of a coal formation during coring, and 3) reducing circulating water to the minimum required for cutting removal.

Casing and Cementing

The casing and cementing plan developed for Well DHM-7 consisted of 1) the installation of a surface casing string and 2) the installation of a production casing string. The surface casing string was installed to protect the surface groundwater

and to provide for a stable surface collar for the deep drilling of the well. The production casing was installed to provide controlled access to the target formation (Blue Creek coal seam) and to provide isolation of the target formation from the overlying formations, especially the Mary Lee coal seam.

The surface casing was set in place immediately following the completion of the rotary drilling of the unconsolidated surface formations on March 5, 1983. Seventeen feet of 10-3/4-inch OD, J-55 casing was used. The casing was set to the hole TD of 16.58 feet and API Class A cement was poured into the annular area between the casing and the open hole. No casing hardware was used and the casing rested on the hole bottom. Details of the cementing of the surface casing are shown in Figure 15.

Following the completion of the reaming on April 7, 1983, installation of the production casing string began. The casing string (7-inch OD, K-55, Range 2, 26-lb/ft) included centralizers along the length of the string and a Halliburton formation packer shoe on the bottom end of the casing string. The packer shoe was used to guide the casing in the hole and to allow for cementing of the casing above the target formation without cementing across the formation. The casing was floated into position in the well with the packer shoe located at 1086.96 feet, which was located in the rock parting between the Blue Creek and Mary Lee coal seams. The open-hole section below the casing string was filled with sand to further protect the target formation, in case of leakage of the packer element in the packer shoe. Once the casing was placed at the target location, the cementing contractor flushed the latch-down plug down the casing, inflated the packer element, and opened the ports obove the packer element. When circulation was established, the casing was cemented into place using API Class A Pozmix cement preceded by a precement gel to assist in fluid-loss control. Details of the cementing operation are listed in Table III and a completed well schematic is shown in Figure 15.

Geophysical Logging

A series of geophysical logs were run to assist in the reservoir testing and hydraulic stimulation design of Well DHM-7. Logging included both open- and cased-hole logs and a directional survey of the well. These logs are described in detail below.

Open Hole Logs

Open-hole logs were run prior to the casing and cementing of Well DHM-7. The logging suites were designed to establish the location of the target coal formations and to determine certain characteristics of the formations. The logs run included 1) single-arm caliper, 2) bed resolution density, 3) long-spaced density, 4) gamma ray, and 5) multi-channel sonic. The caliper, density, and gamma ray logs were used by the logging service company to generate a Seam Thickness Log, Figure 16, and a Coal Quality Log, Figure 17. These logs provide a detailed expansion of the coal group areas and permit accurate determination of coal seam thickness and coal seam specific gravity. The sonic log, Figure 18, was used to establish detailed property profiles of static values for use in fracture propagation models (see Core Testing).

Cased Hole Logs

A micro-seismogram bond log was run prior to the perforation of the casing to expose the Mary Lee coal seam. The bond log, Figure 19, was used by the perforating service company to design the charge size and distribution. Analysis of the bond log indicated an excellent cement bond throughout the total length of the production casing string.

Formation Exposure

Abrasi-Jetting

Following the completion of initial reservoir testing on the Blue Creek coal seam, the well was prepared for coal-seam notching. An abrasi-jetting tool, which was attached to 2-3/8-inch tubing, was positioned in the center of the Blue Creek coal seam. Abrasi-jetting consisted of pumping a water/sand slurry (1-1/2 pounds sand per gallon water) down the tubing and through the abrasi-jetting tool at a rate of 1-1/2 to 2 barrels per minute. The success of the operation was indicated by the presence at the surface of large quantities of coal fines and large pieces (1/8 to 3/8 inch) of coal. Enough coal was produced to warrant its collection for desorption testing (see Desorption Testing). A total of 1200 pounds of 20 x 40 mesh sand and 800 gallons of fresh water were utilized in the operation. Following the completion of the abrasi-jetting, the well was flushed with fresh water to remove any coal fines.

Perforating

To provide access from the wellbore to the Mary Lee coal seam, the 7-inch-OD casing and cement was perforated on September 7, 1983. Prior to the perforation, a cement bond log was run (see Geophysical Logging) to evaluate the condition of the cement behind the casing and to design the perforation charges. Utilizing a wireline perforating gun, the casing was perforated with 8 shots at 4-inch spacings over the interval from 1078 feet to 1080 feet.

Well Abandonment

Prior to the underground mine-through of well DHM-7, the well was plugged. The subsurface pump, tubing, and sucker-rod string were pulled from the well and the casing head and associated surface production equipment was removed prior to the cementing operation. On December 3, 1985, 150 feet of cement was placed in the bottom of the well and 100 feet of cement was placed in the top of the well. This completed the abandonment of Well DHM-7.

RESERVOIR TESTING

Hydrologic Testing

To determine the hydrologic properties of the Blue Creek and Mary Lee coal seams, a series of slug and injection tests were conducted on Well DHM-7. The results of these tests were used to determine in-situ coal-seam permeabilities and possible well-bore damage. The tests were performed separately on the Mary Lee and Blue Creek coal seams and the Blue Creek coal seam was tested both before and after it had been abrasi-jetted.

Well testing was first introduced by ground-water hydrologists but is now used extensively in the petroleum industry. Several assumptions are made for these tests, including 1) complete penetration of the fluid across the height of the formation, 2) no leakage out of the formation, 3) a homogeneous formation, 4) laminar (Darcy) flow, 5) constant formation thickness, and 6) an isotropic aquifer. With these assumptions and the data obtained, the permeability of the Mary Lee and Blue Creek coal seams in the area of the Well DHM-7 were estimated.

Two injection tests were conducted on the Blue Creek coal seam in Well DHM-7 in April and May 1983. The first test was conducted before the coal seam was abrasi-jetted and the second, following abrasi-jetting. Figure 15 shows the completion of the well. The Blue Creek test zone was at a depth of 1086.67 feet with a thickness of 4.50 feet. The 8-3/4-inch-diameter open-hole section from the bottom of the 7-inch-OD to the TD of the well was 29.70 feet in length.

The pressure-buildup testing required determining a base-period water level in the borehole. A stable-water-level period before testing is an important part of a pressure buildup test. If stabilization is impossible, standard data analysis techniques may provide erroneous information about the formation. Fortunately, because of the slow rate of change in hydrostatic head, a 1-week period with stable water levels (corresponding to a bottom-hole pressure of 344 psi) was easily obtained immediately before injection of fluid for the first test. Following the establishment of the base period, water was injected into the borehole at a constant rate of 6.0 to 6.1 gallons per hour with a positive-displacement, piston-type metering pump. A schematic diagram of the test equipment arrangement for the first test is shown in Figure 20. Water flow was measured by a rotameter and occasionaly by timed water samples. Pressure at the coal seam was determined with an electronic downhole pressure sensor and was checked by monitoring the water level in the well to determine the

hydrostatic head.

The results of the pre-abrasi-jetting injection test are listed in Table IV and shown graphically in Figure 21. Using the slope of the injection curve and the method suggested by Earlougher[7], a coal-seam permeability of 1.2 millidarcies (md) was obtained; using a type-curve method described by Agarwal[8], a coal-seam permeability of 2.9 md was obtained, Figure 22.

Following the injection test, a constant-pressure flow test was run for 1000 minutes. In this test, water was pumped into the borehole at a constant rate and the water level was maintained at an equilibrium level. In this case, the hydrostatic head was sufficient to drive the water into the formation at the same rate as it was being pumped into the well. Analysis of this data using a method suggested by Garb[9] gave a permeability of 2.9 md. These values for permeability are similar to other values obtained in the Oak Grove Degasification Field for the Blue Creek coal seam.

Another injection test was conducted after abrasi-jetting the Blue Creek coal seam. This abrasi-jetting treatment enlarged the wellbore diameter to an estimated 24 inches. The plot of the pressure-response data is shown in Figure 23. The downhole pressure stabilized after 2 hours of injection at a rate of 3.7 gallons per hour. The pressure fluctuated within a 2 psi range during the period from 2 hours after the start to the end of the test. This type of pressure response is unusual. The wellbore storage constant (C = 0.0026 bbl/psi) calculated from the first 2 hours of data seems to indicate injection into a small-diameter tubing (Internal Diameter = 1.1 inches). The stabilization of pressure after 2 hours may be due to the development of a small leak at a rate approximate to the injection rate. A straight-line analysis of data from the 4-day period following this second injection test yielded a permeability of 1 md and a skin of -4, Figure 24. Preabrasi-jetting test results indicated an in-situ permeability of 1 md. Within the accuracy of the data, no improvement in the coal-seam permeability resulted from abrasi-jetting. However, the data response from the second test is suspect because of the erratic pressure response.

Following the post-abrasi-jetting hydrologic studies, unsuccessful attempts were made to establish unstimulated gas production. During this period, a thick sludge was produced with the produced water. An injection test was run in August 1983 to determine if this sludge might be reducing coal-seam permeability and inhibiting the production of gas and water. Following the removal of the downhole pump, the water level in the well stabilized at 748 feet above the Blue Creek coal seam. Injection was then begun into the open hole at a constant rate of 3.78 gallons per hour and continued for 48 hours. During

this injection period, the water level in the well and injection rate were monitored continuously. The data obtained, using a method suggested by Earlougher, are presented in Figure 25. The results of this test indicated an in-situ permeability of 1.1 md. Following the injection test, the decline in the water level to an equilibrium level was monitored. Analysis of this data using the Horner Method, Figure 26, also indicated an in-situ permeability of 1.1 md.

The in-situ permeability of the Mary Lee coal seam in the Oak Grove area had never been determined. Once this coal seam was exposed in Well DHM-7, an opportunity existed for this initial measurement. Following the isolation of the Mary Lee coal seam in October 1983 using an inflatable packer, Figure 27, the water level in the well was permitted to equilibrate. After a 1-week period, the change in water level in the well was less than 0.05 foot per hour. Because of the slow rate of rise, indicative of nearing equilibrium, the injection test was started. After 4.5 days of injecting water at a rate of 3.75 gallons per hour, the water level was 629 feet above the Mary Lee coal seam. Analysis of this data indicated an anomalously high permeability. Therefore, the injection was stopped and the change in water level was monitored. The measurements indicated that the water level in the well was rising, not declining, although no water was being added to the well.

The water level was monitored over a 48-hour period during which no water was injected, but the water level continued to rise. After the 48-hour period, with the water level at 634 feet above the coal seam, 60 gallons of water were added as a slug in an effort to bring the water level to equilibrium. The water level following the addition was 670 feet above the coal seam (an increase of 36 feet). The capacity of the well is such that a 60-gallon water addition should have raised the water level 45.5 feet. The difference between calculated and actual water level suggests that 13.2 gallons of the 60-gallon addition flowed into the formation. Following this addition, the water level was monitored to determine if equilibrium conditions had been achieved. Measurements indicated that the water level was still rising.

Because the water level apparently had not yet reached equilibrium, additional water was added to bring the water level to a point 793 feet above the coal seam. This level was equivalent to the hydrostatic equilibrium point for the underlying Blue Creek coal seam, which was measured in May 1983. To reach this level, it was necessary to add 205 gallons of water. The calculated capacity of the well was such that 162 gallons of water should have raised the level to 793 feet above the coal seam. This indicated that 43 gallons of the 205 gallons flowed into the formation. Following the addition of the 205 gallons of water, the water level was monitored and the

level continued to rise at a rate of 2.4 feet per day. At this point, because of a lack of manpower and funds, the test was aborted.

Because of the problems encountered with the injection test of the Mary Lee coal seam in October 1983, a short-term slug test was scheduled which could determine an estimate of the transmissivity of the Mary Lee coal seam. In the slug test method of hydrologic analysis, a known volume of water is suddenly injected into a well and the following decline in the water level in the well is measured at specific intervals over a period of time. A semi-log plot of the change in water level versus time results in a curve from which a match point is obtained. This match point can be used to estimate transmissivity and possibly skin damage[7,10].

Figure 28 shows the well configuration during the slug test. To isolate the Mary Lee coal seam, inflatable packers were installed above and below the coal seam. To reduce the wellbore storage effect, 2-3/8-inch tubing was attached to the top packer. This reduced the water storage from 1.61 gallons per foot for the 7-inch casing to 0.162 gallon per foot for the 2-3/8-inch tubing. A downhole pressure transducer attached to a surface readout and collection device was used to measure and record the changes in water level during the slug test.

The test began on April 9, 1984, with the injection of a 57.5-gallon slug of water. Initially the water level was measured using both the pressure transducer and an electric probe. After the pressure transducer readings were confirmed with the electric probe, the use of the electric probe was discontinued. The collected data were analyzed by the type-curve method of Ramey[11], and are shown in Figure 29. This analysis yielded a permeability of slightly less than 1 md with practically no skin damage observed. The match of the data to the type curve is quite good and can be attributed to the reliable static water level obtained before the start of the test and the careful monitoring of the water level following the injection of the slug of water.

The results obtained both before and after the Blue Creek coal seam was abrasi-jetted, the results of the tests on the Blue Creek coal seam following the sludge production, and the results of the Mary Lee coal seam slug test are presented in Table IV. In all five tests, different methods were utilized to calculate permeability from the collected data. The first three methods use the slope of the plotted data to determine the permeability. The fourth method uses the pressure drop developed at a constant injection rate and a constant head to determine permeability. The fifth method involves fitting test data against previously established curves to determine permeability. All these methods require judgment decisions by the investigator. Therefore, the

variation in results for the Blue Creek coal seam, 1.0 to 1.3 md for the first three methods and 2.3 to 2.9 md for the last two methods, would indicate little variation in permeability of the formation under three conditions studied. In general, the permeability of the Blue Creek and Mary Lee coal seams in the vicinity of Well DHM-7 was about 1 md.

In-Situ State-of-Stress Testing

In March 1983, a series of in-situ state-of-stress measurements were conducted on four zones in the open-hole sequence of DHM-7 prior to installation of production casing. These tests consisted of a series on minature hydraulic stimulations, "micro-fracs", using water as the stimulation fluid and total injection volumes less than a few hundred gallons. The tests were planned to determine some of the stratigraphic mechanical properties which affect the propagation of hydraulically induced fractures. However, the tests were conducted from a research perspective with one objective being to identify procedures to be used in subsequent tests of coalbed reservoirs. Further details of the test procedure and analysis are provided in Appendix B.

The zones selected ranged from the rock above the Mary Lee coal seam through the rock below the Blue Creek coal seam, Figure 30, and included one coal and three rock intervals. The zones were sequentially isolated with a nitrogen-gas-activated, surface-infatable straddle packer set to a 3.5 foot interval. The surface-inflatable feature was selected to enable the straddle packer to be relocated and reset within the hole without being removed to the surface for refitting. At the time of the tests, it was not possible to reset liquid- (water) set packers without refitting on the surface. Problems encountered during this test sequence associated with the gas-set packers can now be eliminated using resettable water-set units.

Pumping rates for the "micro-frac" tests were nominally 2.25 to 3.5 gallons per minute. Breakdown, propagation, and shut-in pressures were recorded during a minimum of four pumping cycles per zone (see Figure 1, Appendix B for a schematic illustration of the key features of the micro-frac logs obtained in in-situ stress tests).

The micro-frac logs from the three rock intervals initially appeared to exhibit the classical breakdown behavior during the initial cycle. However, a series of field tests were designed and conducted on-the-fly to confirm the integrity of the test procedure. In this series, injection tests were run for a series of different packer setting pressures. The adjustments in setting pressure could easily be made by

regulating the gas inflation pressure on the surface. These tests clearly showed that the packers were not maintaining a good seal with the wellbore (for example see Figure A11, Appendix B). The characteristic features in the micro-frac logs were a result of the injection fluid breaking through the packer-rock contact.

Consequntly, usable data were not obtained from any of the rock intervals. However, data for the parting between the two coal seams were interpreted as indicating breakdown pressures in excess of 1450 psi and instantaneous shut-in pressures in excess of 1150 psi. These interpretations are theoretically consistent with horizontal stresses in the range 900 to 1100 psi which would be expected on the basis of depth of burial and with tensile strengths in the range 200 to 1000 psi which are similar to values measured for correlated rocks from other sites. Using these values, breakdown pressures would be predicted to be as high as 2000 psi. It would have been impossible to isolate injection fluid pressures in excess of 1800 psi with the gas-set packer configuration used. Note, in particular, that the tensile strength range is consistent with Brazilian tensile tests on laboratory samples of parting material from the core; whereas, the stress and breakdown values quoted are consistent with more recent and detailed results from the Rock Creek site[12].

The micro-frac tests on the Blue Creek coal seam appeared to be successful. During the initial pressurization cycle, the micro-frac logs for the Blue Creek coal seam interval showed a rollover characteristic of pre-fractured media instead of the breakdown peak associated with competent rock, Figure 31. Analysis of the propagation data provided a value of 1080 psi for the instantaneous shut-in pressure which was subsequently identified with the minimum vertical component of the in-situ stress in the coal seam.

More detailed analyses of the micro-frac tests were conducted in conjunction with a rock mechanics study described later, see Appendix D. Analysis of the pressure decline following shut-in indicated the presence of two closure stresses. The higher pressure closure which is in the range 1080 to 1280 psi is potentially associated with secondary vertical fractures in the maximum horizontal stress direction or, more likely, with horizontal fractures. The vertical stress opposing horizontal fractures is calculated to be 1180 psi based on a geostatic gradient of 1.08 psi per foot. The second, or lower pressure, closure is in the range 850 to 950 psi and is potentially associated with primary vertical fractures propagating perpendicular to the minimum horizontal stress direction.

As part of the initial in-situ stress test plan, an oriented impression packer (122 inch active length) was set

against the coal seam interval at a pressure of 1500 psi for 2.5 hours following the micro-frac tests. Upon retreival, the membrane showed a prominent vertical fracture with the same orientation as the impressions of the face cleat of the coal seam. Furthermore, the direction of the cleat from the orineted impression packer was consistent with the average direction observed in nearby mining operations, N65E.

Values for the fluid leak-off coefficient for the coal seam were obtained during the detailed analysis of the post micro-frac shut-in period. A history match of the shut-in pressure decline data to type curves reported by Nolte[13] gave values for the leak-off coefficient in the range 0.001 to 0.002 $ft/(min)^{1/2}$. This range is consistent with values (0.0013) calculated from the Howard and Fast equation for a pressure drop of 500 psi and assuming a coal seam compressibility of 3.5×10^{-5} psi-1, permeability of 4 md, and porosity of 0.04. More extensive field tests, simulations, and correlations at the nearby Rock Creek site[12] have produced values for coalbed reservoir properties that are generally consistent with these assumed values.

Subsequent to additional prestimulation well testing and production studies and just prior to the major hydraulic stimulation, a mini-frac test was conducted on the isolated Blue Creek coal seam. In this test 20 barrels of a cross-linked gelled water (Dowell Waterfrac 40) were pumped at an average rate of 3.57 barrel per minute. Values for the leakoff coefficient of about 5×10^{-4} $ft/(min)^{1/2}$ were obtained from analysis of pressure decline data following the mini-frac shut-in. This value is lower than that obtained in the micro-frac test by an amount which can be accounted quantitaively by the difference in viscosities of the fluids used in the two tests.

Methane Desorption Testing

During the abrasi-jetting of the Blue Creek coal seam in April 1983, substantial quantities of coal chips and fines were generated. Until then, no gas was produced from the Blue Creek coal seam, and the seam had been under a hydrostatic head equal to or greater than formation pressure. Because of this, the gas content of the coal seam should have been near the virgin gas content. In addition, during the collection of the large-diameter core, the coal was seen to be visibly degassing on the surface. However, no attempt was made to measure the gas content of the core because of its planned use in core tests.

An attempt was made to collect the coal chips recovered during the abrasi-jetting and perform the standard U. S. Bureau

of Mines desorption testing[14]. It was hoped that the measured gas content would be near the anticipated in-situ gas content. Chips were collected and placed in two methane desorption canisters for testing. Data collected during the 8 months of desorption testing are presented in Tables V and VI and displayed graphically in Figures 32 and 33.

Analysis of the desorption data indicated that the gas content of the collected chips, identified as Canister A and B, was 183 and 242 cubic feet of methane per ton of coal (cft) (5.69 and 7.54 cc/gram), respectively. These values are low when compared to core samples recovered from the Blue Creek coal seam in other areas of the Oak Grove Degasification Field, which averaged 450 cft. The discrepancy between this average value and the average of the two abrasi-jet chip samples (212 cft) can probably be attributed to the method of collection of the two types of samples. The core samples represent the in-situ virgin gas content conditions because of the size of the samples and the speed in which the samples are recovered and placed in the desorption canisters. On the other hand, the chips are very small, allowing for a more rapid desorption and loss of gas prior to placement in the canister. In addition, the time required to recover the chips from downhole is longer than in core recovery, due in part to the velocity of the flushing water and the size and specific gravity of the chips.

CORE TESTING

Rock and coal samples from the six-inch diameter core were selected for laboratory studies of reservoir and mechanical properties. Because of the limited amount of intact coal retreived, the core material was supplemented with coal samples obtained from underground mining operations in nearby parts of the Blue Creek seam. A summary is presented here of results for selected properties which have a direct bearing on interpretation of field tests, design of stimulation treatments, and prediction of methane and water production. The more general study was performed be Dowell Rock Mechanics Laboratory and is discussed in the following General Core Evaluation Sub-Section; more details can be found in Appendix D. An extensive study of the stress-dependence of permeability and of gas sorption effects conducted by the University of California at Berkeley is reviewed in a subsequent Sub-Section; details are presented in Appendix C,

General Core Evaluation

Gas permeabilities of the rock strata, which were primarily shales, were found to be very low. Measured values were less than 0.004 md at a confining pressure of 1000 psi and were near the limits of the equipment used. Rock porosities were measured by standard core laboratory techniques and found to be of the order of a few percent.

Coal seam cleat porosities were determined both by a water saturation technique and by a time-dependent analysis of a Boyle's law procedure. Measured porosity values were in the range of 3 to 6 percent. Conventional Boyle°s law analysis produced values for total coal matrix porosity which were in the range from 16 to 23 percent. A single gas permeability measurement for a coal sample gave a value of 1 md. Generally laboratory measurements of coal samples give permeabilities that are one or more orders of magnitude lower than field or in-situ values. However, the value from the present laboratory study compares favorably with field values which have been inferred to be about 2.5 md. These porosity and permeability measurements support the conjecture that the coal seams are the only effective reservoir strata or aquifiers in communication with the wellbore.

Static and dynamic mechanical properties were measured for rock and coal samples. The rock samples were highly competent and, consequently, were amenable to a variety of tests. Only a few preliminary mechanical property tests could be conducted on the friable coal samples.

One primary objective of the test plan was to provide a basis for interpreting or calibrating sonic well-log responses (dynamic values) to obtain detailed property profiles of static values for use in fracture propagation models. Dynamic moduli and Poisson's ratio are generally higher and lower, respectively, than the static values; however, in general the static and dynamic values are well correlated. For the shales tested, static values for Young's modulus ranged from 5 to 7×10^6 psi, Poisson's ration ranged from 0.20 to 0.25, and specific gravities were in the range from 2.70 to 2.76.

Brazilian tensile tests for shale samples indicted strengths in the range 600 to 1500 psi for horizontal fractures and in the range 2000 to 3400 psi for vertical fractures. Compressive strengths for shale samples ranged from 10,000 to 25,000 psi; whereas, coal compressive strengths were commonly in the range from 1000 to 4000 psi. Coal samples did not show any tensile strength within the limits of the Brazilian tests.

Samples were cut from the core corresponding to the shale parting between the Mary Lee and Blue Creek coal seams for differential strain curve (DSC) and differential wave velocity analyses (DWVA) to further define in-situ stresses. Based on a vertical stress calculated from the geostatic gradient, the principal horizontal stress components in the shale parting were determined from DSCA to be 1010 and 1060 psi with the minimum stress direction being N60W. The stress orientation was corroborated by the DWVA study. The low horizontal stress ratio in the shale strata is consistent with the general correlation with rock type observed in the more extensive tests at the Rock Creek site[12]. The stress contrast between the coal seam and the parting is slightly higher than determined at the nearby Rock Creek site; whereas, the direction of the minimum stress is normal to the generally accepted cleat direction and more nearly aligned with the joint orientation in the region.

Coal Permeability/Sorption Evaluation

An extensive study was made of the permeability, porsity, and sorption characteristics of coal samples. Because of the limited amount of intact coal obtained from the core, tests were also conducted on coal obtained from the Oak Grove Mine which was extracting coal from the same Blue Creek coal seam of the Mary Lee coal group. Details of this study are presented in Appendix C.

Laboratory measurements of permeability of coal samples usually return values one or more orders of magnitude less than obtained from well tests or production history matches. This difference is generally attributed to selection of coherent

HYDRAULIC STIMULATION

Stimulation Design

In preparation for the hydraulic stimulation of Well DHM-7, a stimulation design was selected in April 1984 based on available data. These data included 1) preliminary fracture modeling by the selected pumping company, 2) preliminary fracture modeling by the DOE, 3) results from previous stimulations in the Oak Grove area, 4) reservoir tests performed on Well DHM-7 (hydrologic and in-situ state-of-stress), and 5) coal and rock core tests performed on samples recovered from DHM-7. The selected design consisted of 95,000 to 100,000 gallons of a guar gum (linear) gel with 35,000 to 40,000 pounds of 20- x 40-mesh sand as proppant. The pumping rate will be dependent upon the measured bottomhole pressure. A bottomhole pressure threshold of 2500 psi was selected to minimize potential damage to the rock unit overlying the Blue Creek coal seam. In addition, a small volume (1000 gallons) mini-frac was to be implemented one day prior to the main stimulation. Any additional data collected during this mini-frac could then be utilized to modify the planned stimulation.

Stimulation Implementation

Well DHM-7 was hydraulically stimulated on May 6, 1984, following the completion of the reservoir tests. The Blue Creek coal seam, exposed in the open-hole section of the well, was selected as the target zone for the treatment. To isolate the target seam from the overlying Mary Lee coal seam, which was exposed through perforations, an inflatable packer was set below the perforations and the treatment was through the tubing, Figure 34. To monitor bottomhole treating pressure during the stimulation, 1/4-inch-diameter stainless steel tubing was installed in the 2-3/8-inch-OD production/treating tubing and was terminated downhole at the target formation. A pressure transducer was attached to the stainless steel tubing at the surface to record the static surface pressure and permit the calculation of a reflected bottom-hole pressure, Figure 34. In addition, the treating-line pressure and fluid density were monitored, along with pumping rates.

Throughout the treatment, the bottomhole pressure was controlled by adjusting the pump rate. The maximum bottomhole treating pressure was limited to 2500 psi to avoid excessive fracture-height growth. This pressure was selected based on experience at other coalbed methane wells in the nearby area. The time versus pressure and pump-rate record is shown in

Figure 35 and a treatment summary is presented in Table VII. A Nolte-Smith plot[17] of the same data, using a bottomhole closure stress of 1200 psi, is shown in Figure 36. In addition, results of a prestimulation mini-frac are presented in Appendix E and the evaluation of the mini-frac and main stimulation treatment by the contracted pumping company is presented in Appendix F.

One possible analysis of the stimulation record which correlates fracture geometry with the observed pressure record would be that 1) initially and up to 1 hour into the treatment, the pressure increased with time, indicating that a vertical fracture was being extended in length with a contained height; 2) from 1 hour until 3.5 hours pumping time, the pressure continued to decline slowly, indicating possible formation of a horizontal fracture in combination with vertical fracture extension; 3) at 3.5 hours into the treatment, a sudden pressure increase may represent a plugging of part of the fracture system at or near the wellbore; and 4) the instantaneous drop in bottomhole pressure recorded at the end of the job could be attributed to removal of the fracture-entry pressure loss after shut-in. The entry-loss (plugging) explanation for the pressure rise is corroborated by the fact that the pressure records before the rise can be extrapolated through the bottomhole instantaneous shut-in pressure. The main fracture probably continued to extend smoothly and the observed pressure rise occurred because of this near-wellbore obstruction of part of the fracture cross-section.

One other feature of the stimulation of Borehole DHM-7 was the use of a locking agent to immobilize the propping sand. Mobile proppant sand reaching the wellbore has been a recurring production problem with coalbed methane wells in the area. An epoxy-coated sand slurry was injected at the end of the treatment with a planned penetration distance of 30 to 50 feet into the fracture. When cured, this sand/resin mixture retains 80 percent of the permeabilty of the uncoated sand which, for the 40x60-mesh sand used in the treatment, was 36 darcys. Following the underground mine-through of the induced fracture, samples of this hardened sand/resin mixture were collected. Although no laboratory tests were conducted on these samples, it was observed that the hardened sand/resin mixture had maintained very high permeability. Water poured on a hand-held sample quickly ran through the sample and no coal fines were visually observed within the hand sample.

Stimulation Modeling

A series of fracture stimulation simulations were run throughout the course of this study using conventional service-company design programs and developmental models. A

particularly detailed and well-documented series of studies were conducted by Dowell Rock Mechanics Laboratory; see Appendix D, E and F for more details.

Following the full set of pre-stimulation studies, a final set of simulations was conducted based on the proposed stimulation design. Propagation of both vertical and horizontal fracture wings were simulated for several reasons. First, the difference between the vertical stress component and the minimum horizontal stress obtained from field-based micro-frac data and from laboratory differential strain analyses were small. This difference is much less than the large propagation over pressures generally encountered in coal seam stimulations. Consequently, from a theoretical and model perspective, horizontal and vertical fractures are possible. Furthermore, direct observations of mined-through stimulations in nearby parts of the Blue Creek coal seam have disclosed fractures with both horizontal and vertical components[18].

In-mine and core observations have shown that slicken-sided faces are common at the coal seam-shale parting interface. These smooth, noncoherent surfaces indicate that slippage had occured on this plane during geologic time and could be a factor both in containing vertical fracture growth and in initiating horizontal fractures. Other observations of mined-through induced-fractures in this region supported this expectation. Consequently, vertical fracture propagation was studied in terms of a Khristianovich type model to account for vertical containment.

Three simulations based on the major hydraulic design stimulation schedule were conducted corresponding to (1) vertical fracture only, (2) horizontal fracture only, and (3) combined vertical and horizontal components with 25% of the frac fluid entering the horizontal component. The results are summarized in Table VIII; more details are presented in Appendix F. In view of the then current state-of-the-art in simulation of hydraulic fracture propagation in coal stratigraphies, these results are in impressive agreement with the observations discussed subsequently.

One salient feature of these simulations is that the excess pressure required to maintain the induced fractures is, in all cases, less than 100 psi. Recently, possible causes for the high over pressures observed in coal seam stimulations have been proposed and analyzed. However, none of the models available at the time of these simulations were capable of accounting for high propagation pressures.

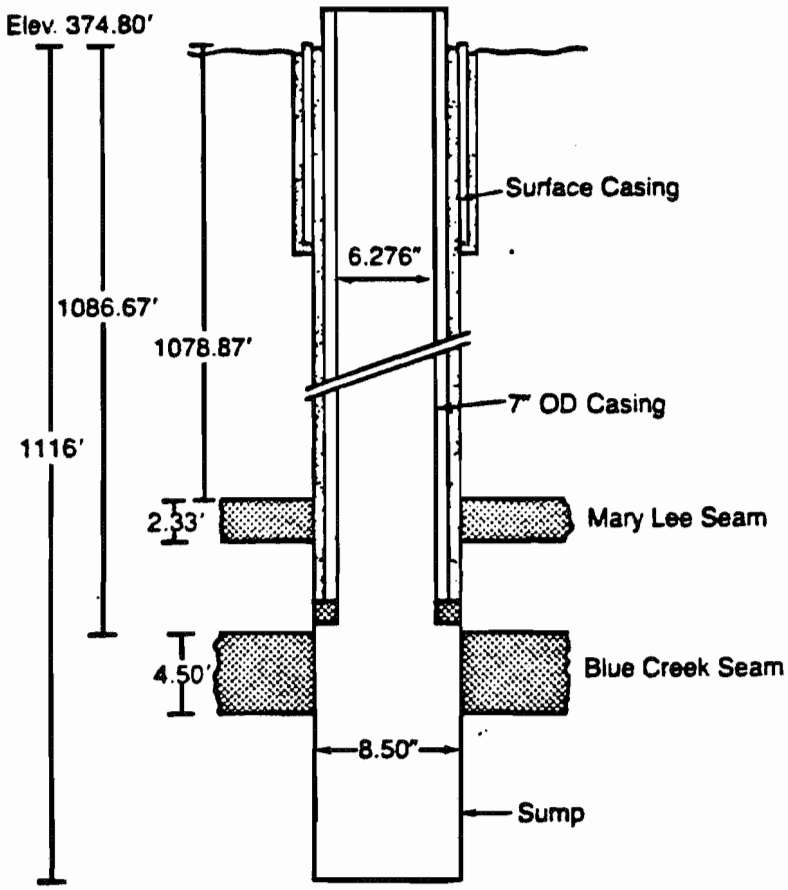


Figure 15 - Well DHM-7 Schematic
Post Casing and Cementing

Figure 16 - Seam Thickness Log, Well DHM-7
Oak Grove, Alabama

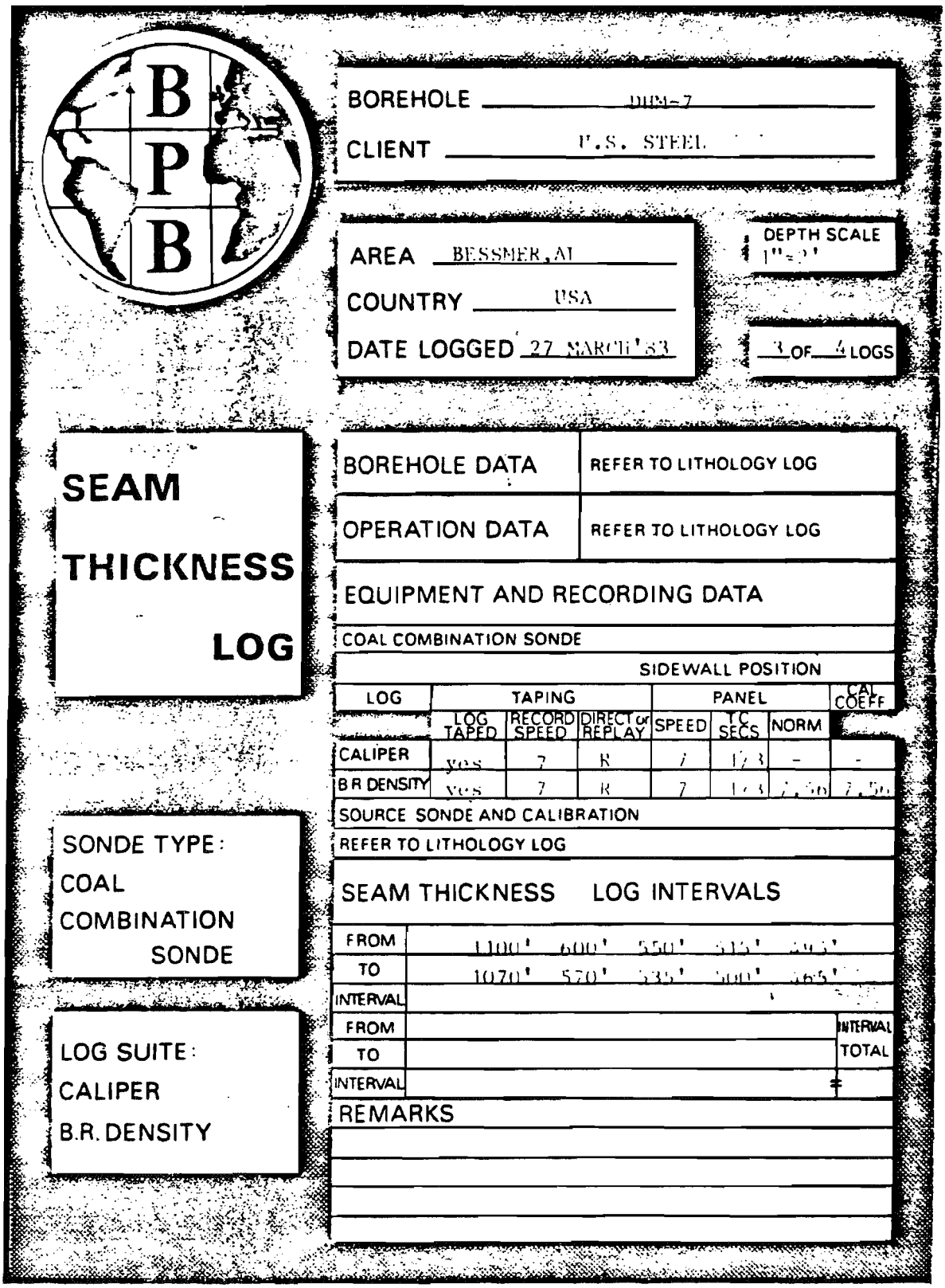


Figure 16 (cont)

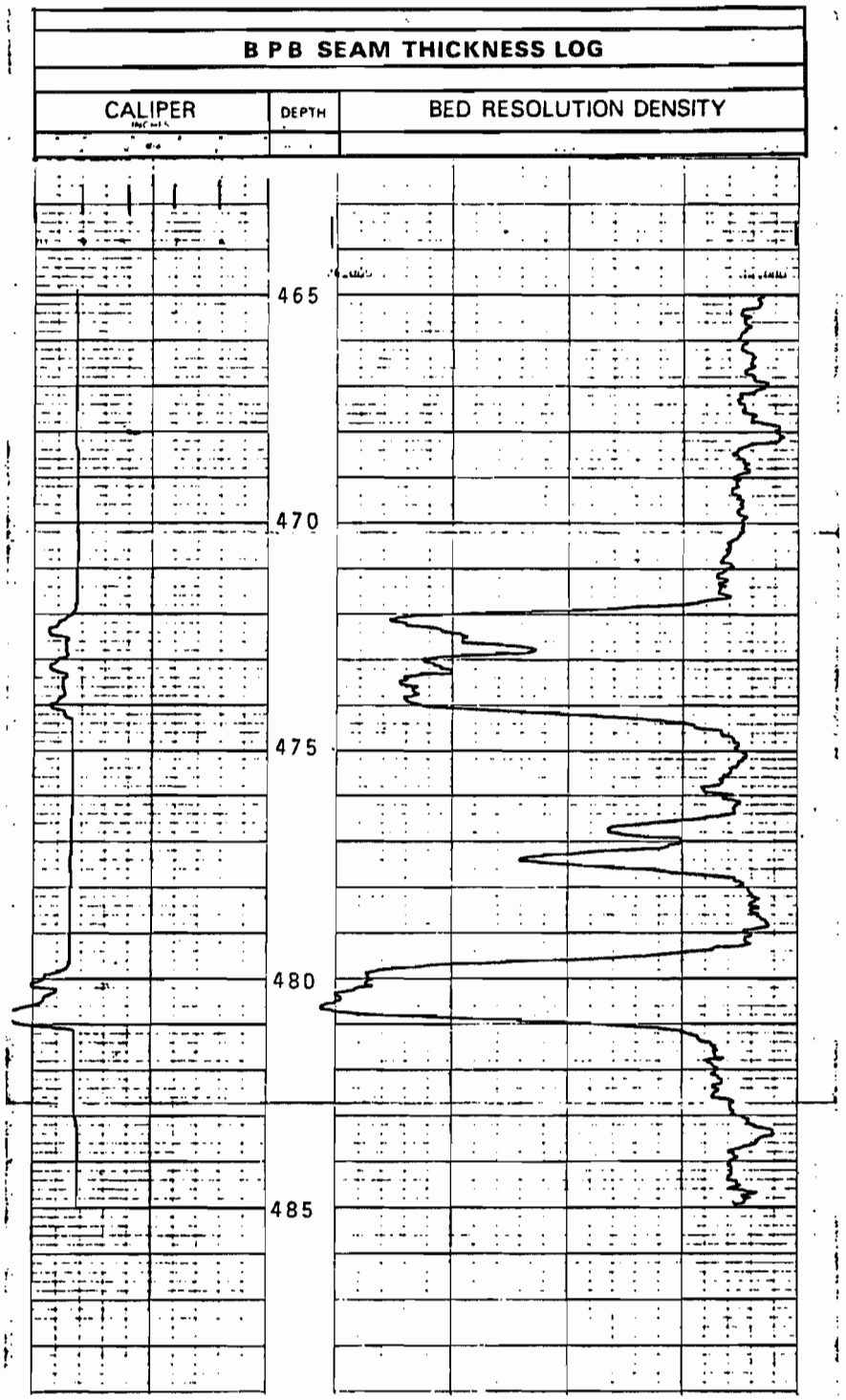
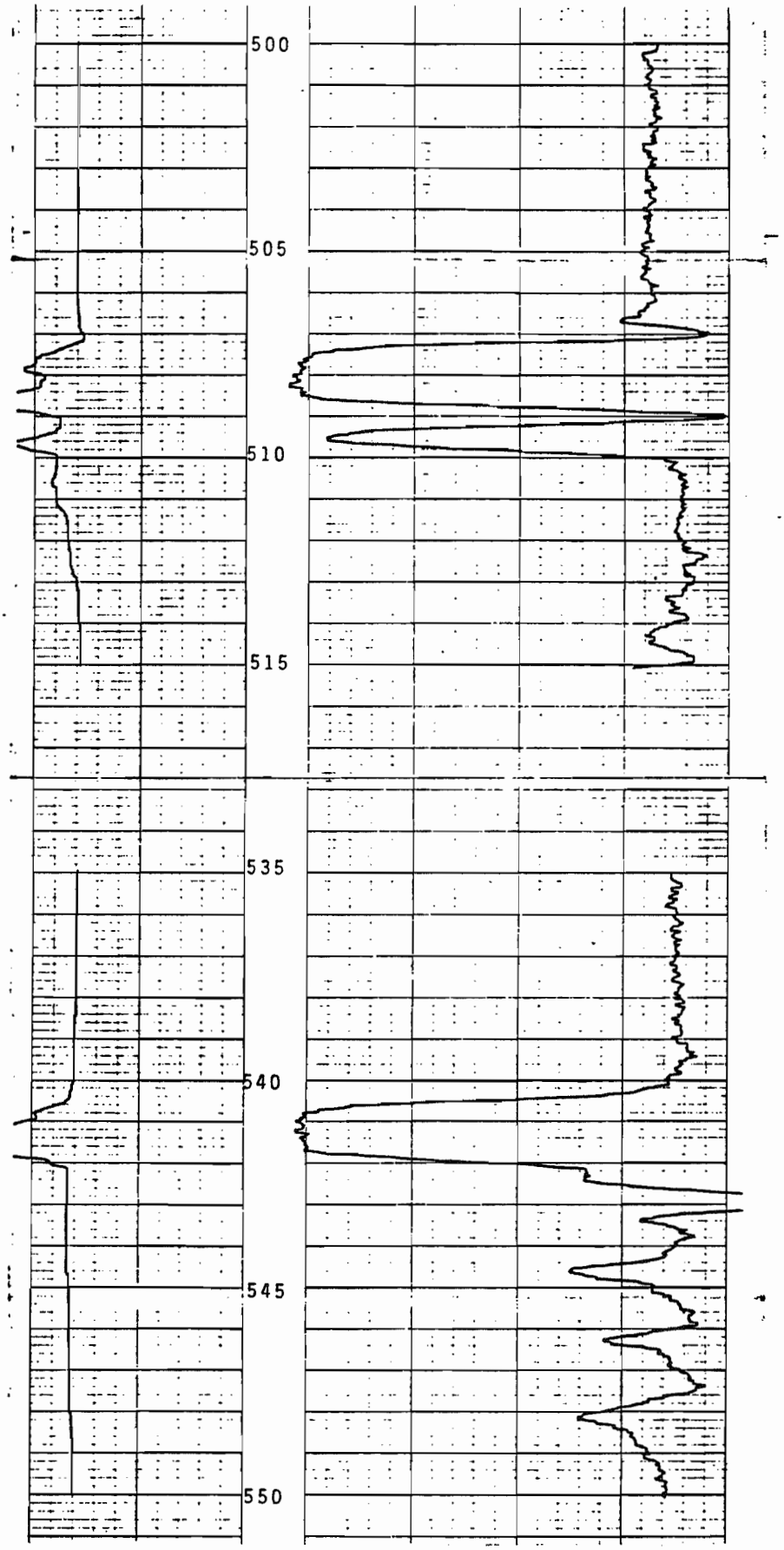


Figure 16 (cont)



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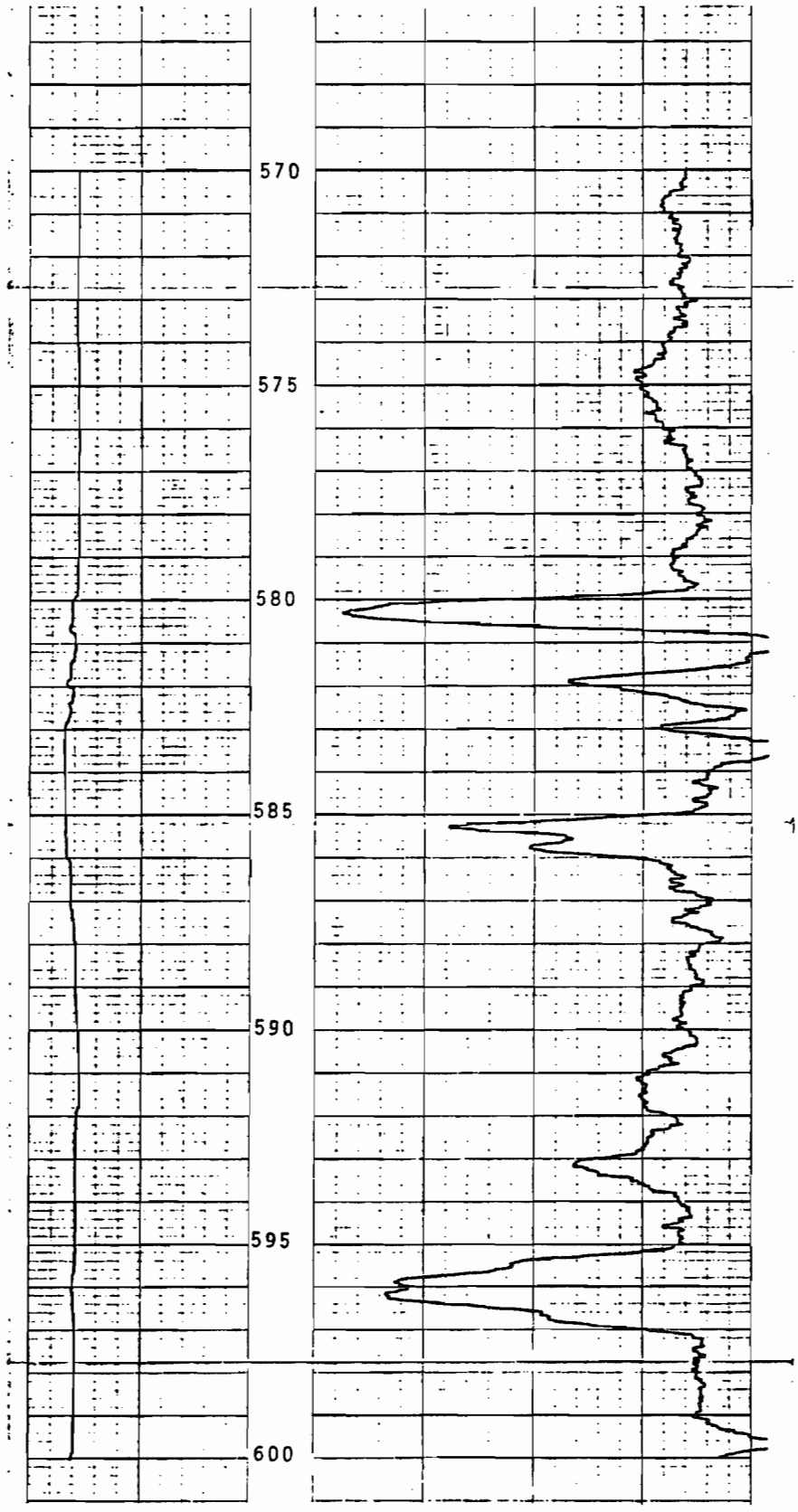

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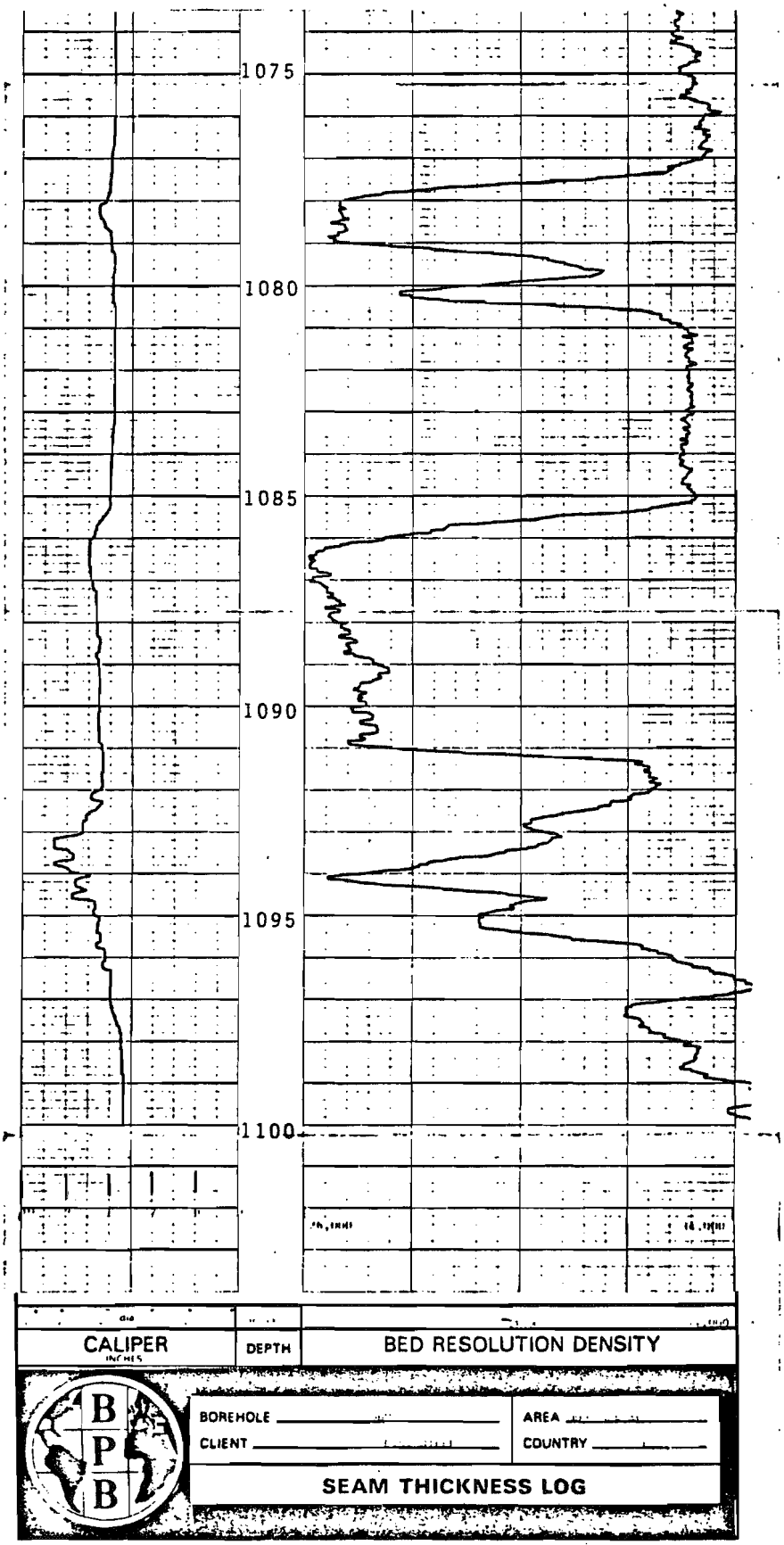
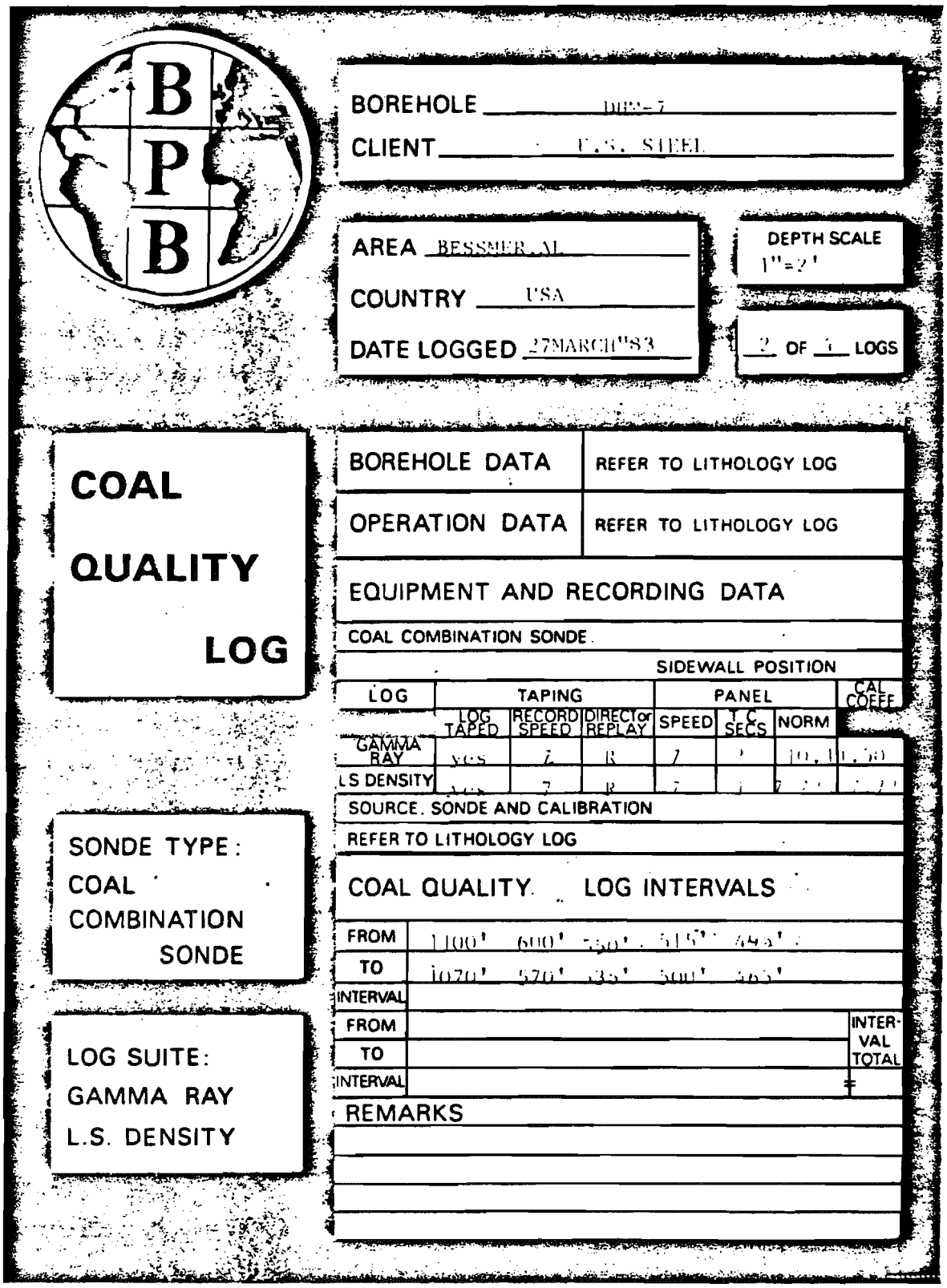


Figure 17 - Coal Quality Log, Well DHM-7
Oak Grove, Alabama



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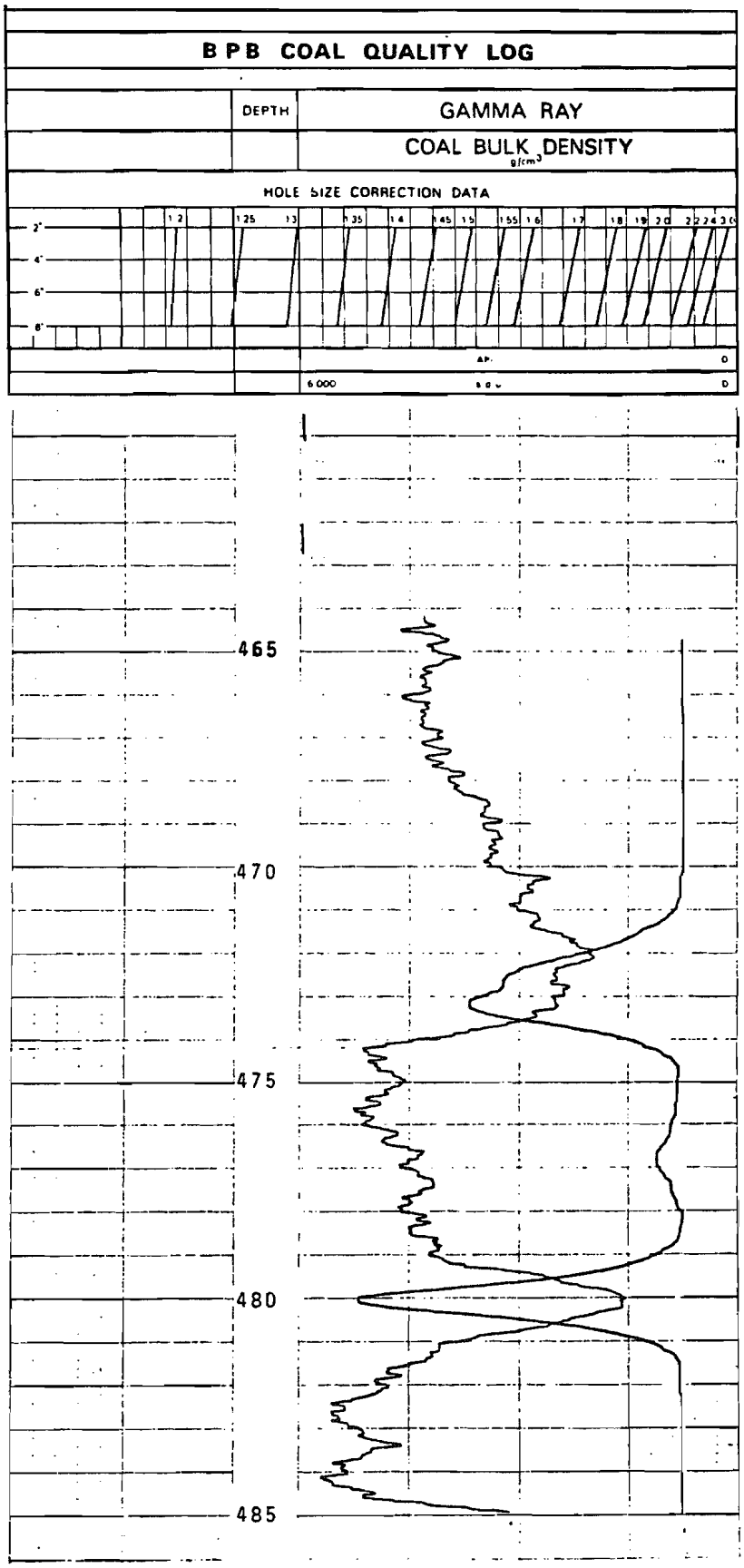

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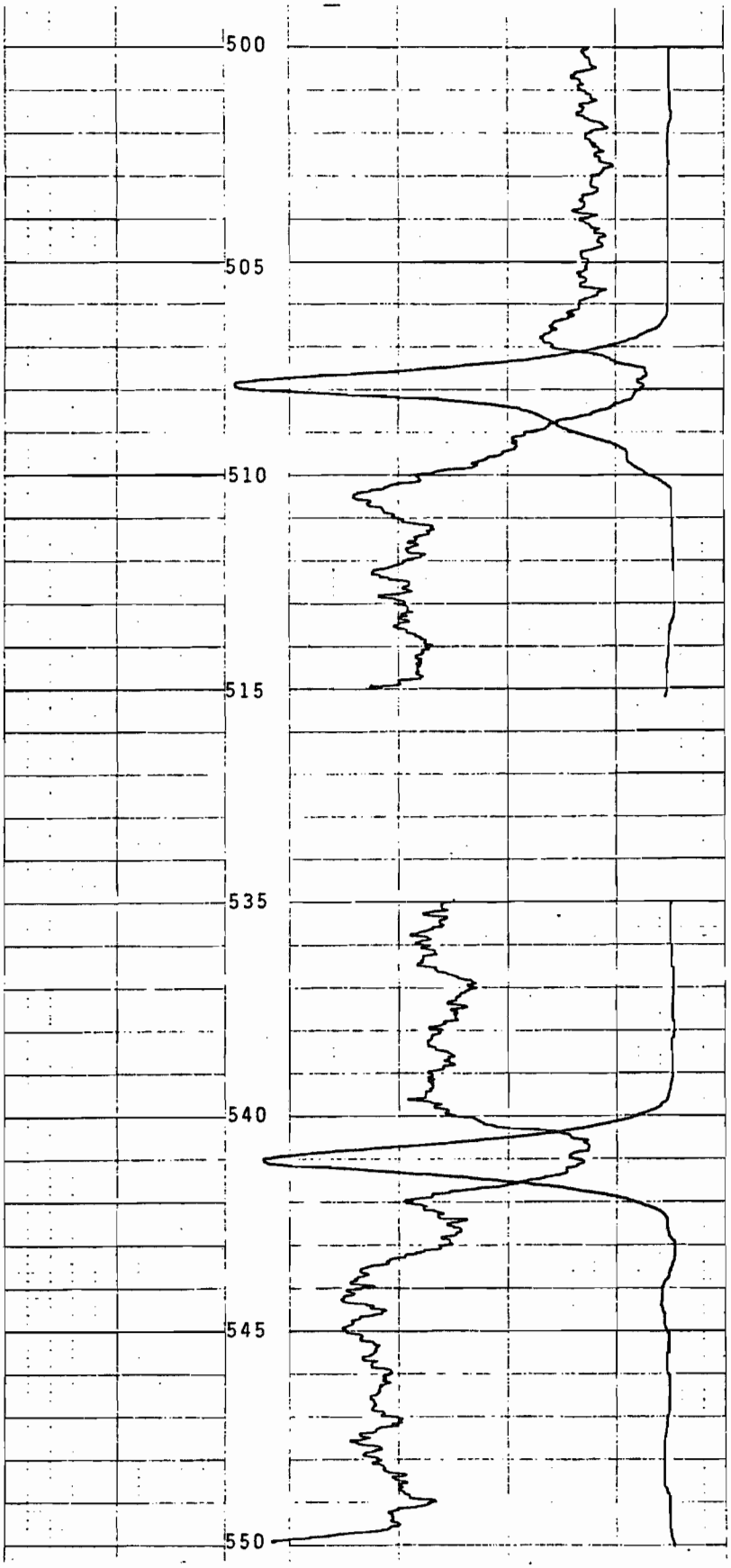

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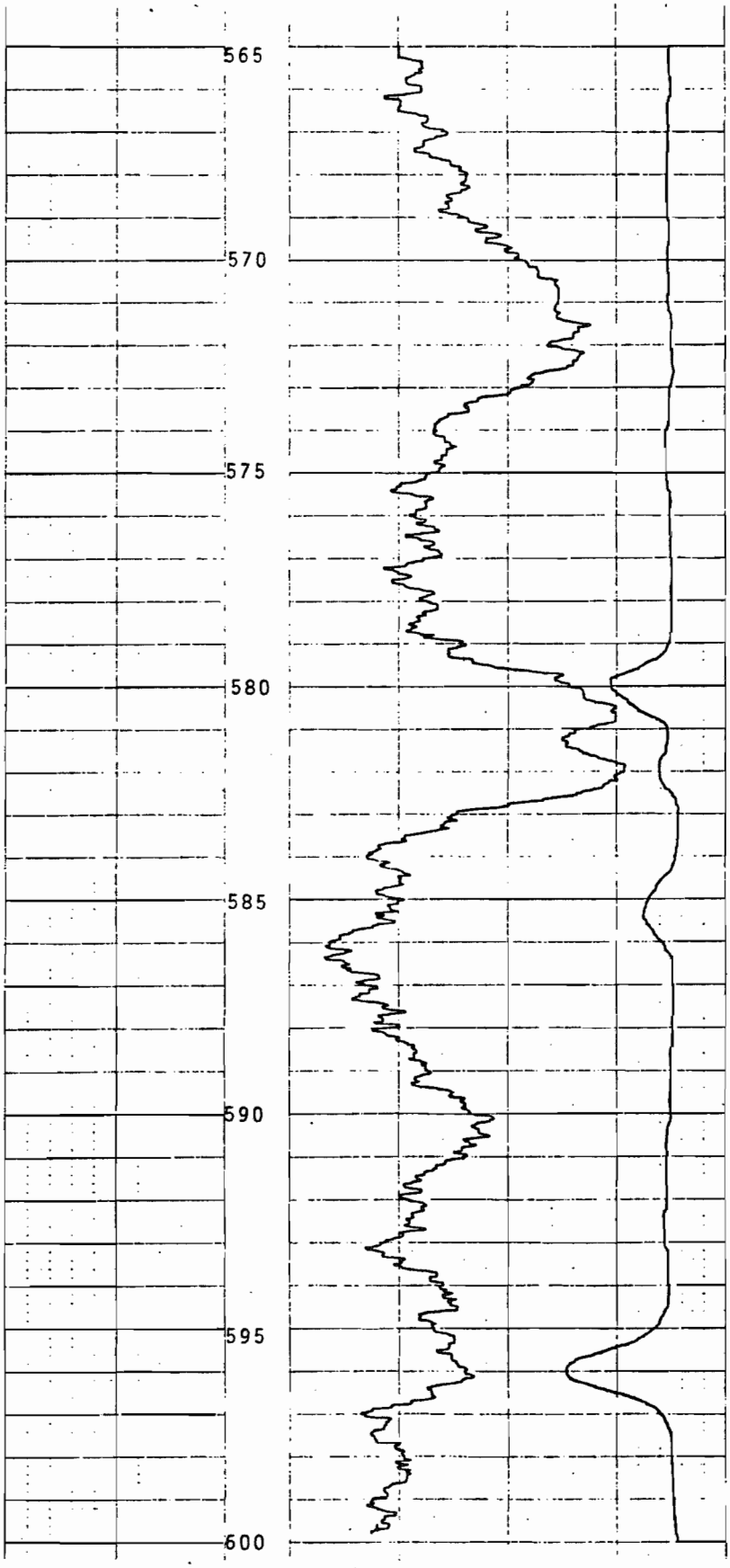

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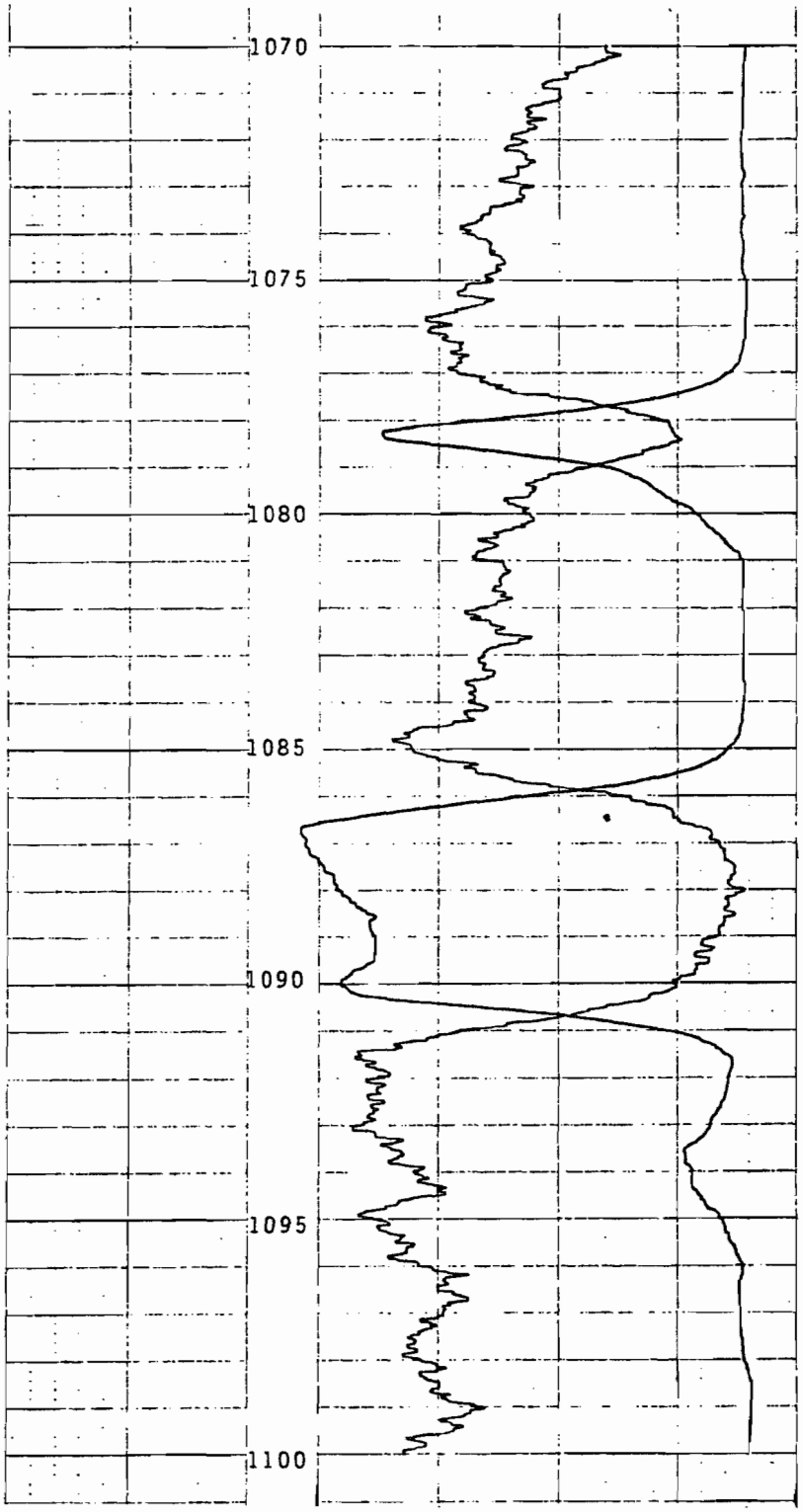
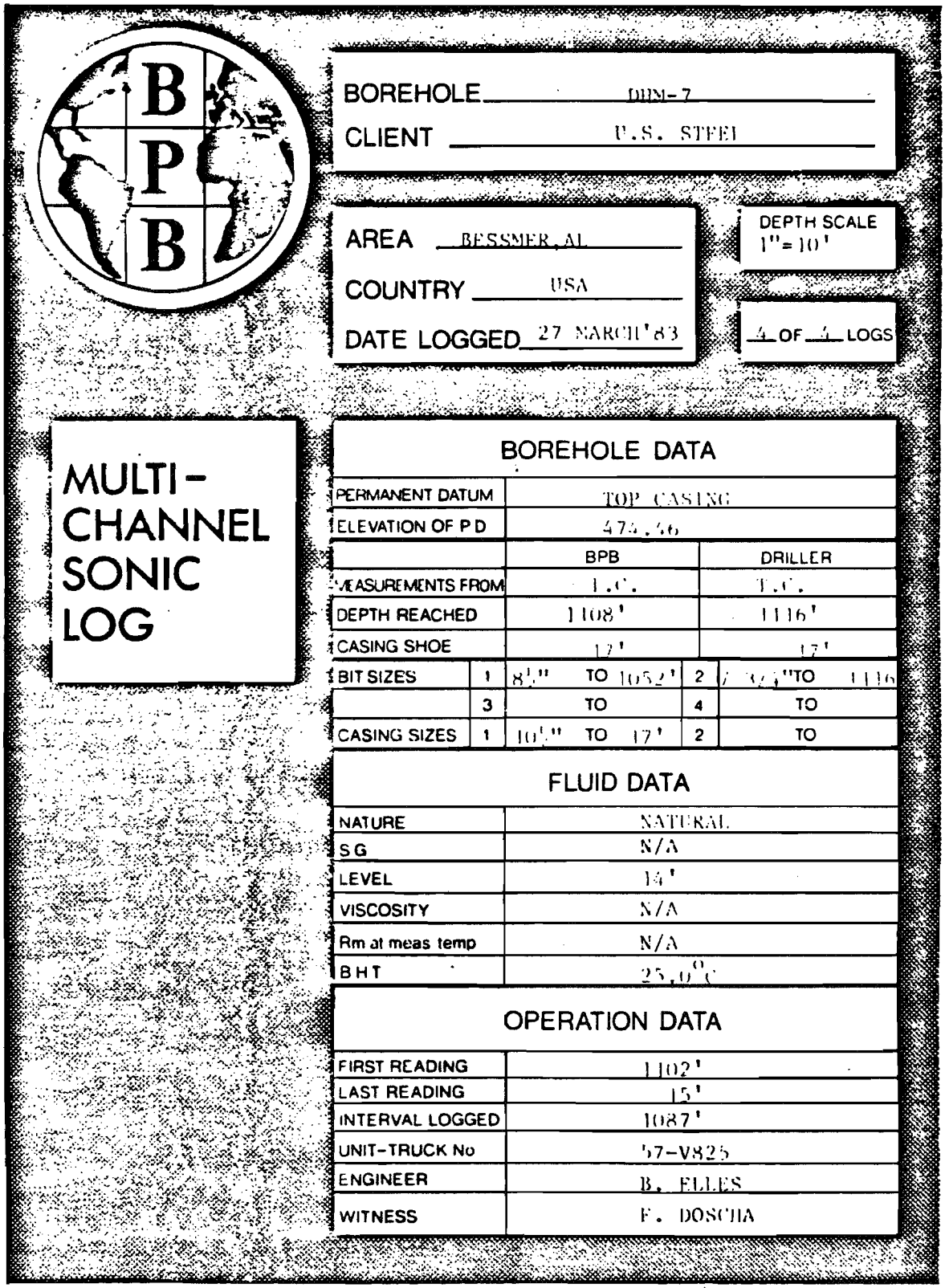


Figure 18 - Multi-Channel Sonic Log, Well DHM-7
Oak Grove, Alabama



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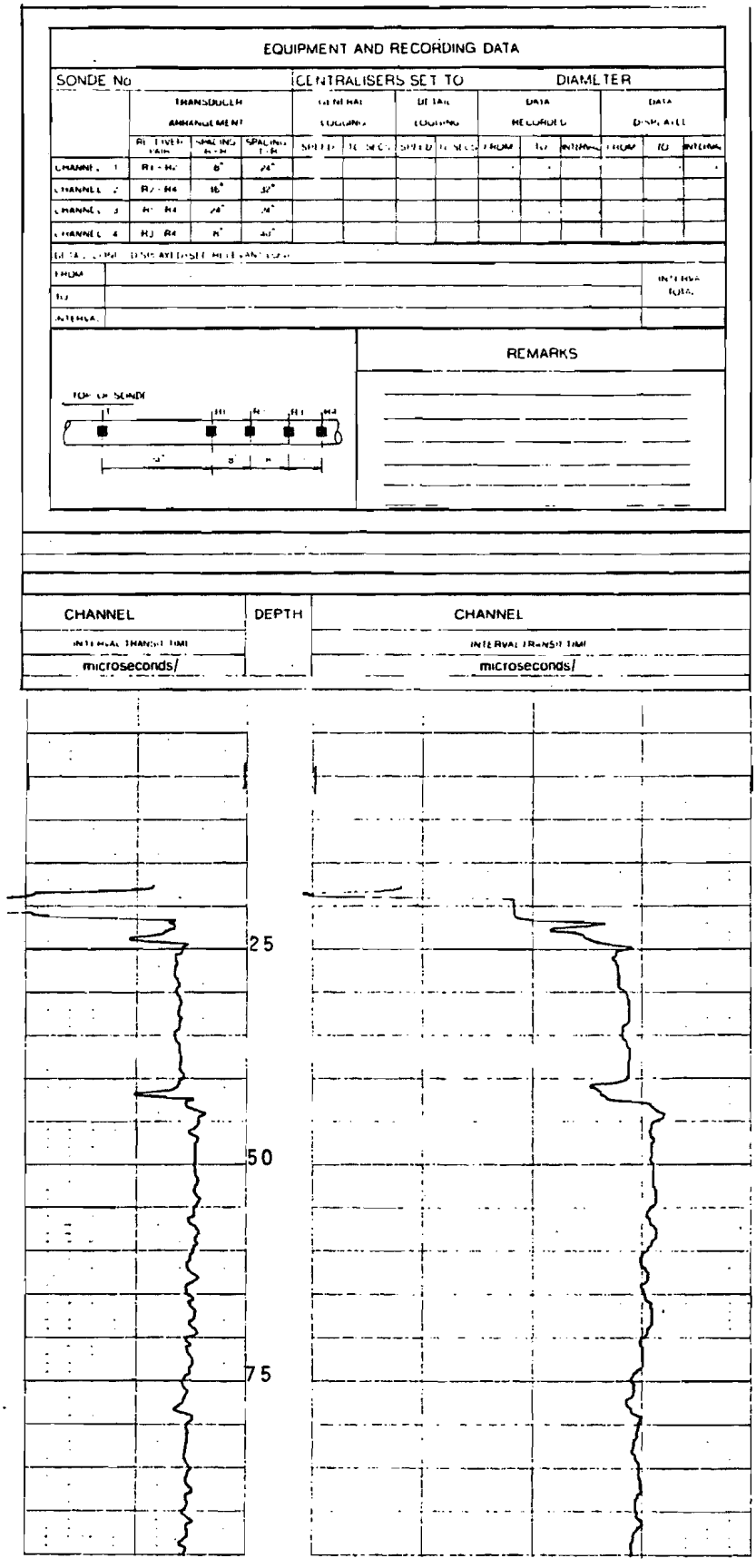

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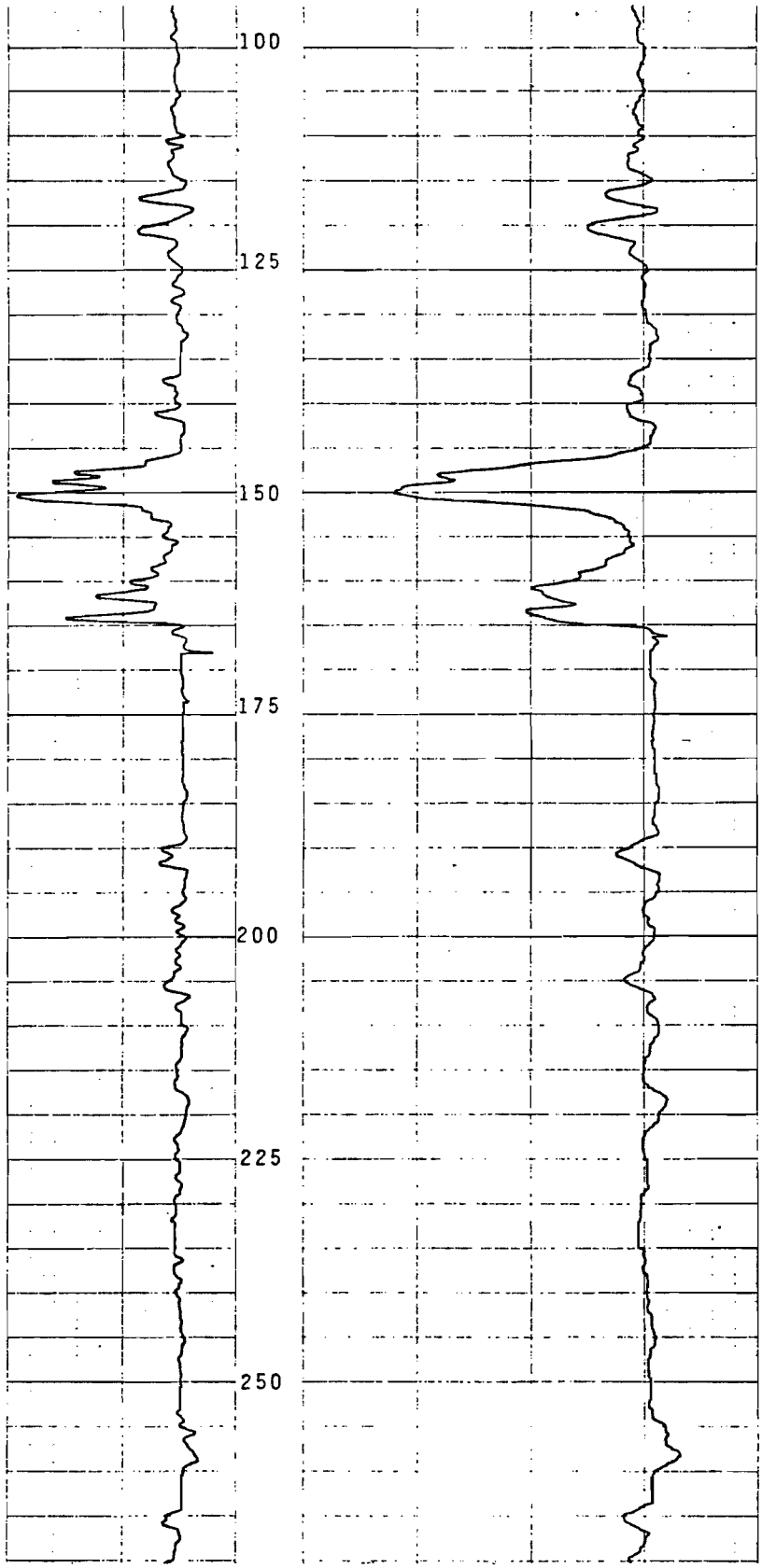

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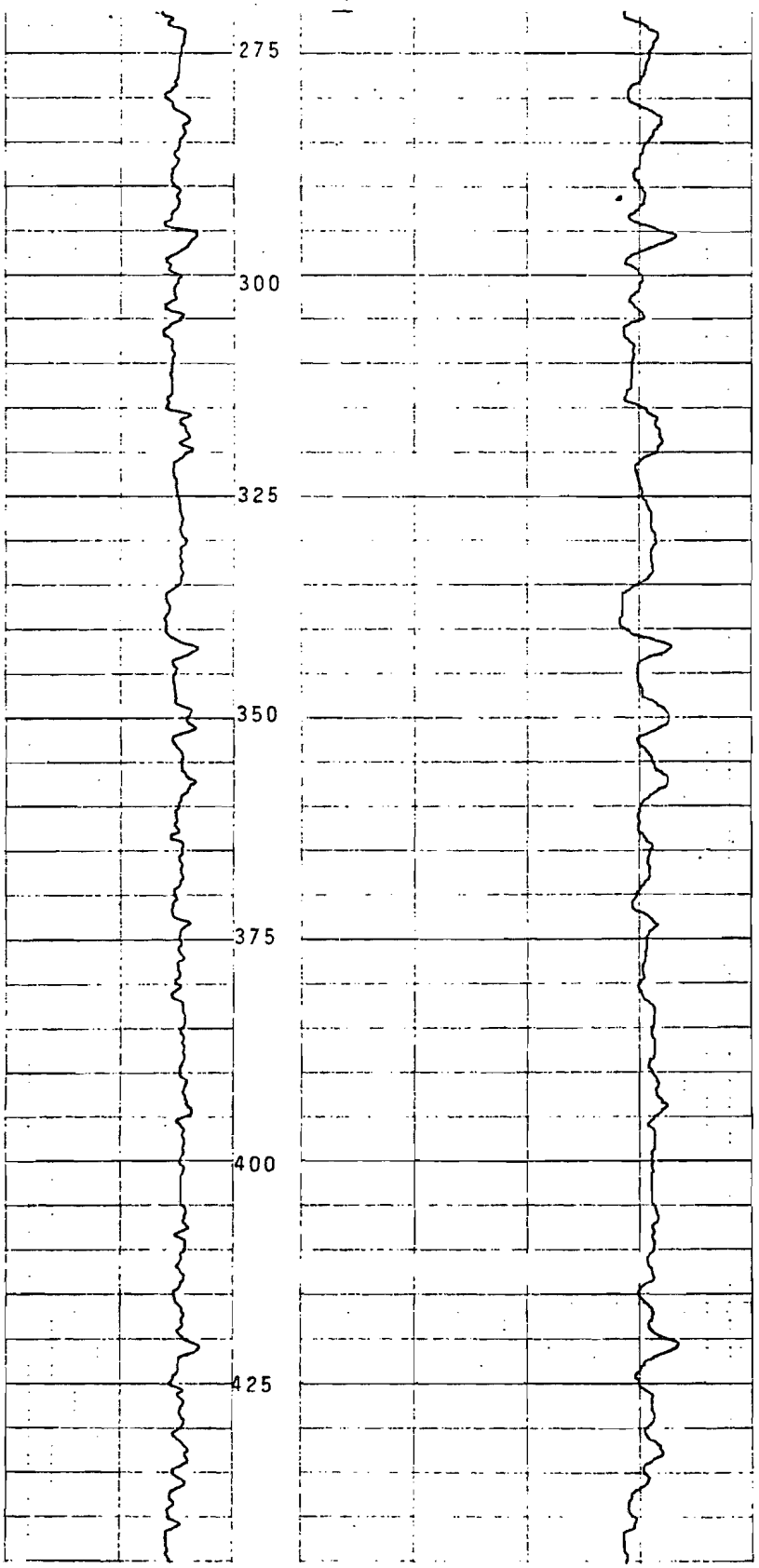

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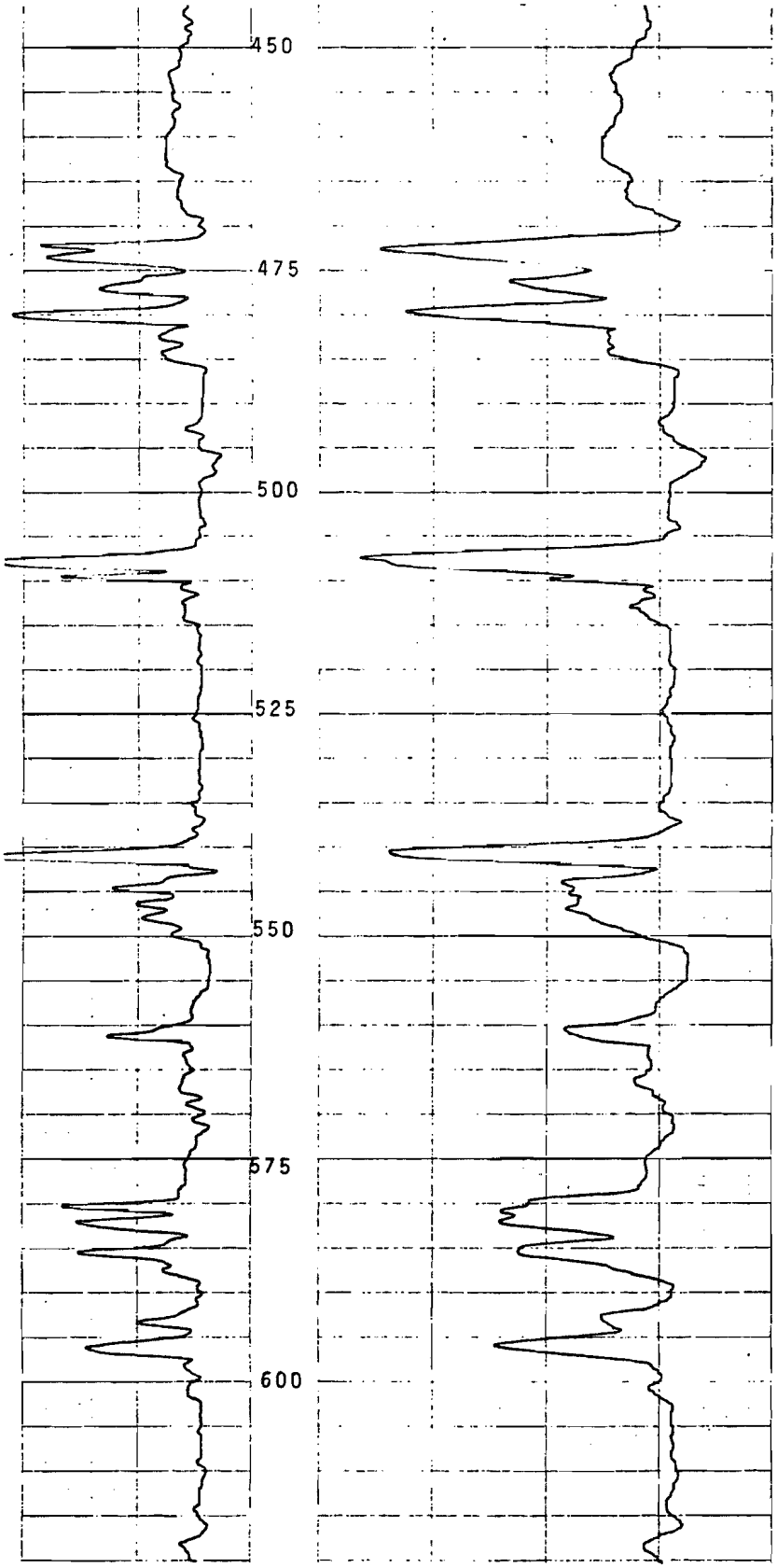

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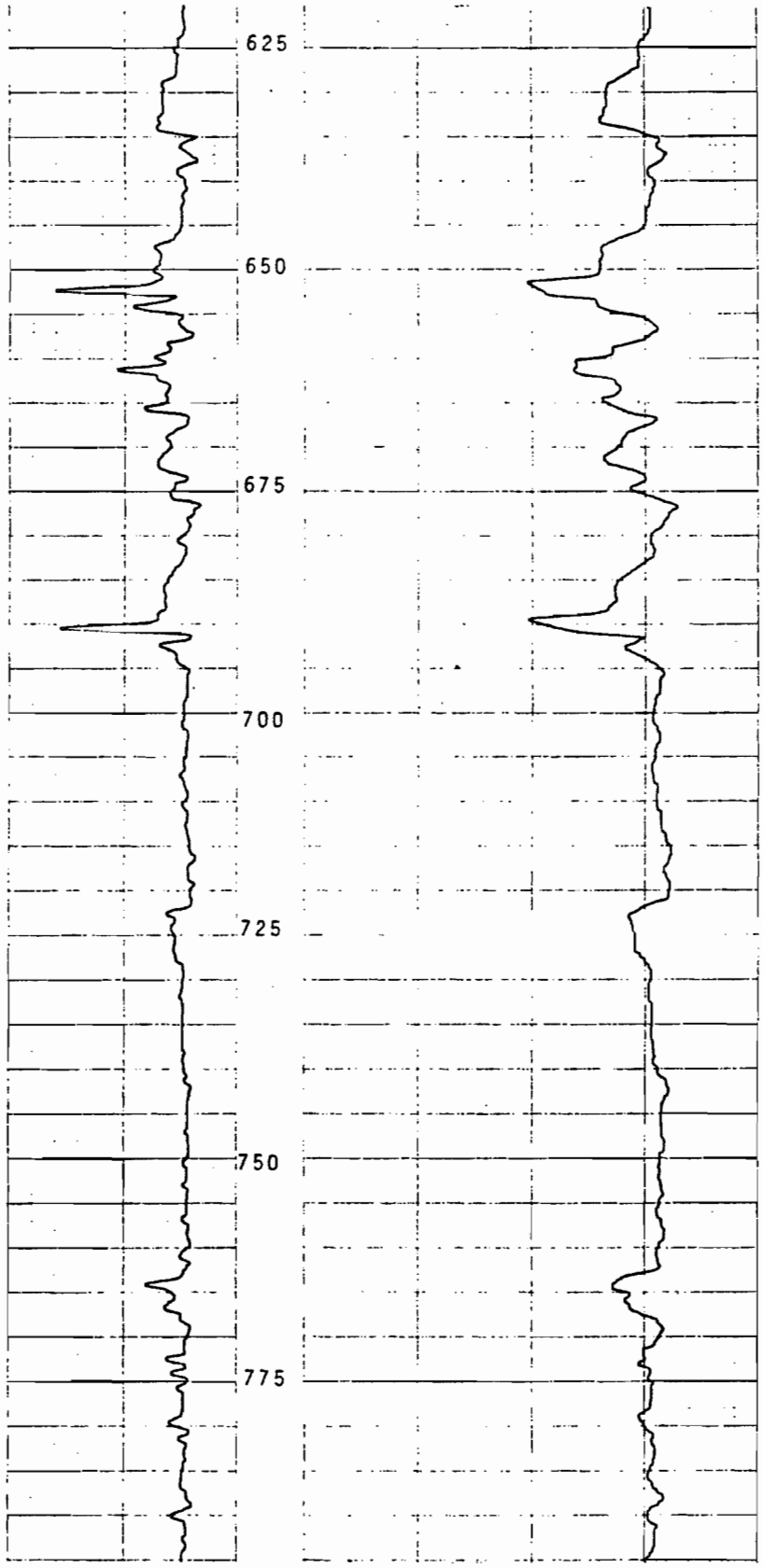

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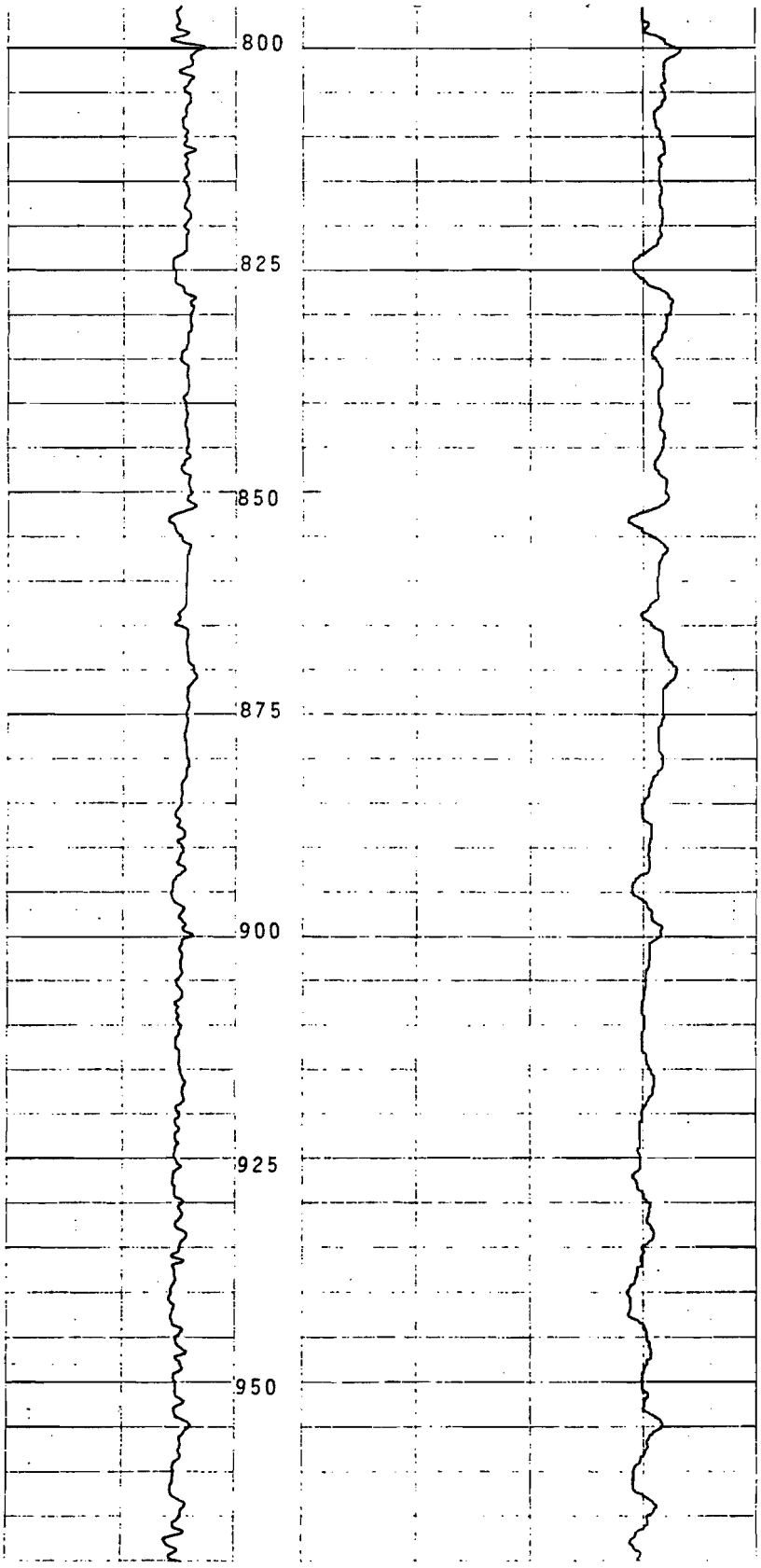

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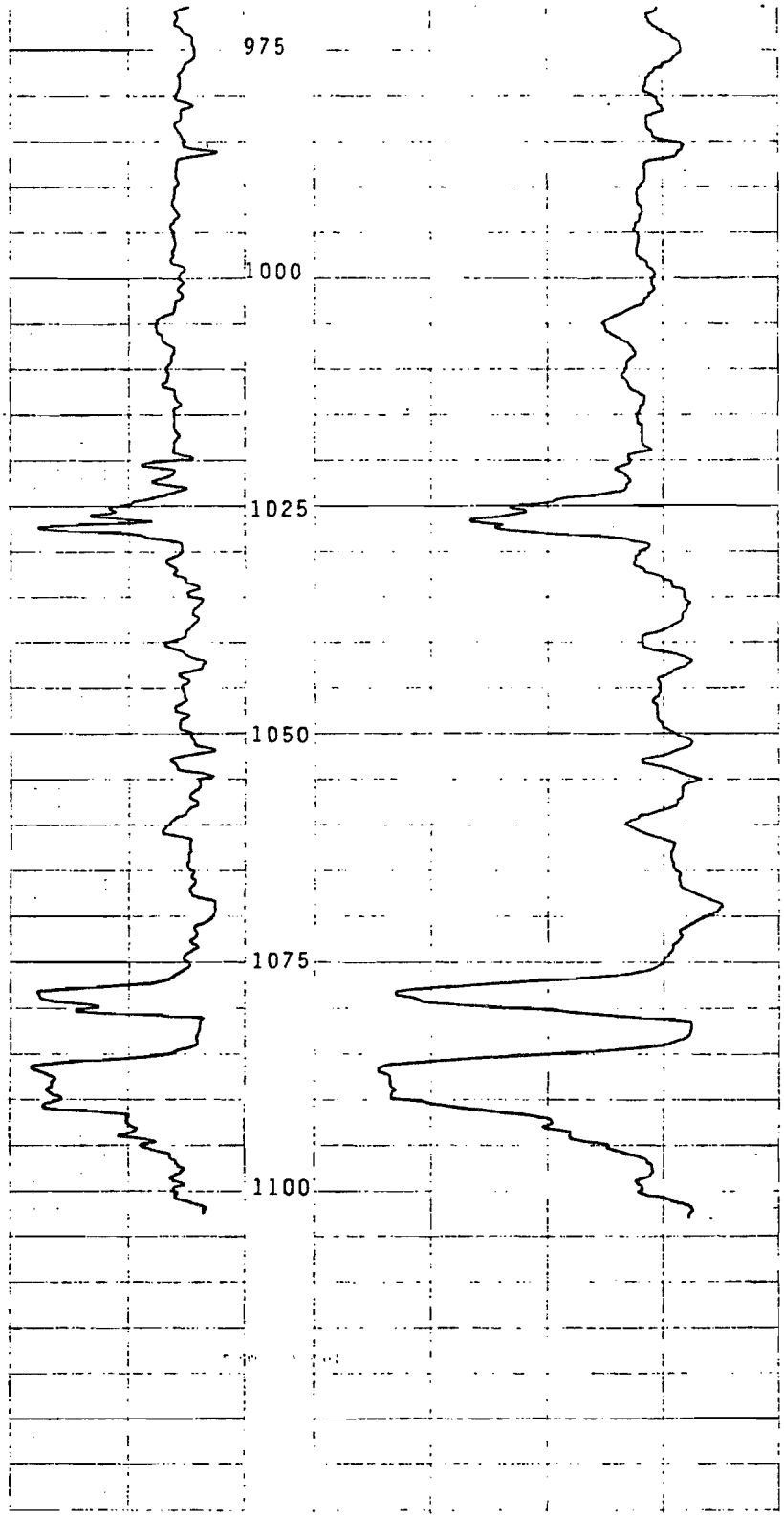

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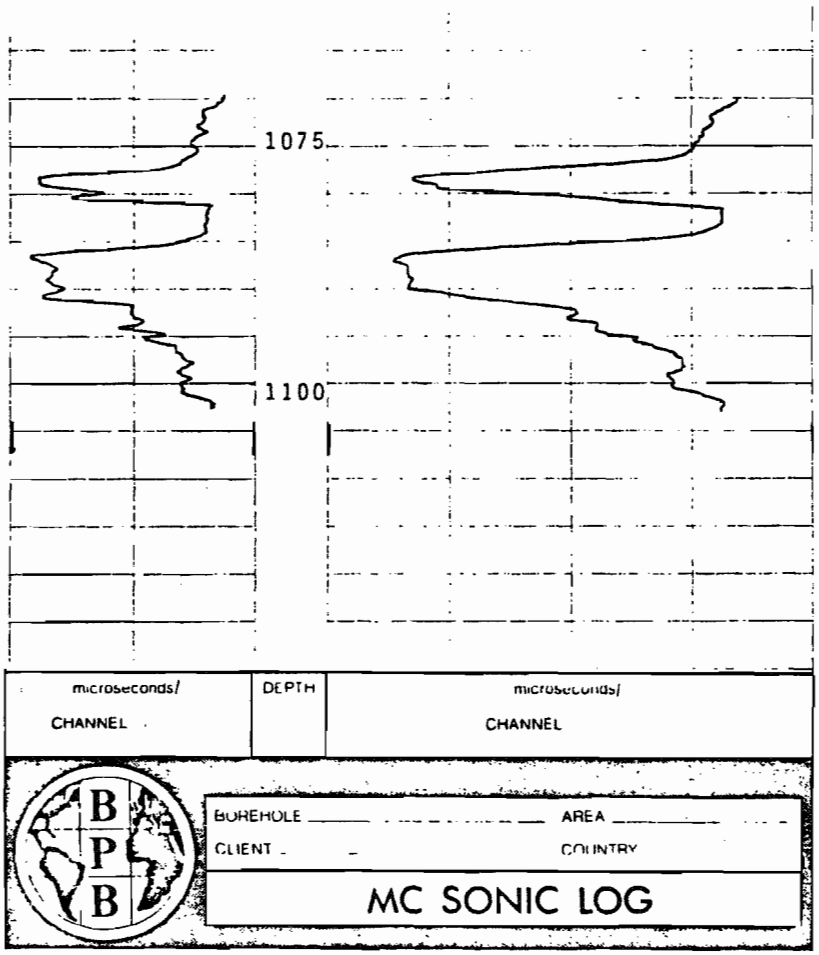
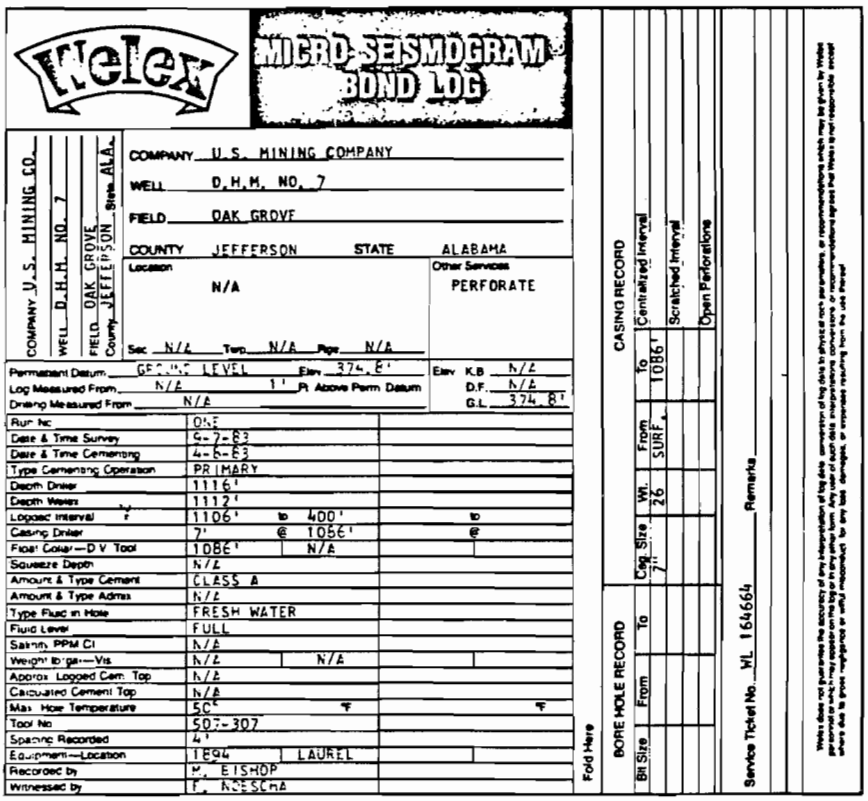


Figure 19 - Micro-Seismogram Bond Log, Well DHM-7
Oak Grove, Alabama



Welex

MICRO-SEISMOGRAM BOND LOG

COMPANY U.S. MINING CO.
WELL D.H.M. NO. 7
FIELD OAK GROVE
County JEFFERSON State ALA.

COMPANY U.S. MINING COMPANY
WELL D.H.M. NO. 7
FIELD OAK GROVE
COUNTY JEFFERSON STATE ALABAMA
Location N/A
Other Services PERFORATE
Sec N/A Twp. N/A Rge. N/A

Permanent Datum GROUND LEVEL Elev. 374.8'
Log Measured From N/A 1' Ft. Above Perm. Datum
Drilling Measured From N/A
Elev. K.B. N/A
D.F. N/A
G.L. 374.8'

Run No.	ONE	
Date & Time Survey	4-7-83	
Date & Time Cementing	4-6-83	
Type Cementing Operation	PRIMARY	
Depth Driller	1116'	
Depth Weller	1112'	
Logged Interval	1106' to 400'	to
Casing Driller	7" @ 1056'	@
Float Collar—D V Tool	1086' N/A	
Squeeze Depth	N/A	
Amount & Type Cement	CLASS A	
Amount & Type Admix	N/A	
Type Fluid in Hole	FRESH WATER	
Fluid Level	FULL	
Salinity, PPM Cl	N/A	
Weight lb/gal—Vis	N/A N/A	
Approx. Logged Cem. Top	N/A	
Calculated Cement Top	N/A	
Max. Hole Temperature	56° F	F
Tool No.	507-307	
Spacing Recorded	4'	
Equipment—Location	TEQ4 LAUREL	
Recorded by	M. BISHOP	
Witnessed by	F. ROESCH	

Fold Here

BORE HOLE RECORD

Bit Size	From	To

CASING RECORD

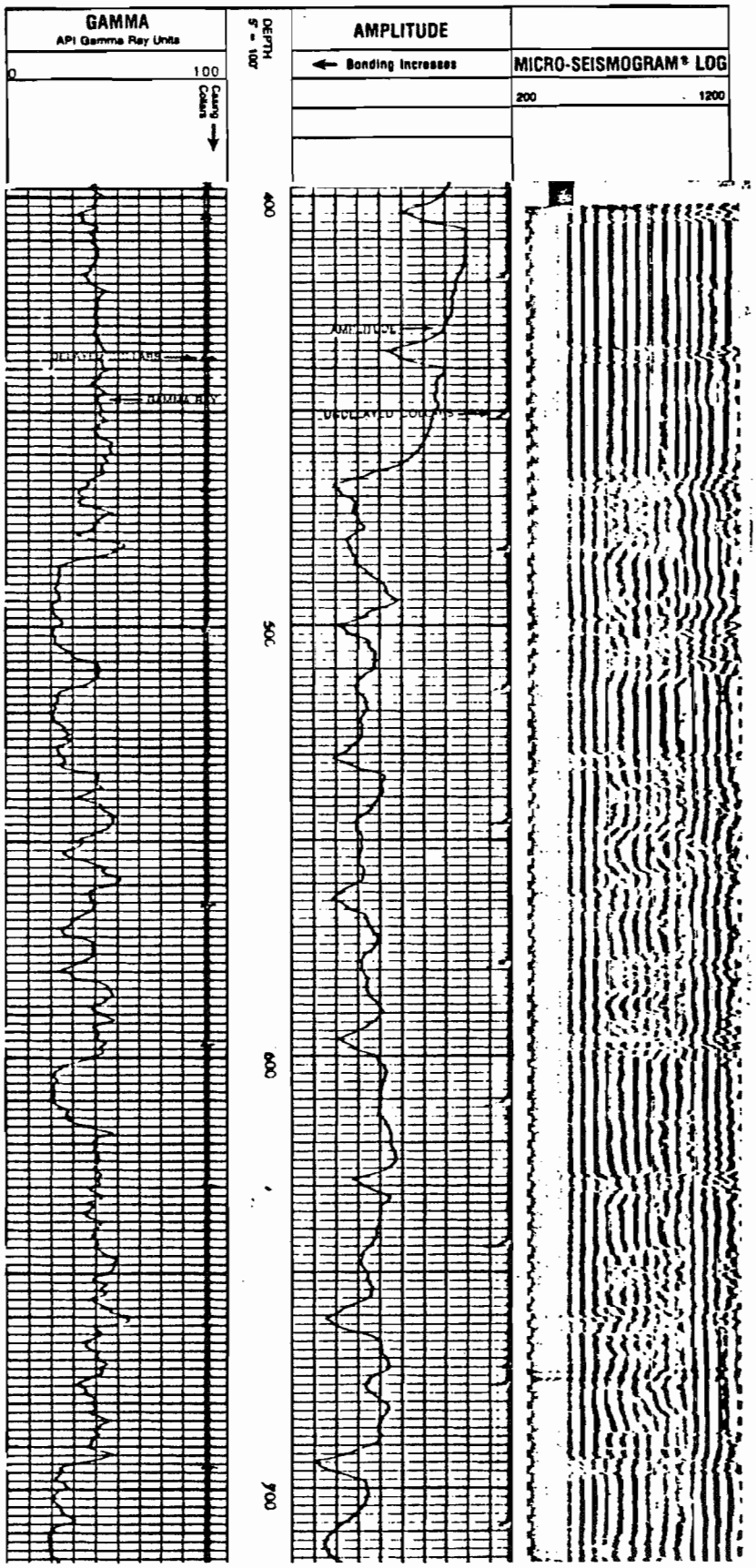
Csg. Size	Wt.	From	To
7"	26	SURF.	1086'

Centralized Interval
Scratched Interval
Open Perforations

Service Ticket No. WL 164664 Remarks

Welex does not guarantee the accuracy of any interpretation of log data, generation of log data by physical rock properties, or recommendations which may be given by Welex personnel or which may appear on this log or in any other form. Any use of such data, interpretations, conclusions or recommendations signifies that Welex is not responsible except where due to gross negligence or willful misconduct, for any loss, damages, or expenses resulting from the use thereof.

Figure 19 (cont)



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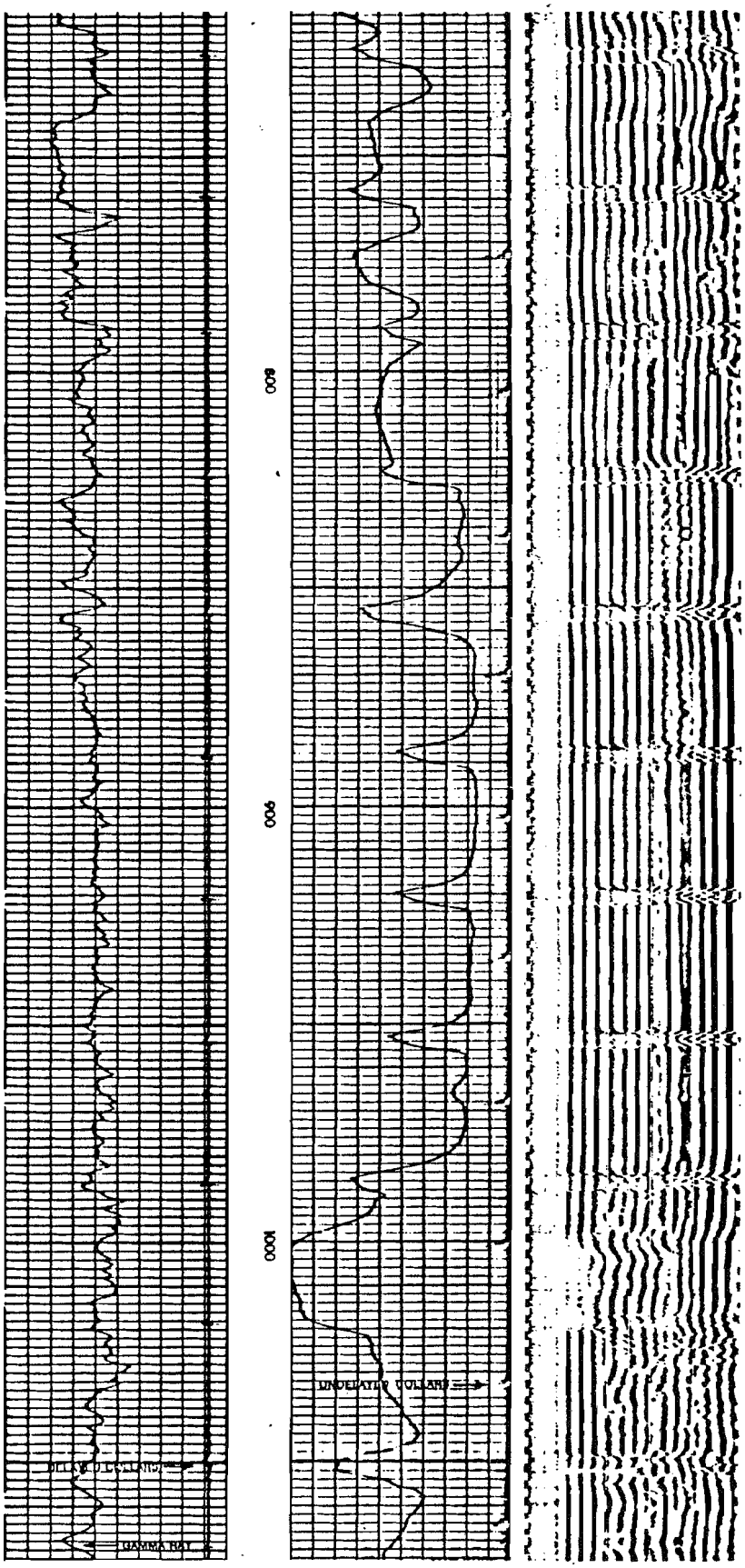

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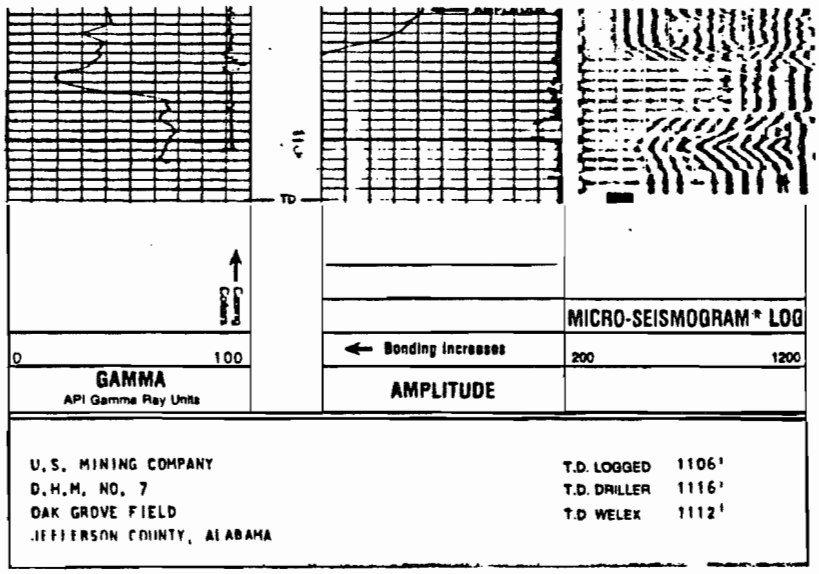


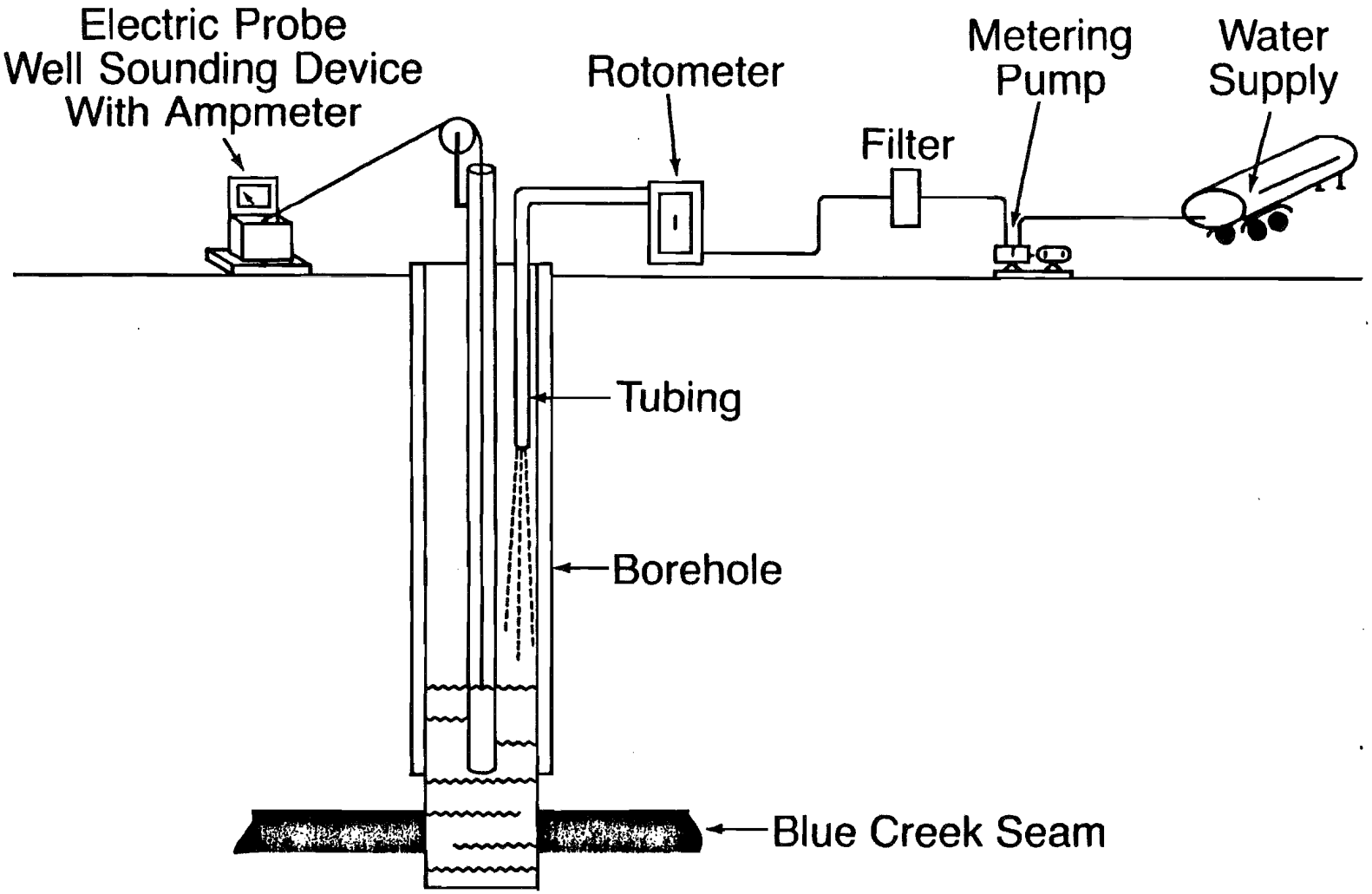


Figure 20 - Water Injection Test Equipment Schematic

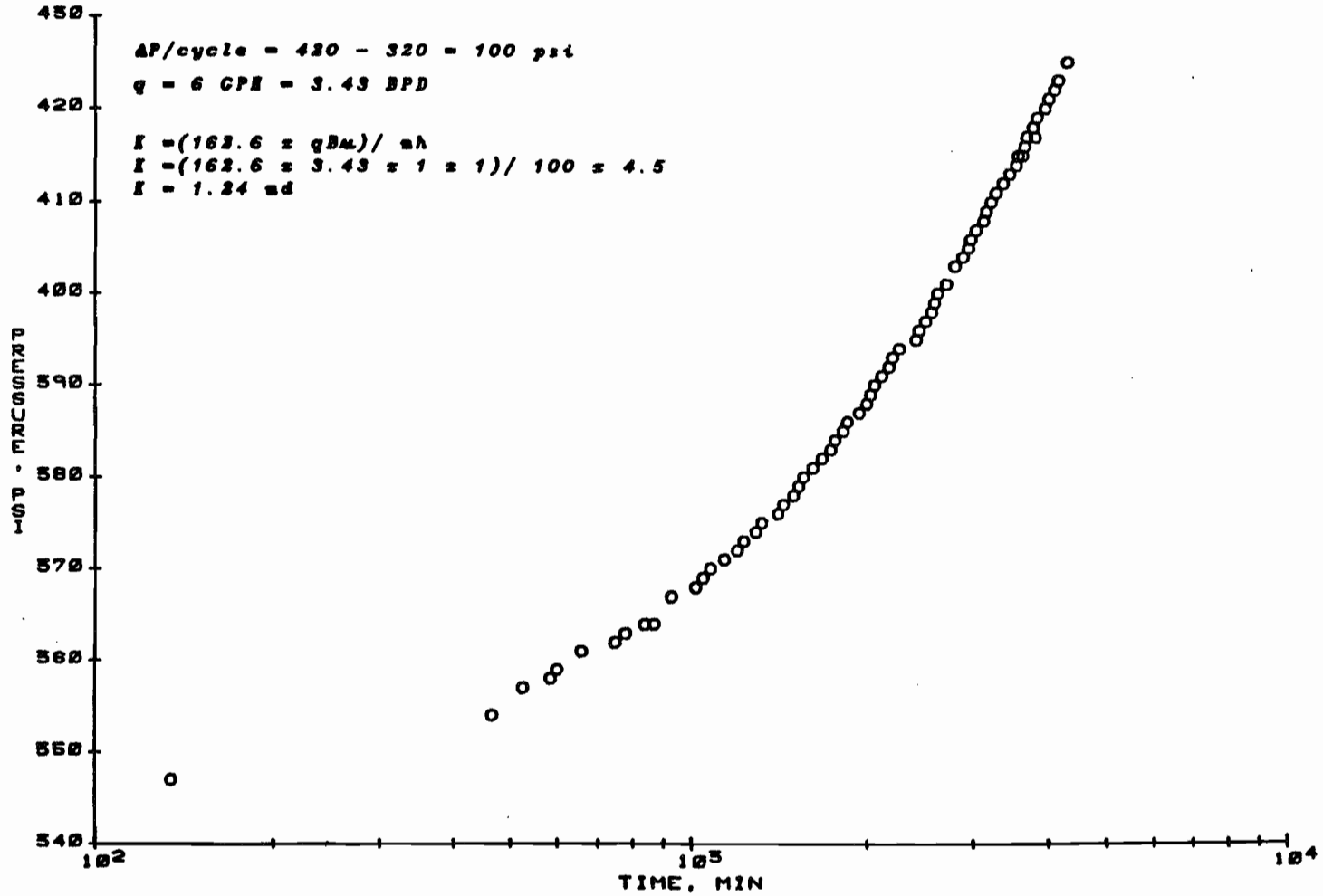


Figure 21 - Pre-Abrasi-jetting Injection Test Results
Earlougher Method, Well DHM-7
Oak Grove, Alabama

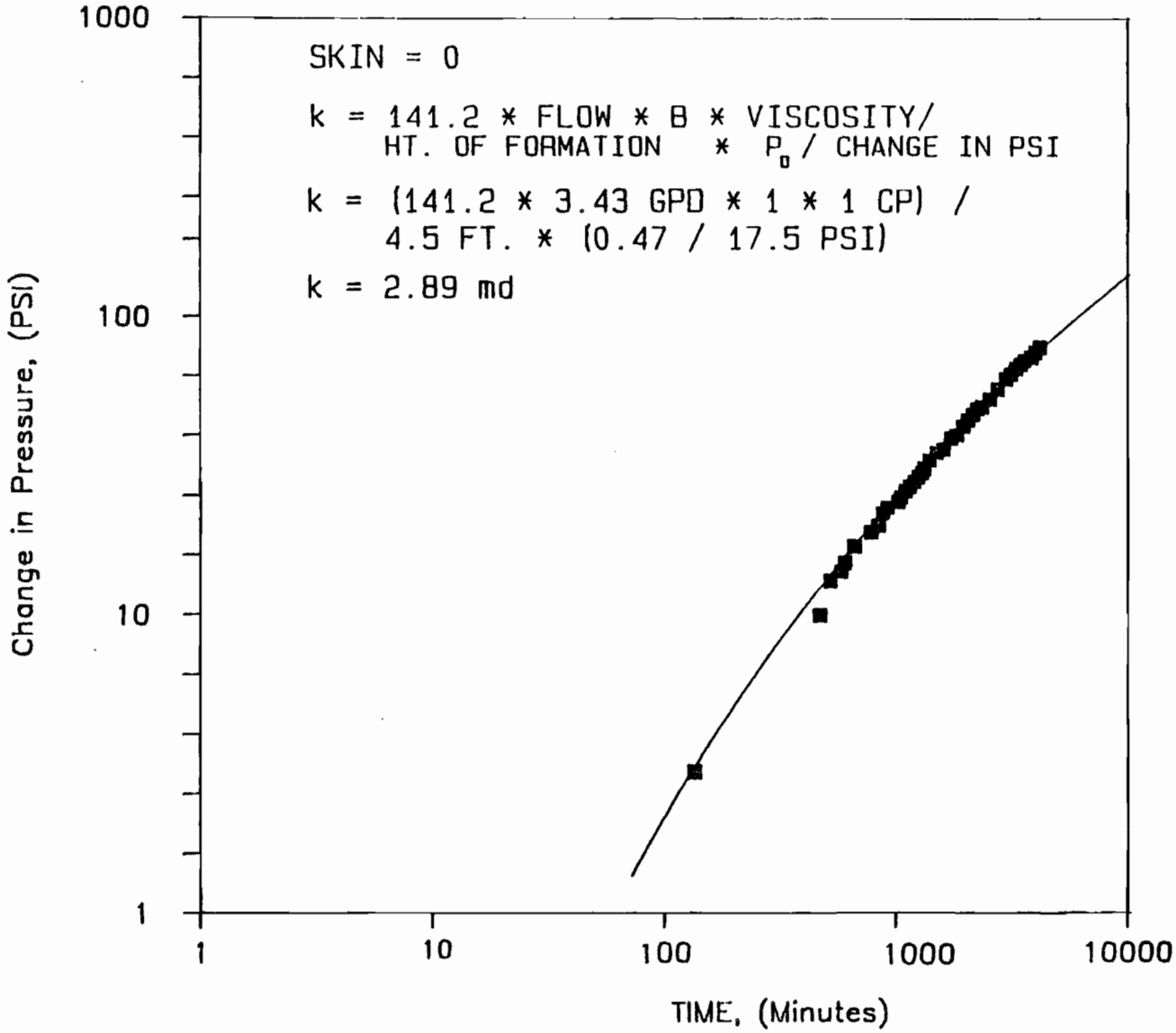


Figure 22 - Pre-Abrasi-jetting Injection Test Results
Agarwal Method, Well DHM-7
Oak Grove, Alabama

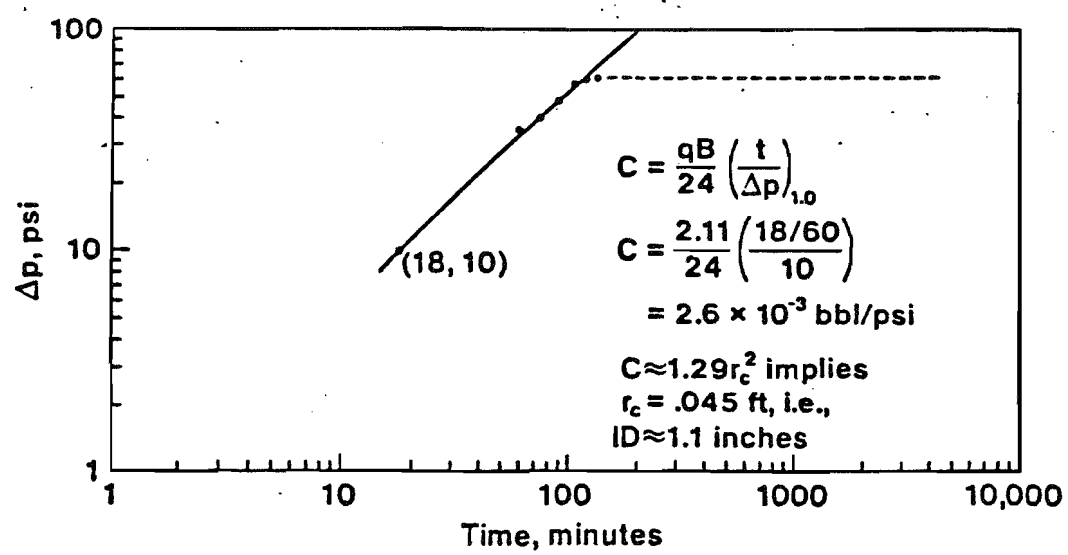


Figure 23 - Post-Abrasi-jetting Injection Test Results
Well DHM-7, Oak Grove, Alabama

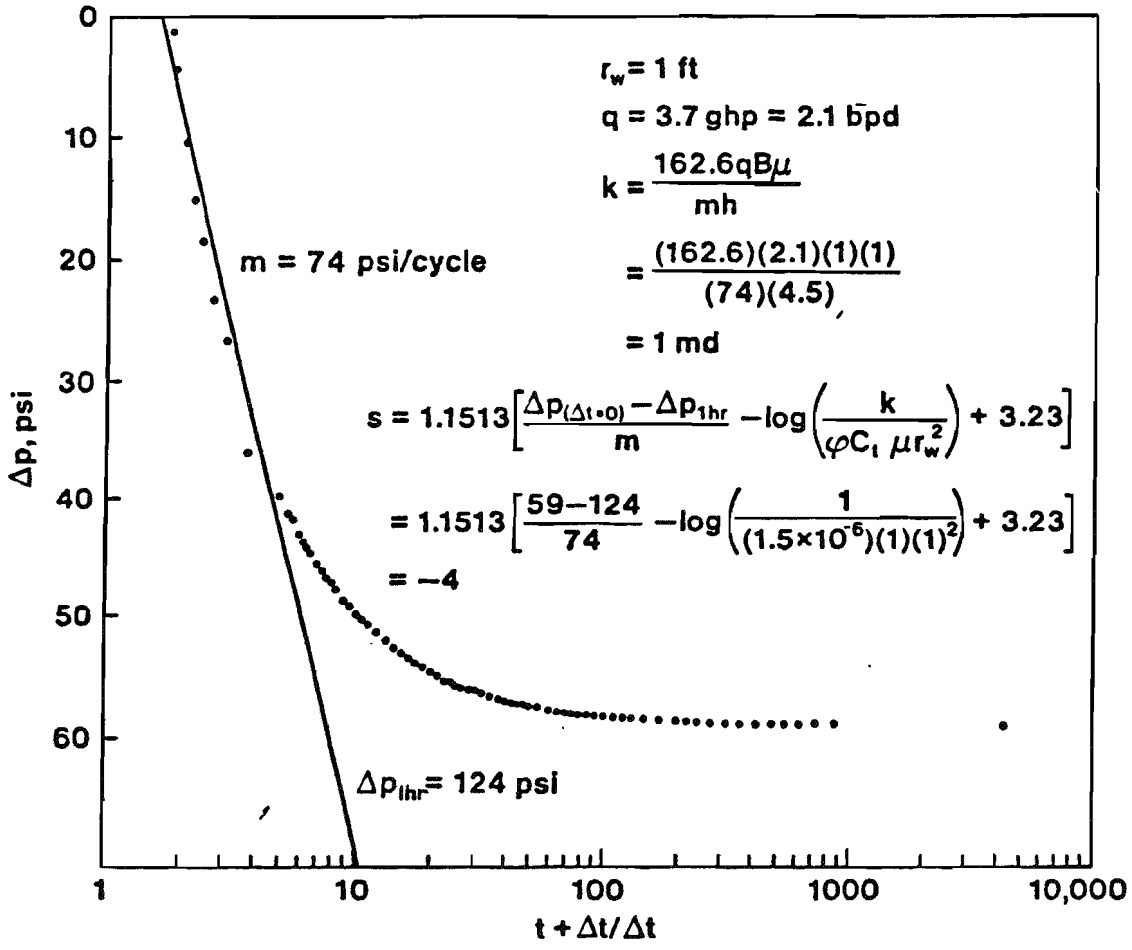


Figure 24 - Post-Abrasi-jetting Injection Test
Recovery Results, Well DHM-7
Oak Grove, Alabama

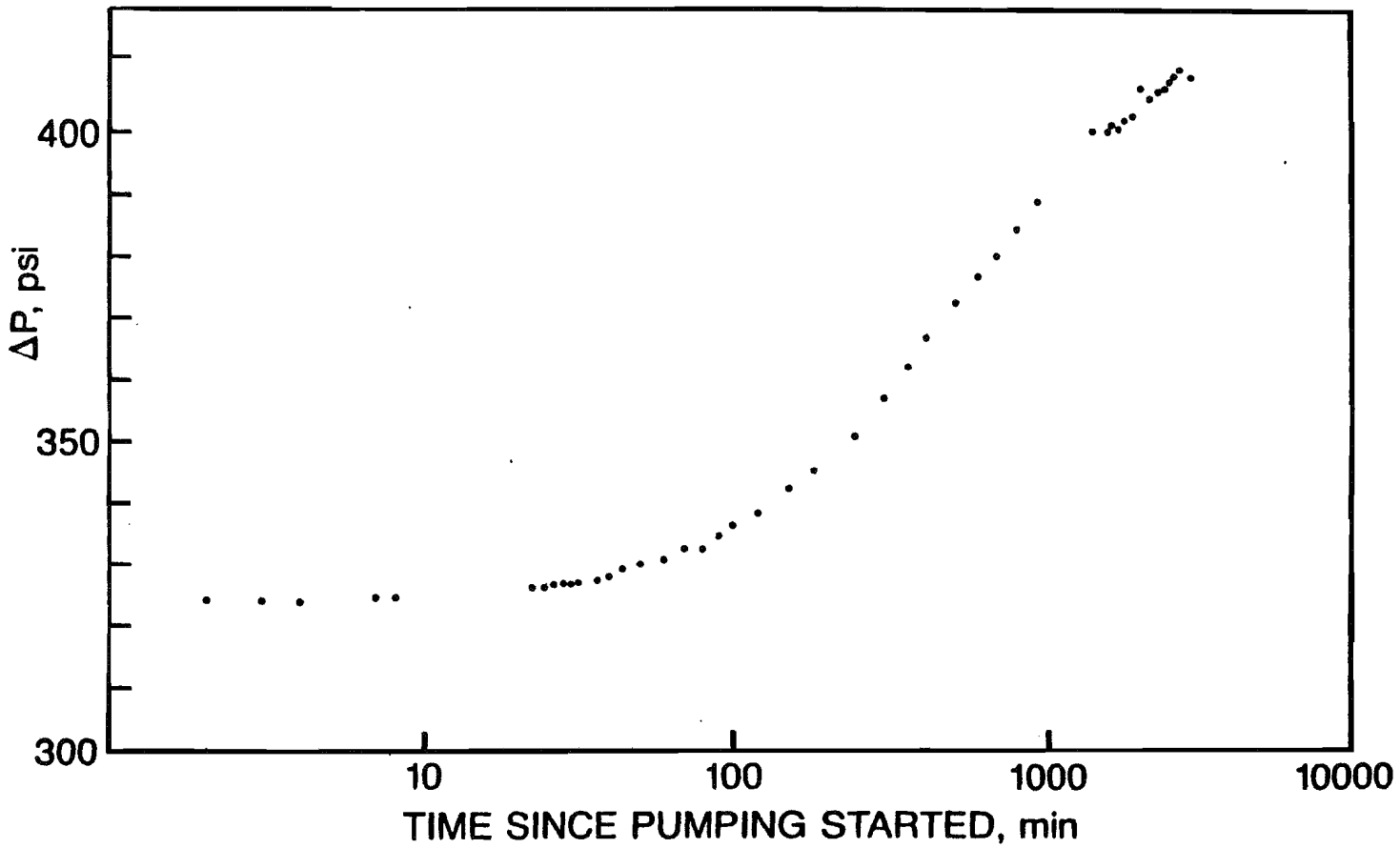


Figure 25 - Post-Production Injection Test Results
Well DHM-7, Oak Grove, Alabama

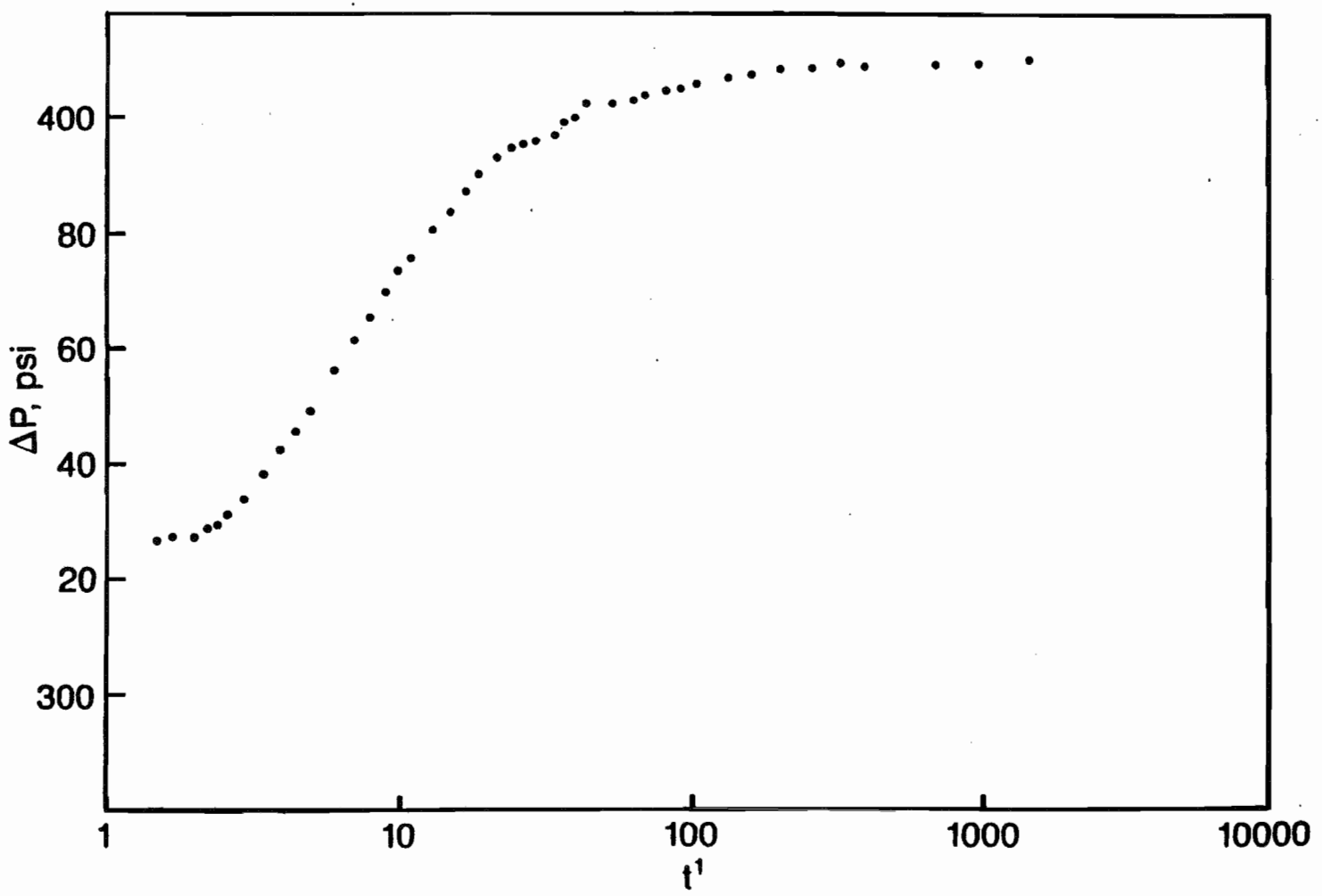


Figure 26 - Post-Production Injection Test
Recovery Results, Well DHM-7
Oak Grove, Alabama

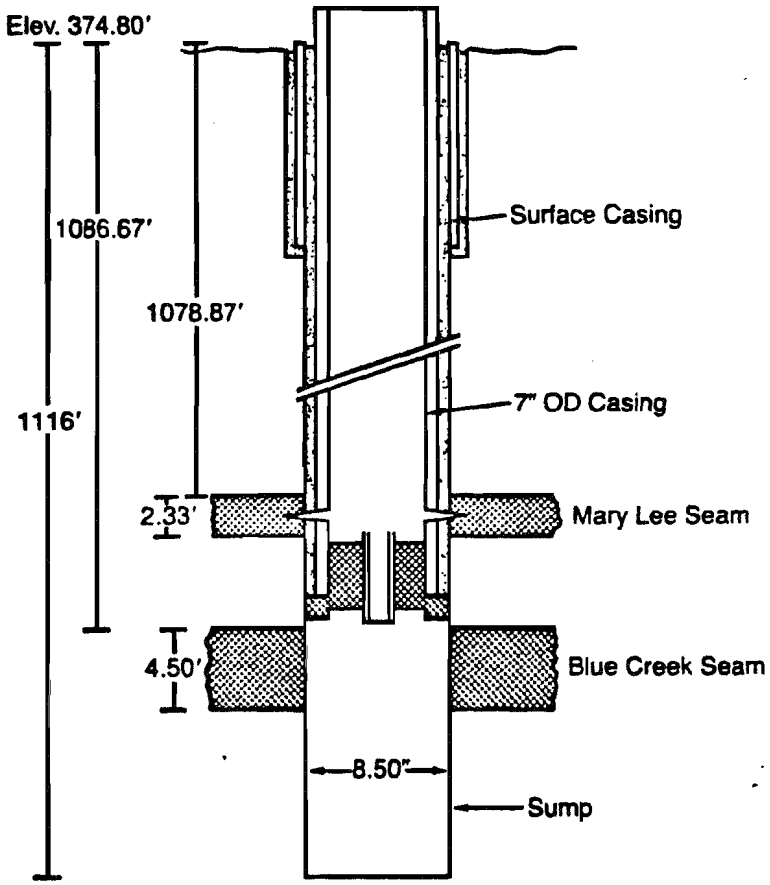


Figure 27 - Wellbore Configuration, Mary Lee Injection Test
Well DHM-7, Oak Grove, Alabama

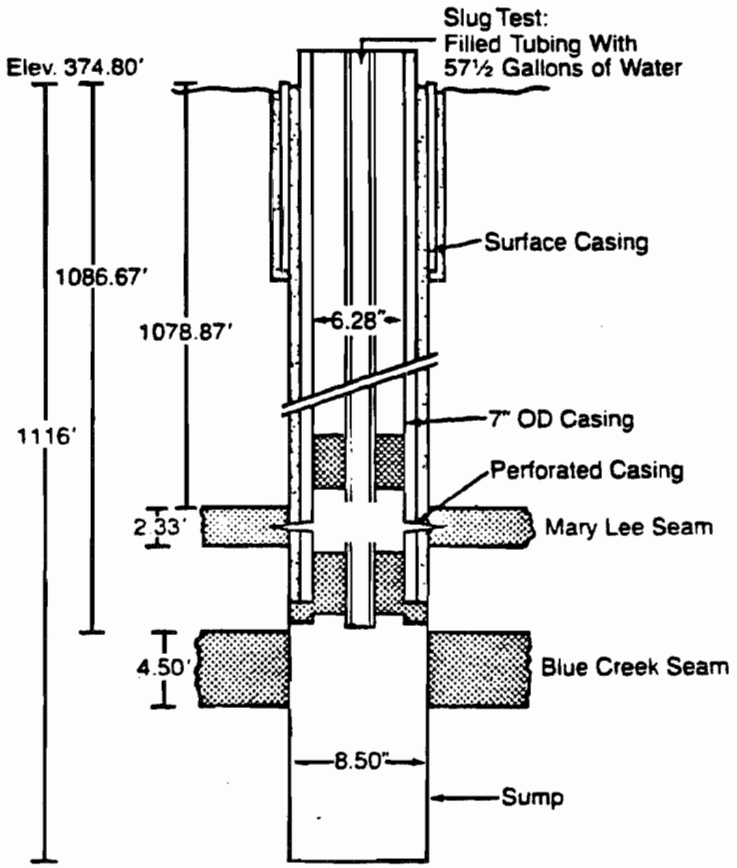


Figure 28 - Wellbore Configuration, Mary Lee Slug Test
Well DHM-7, Oak Grove, Alabama

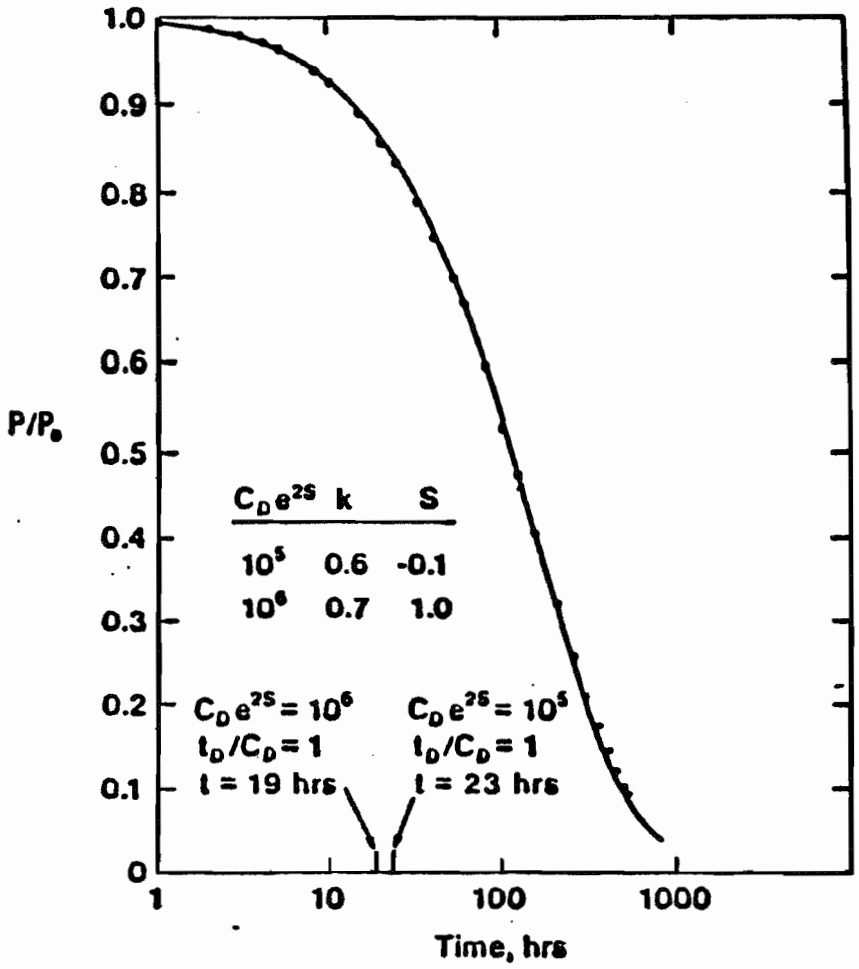


Figure 29 - Mary Lee Slug Test Results
Well DHM-7, Oak Grove, Alabama

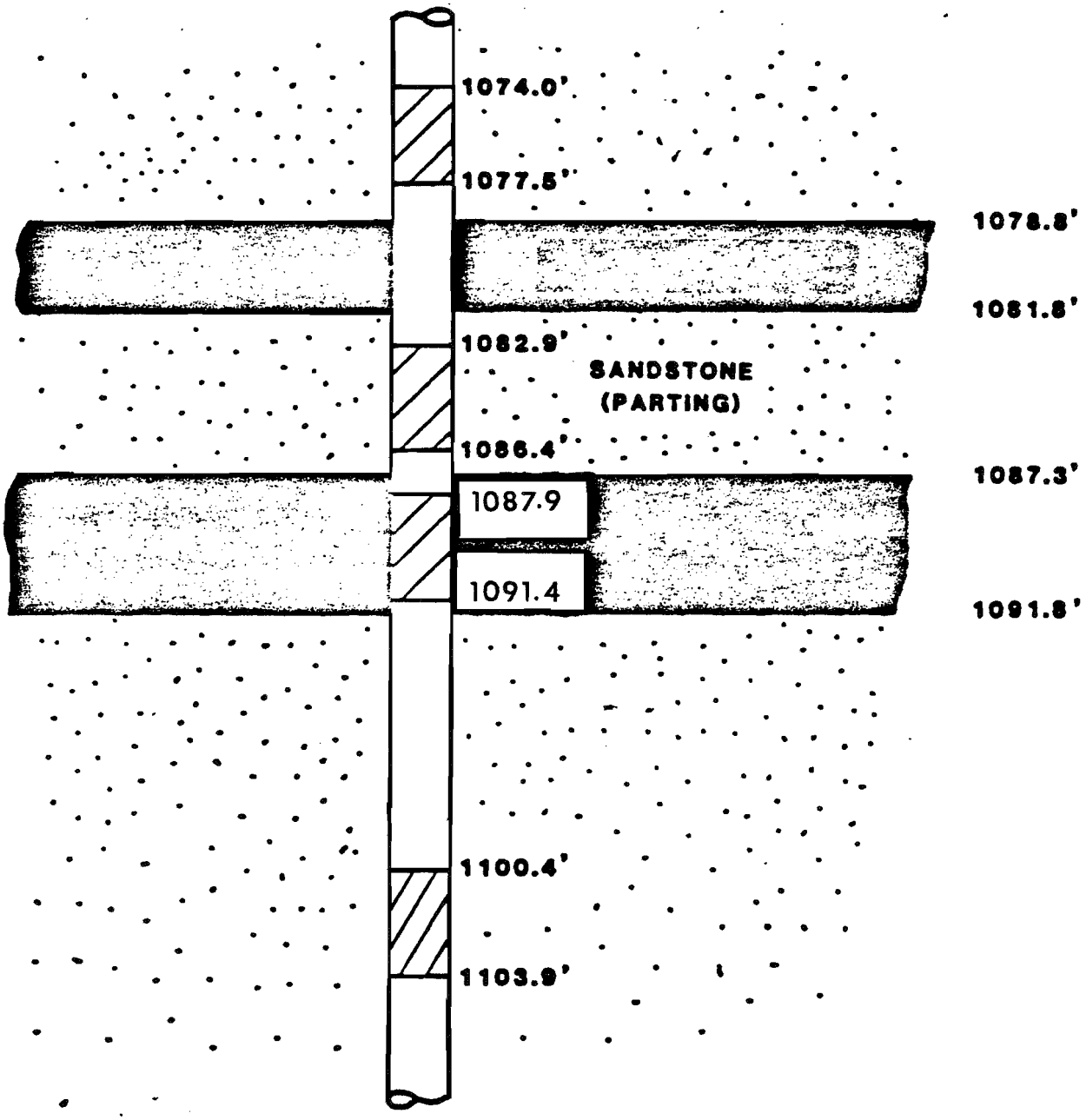


Figure 30 - In-Situ State-of-Stress Measurement Intervals
Well DHM-7, Oak Grove, Alabama

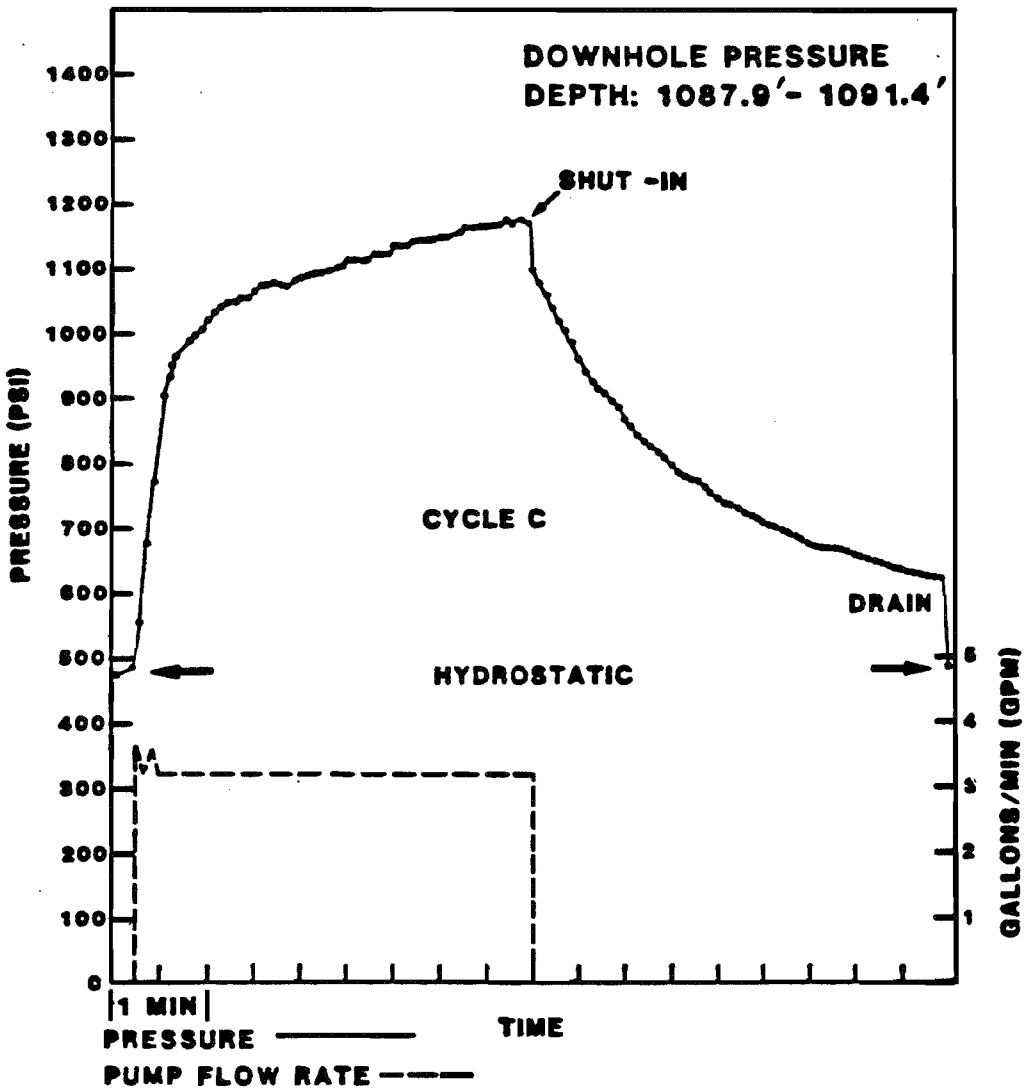


Figure 31 - In-Situ State-of-Stress Test Results
Blue Creek Coal Seam, Well DHM-7
Oak Grove, Alabama

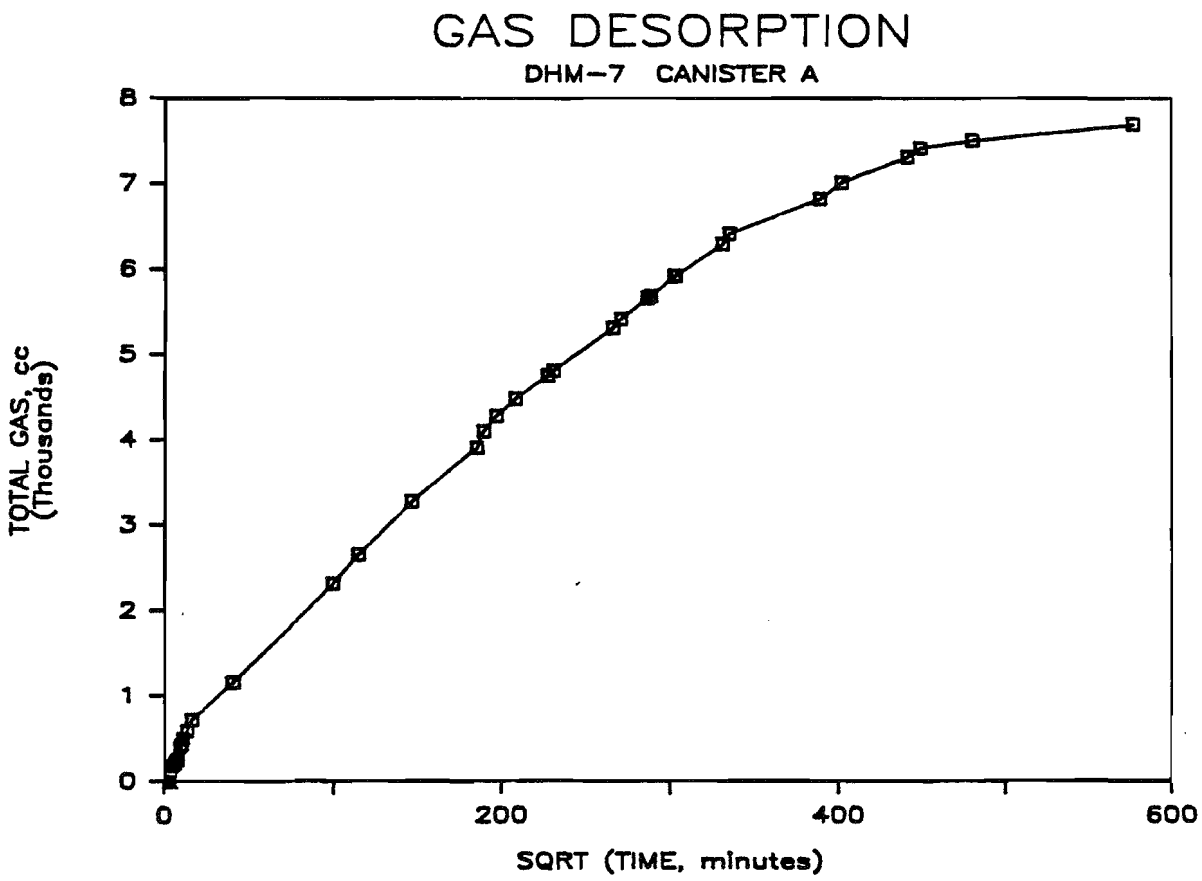


Figure 32 - Desorption Results, Cannister A
Abrasi-jet Cuttings
Well DHM-7, Oak Grove, Alabama

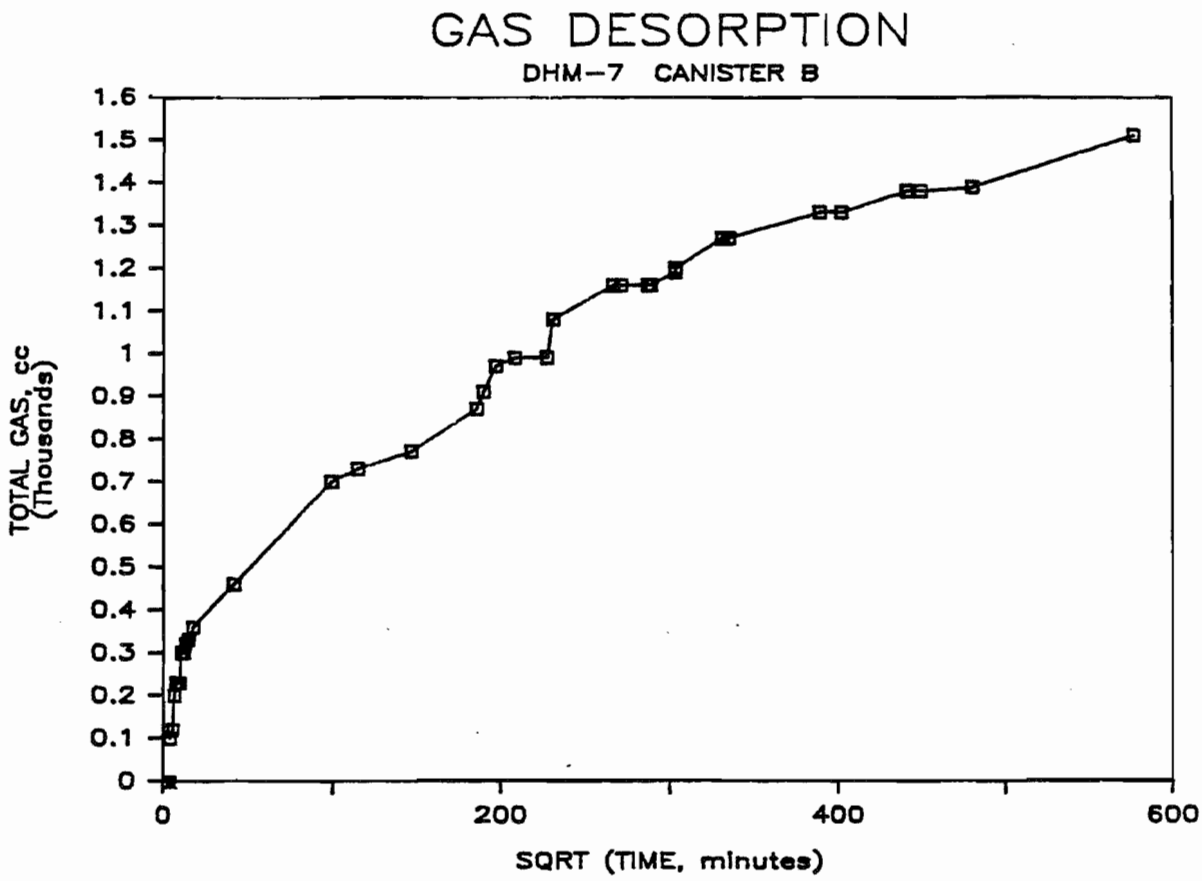


Figure 33 - Desorption Results, Cannister B
Abrasi-jet Cuttings
Well DHM-7, Oak Grove, Alabama

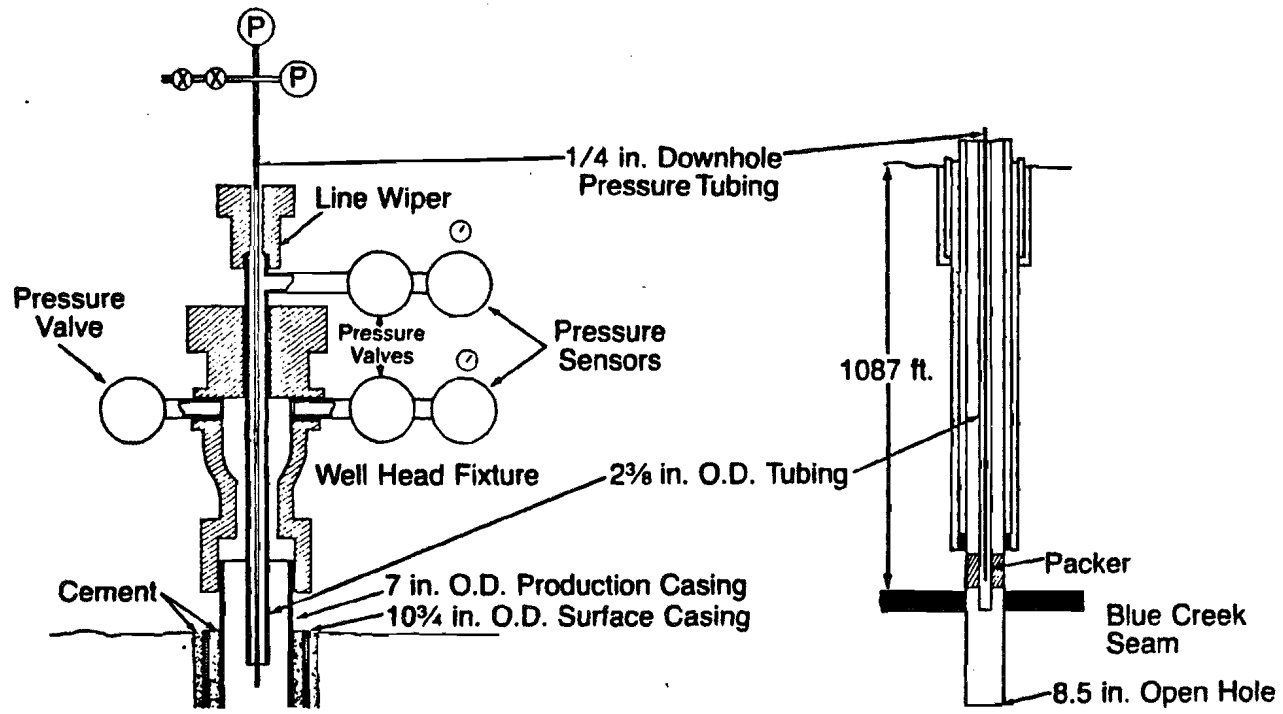


Figure 34 - Wellbore Configuration During Hydraulic Stimulation
Well DHM-7, Oak Grove, Alabama

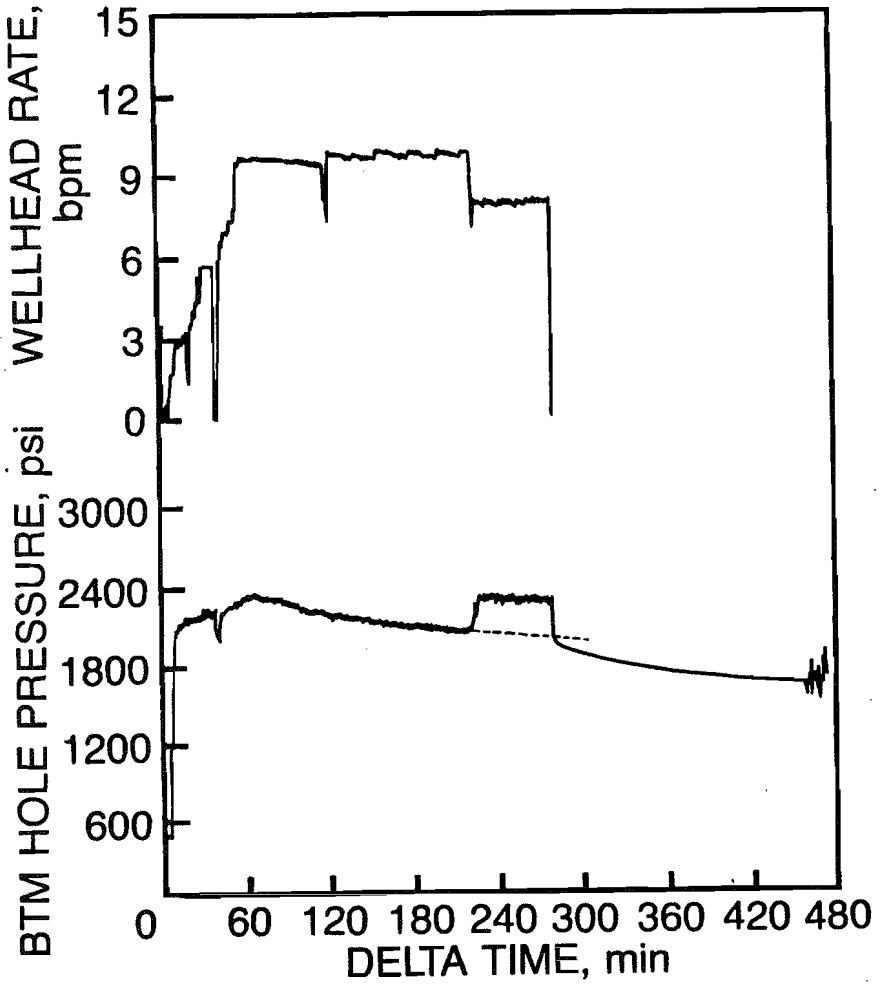


Figure 35 - Hydraulic Stimulation Pressure/Rate Curves Well DHM-7, Oak Grove, Alabama

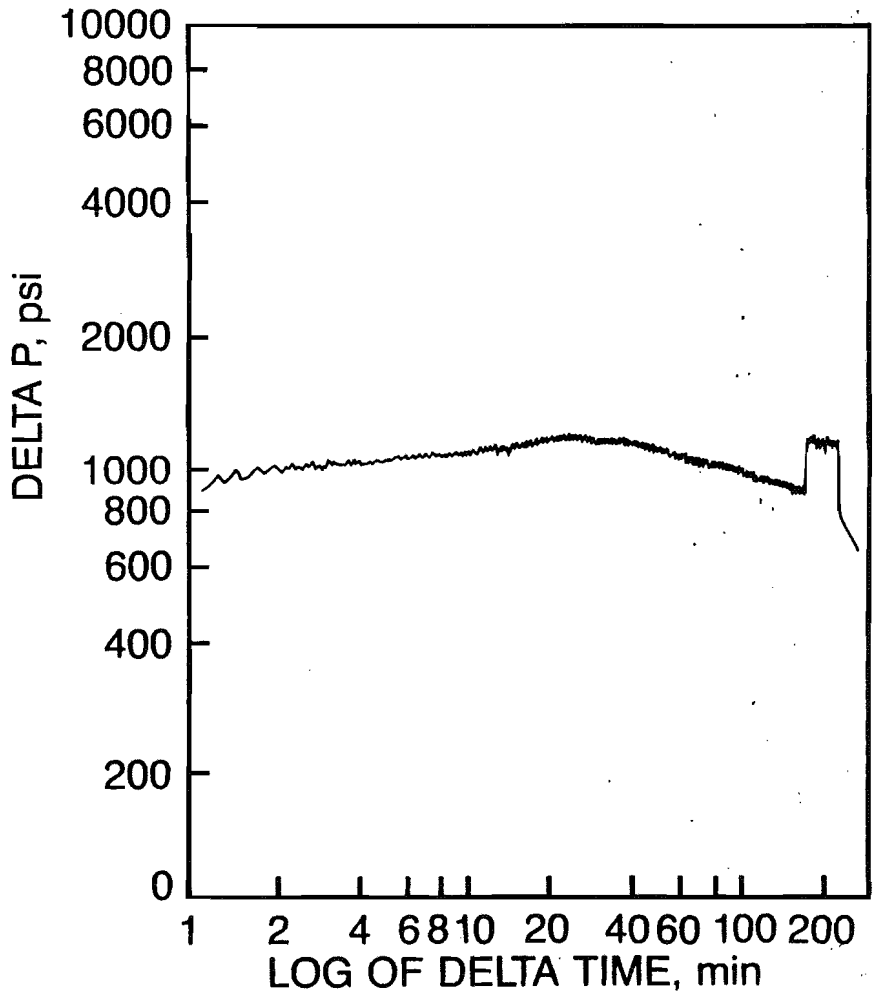
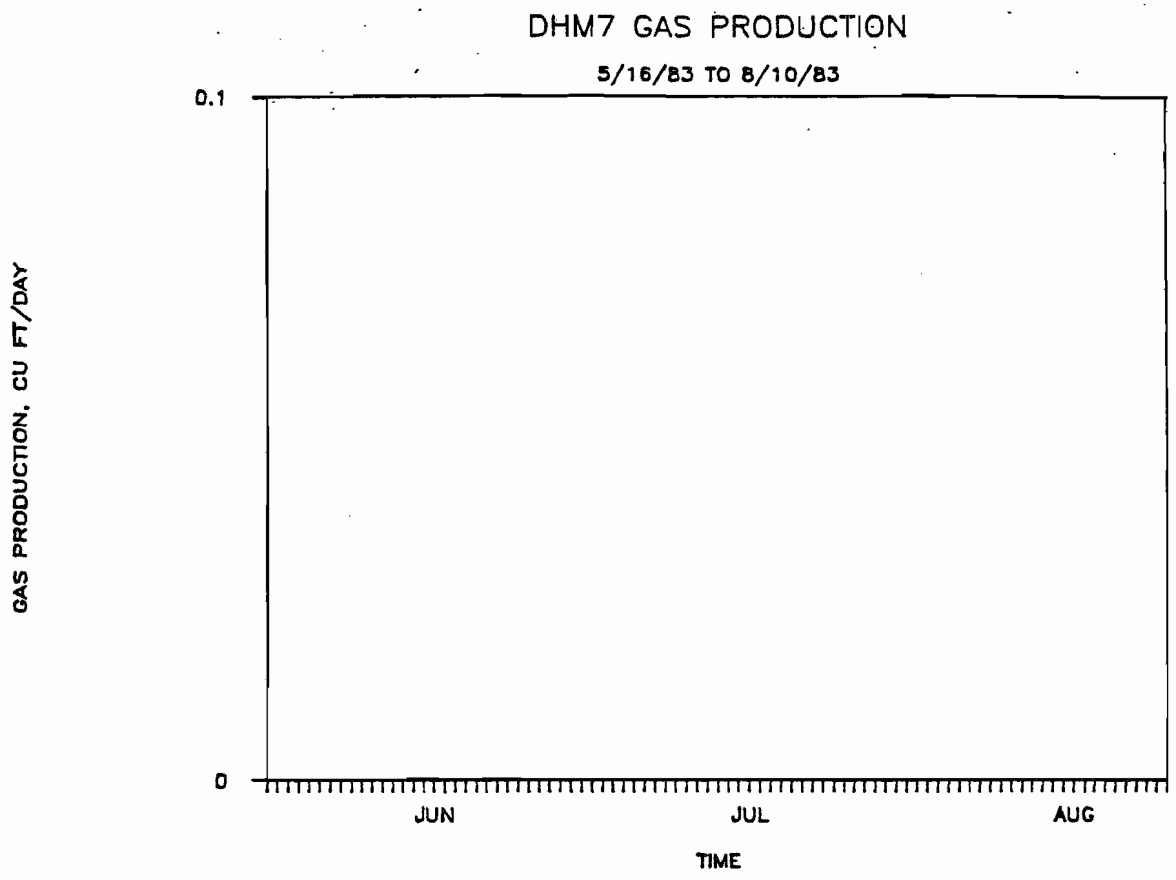


Figure 36 - Nolte-Smith Analysis Curve of Hydraulic Stimulation Well DHM-7, Oak Grove, Alabama

Figure 37 - Unstimulated Gas and Water Production
Blue Creek Coal Seam, Well DHM-7, Oak Grove, Alabama



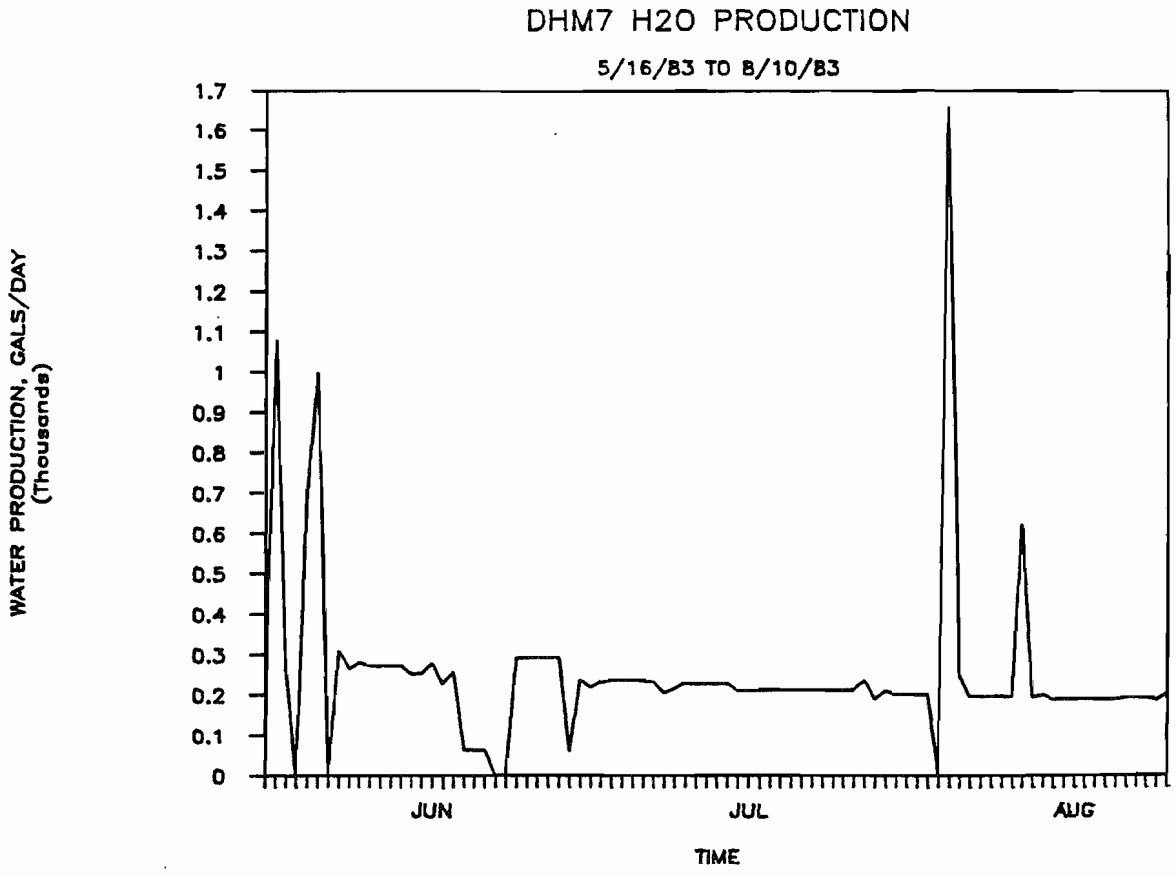
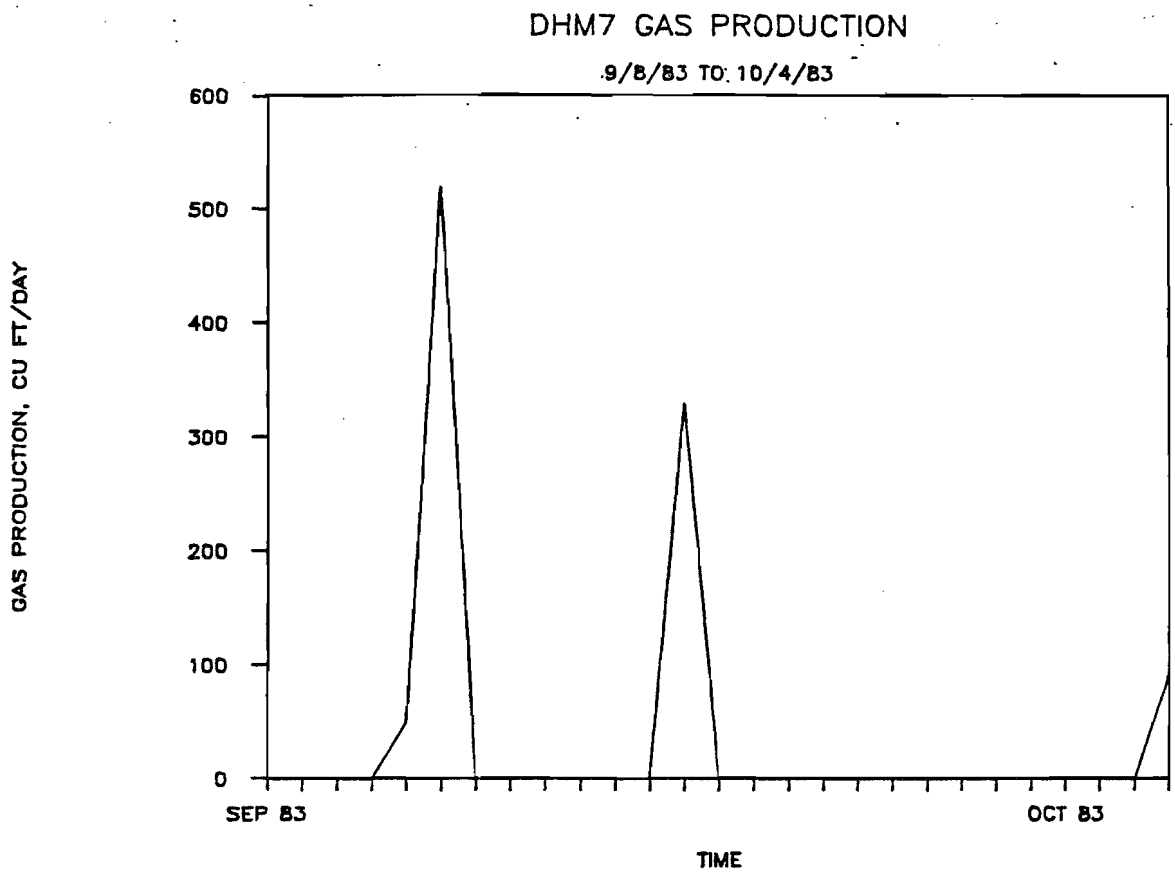


Figure 38 - Unstimulated Gas and Water Production
Mary Lee Coal Seam, Well DHM-7, Oak Grove, Alabama



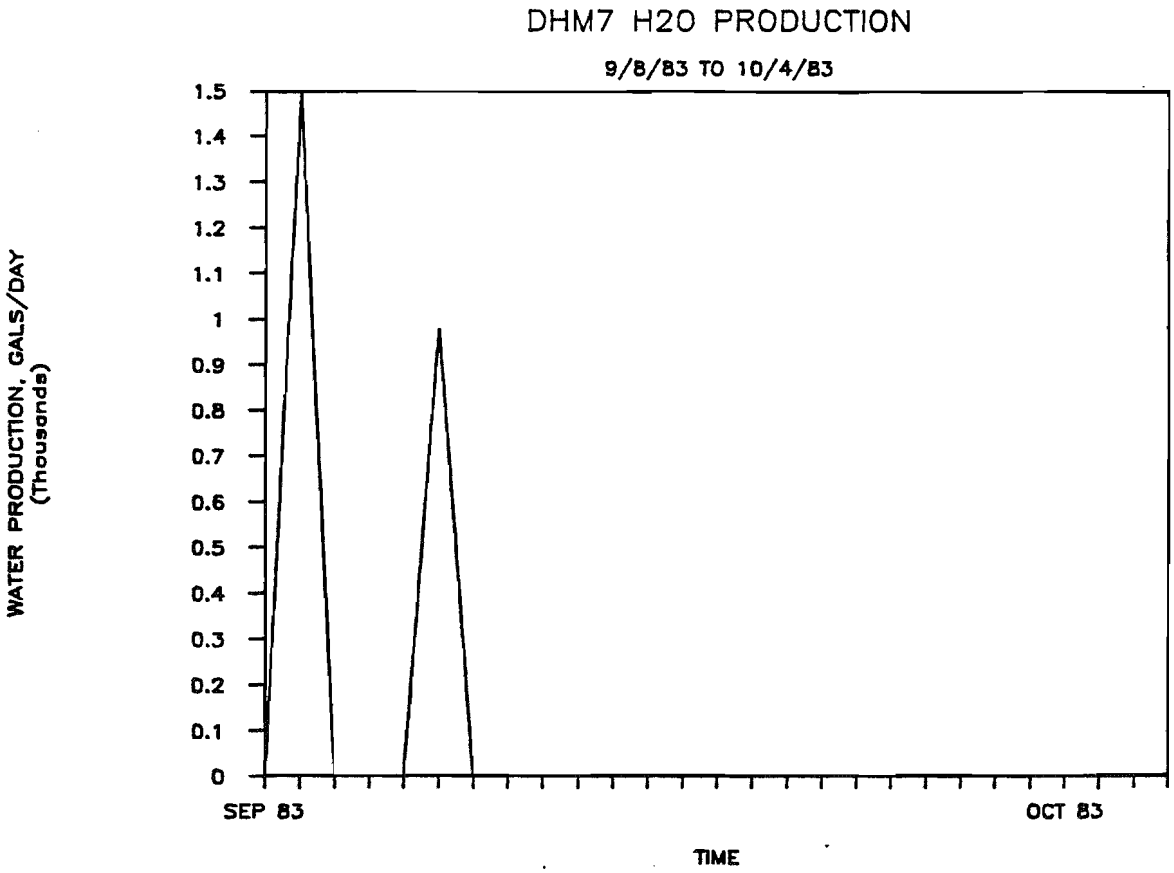
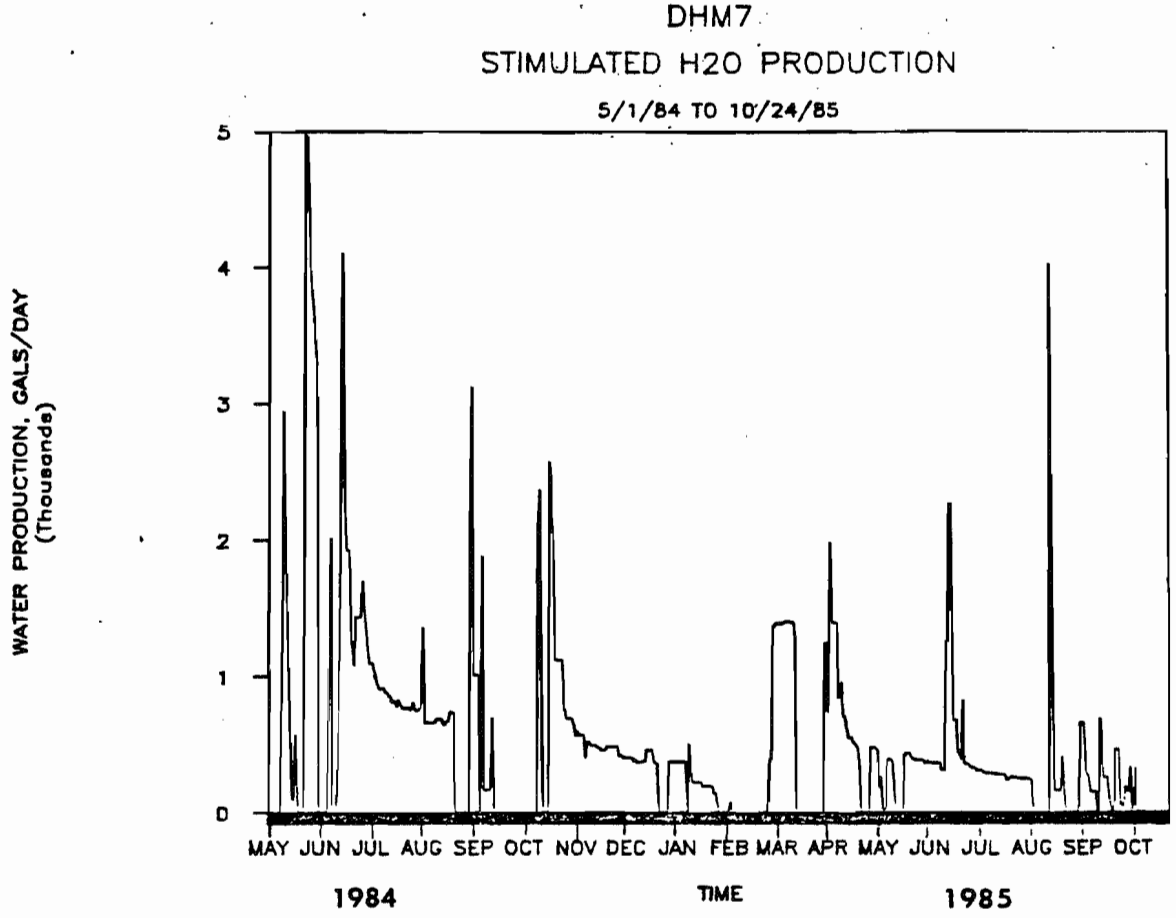


Figure 39 - Stimulated Water Production and Mine Face Distance
Well DHM-7, Oak Grove, Alabama



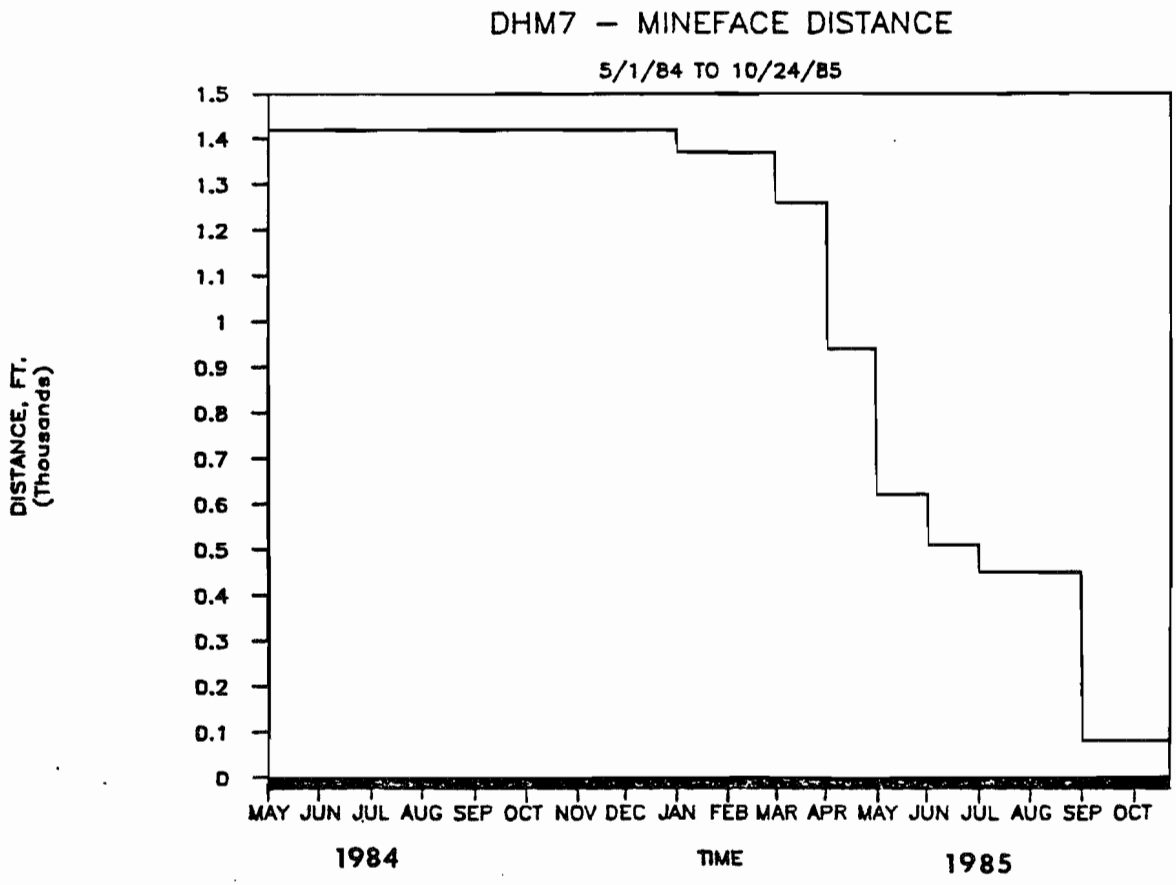
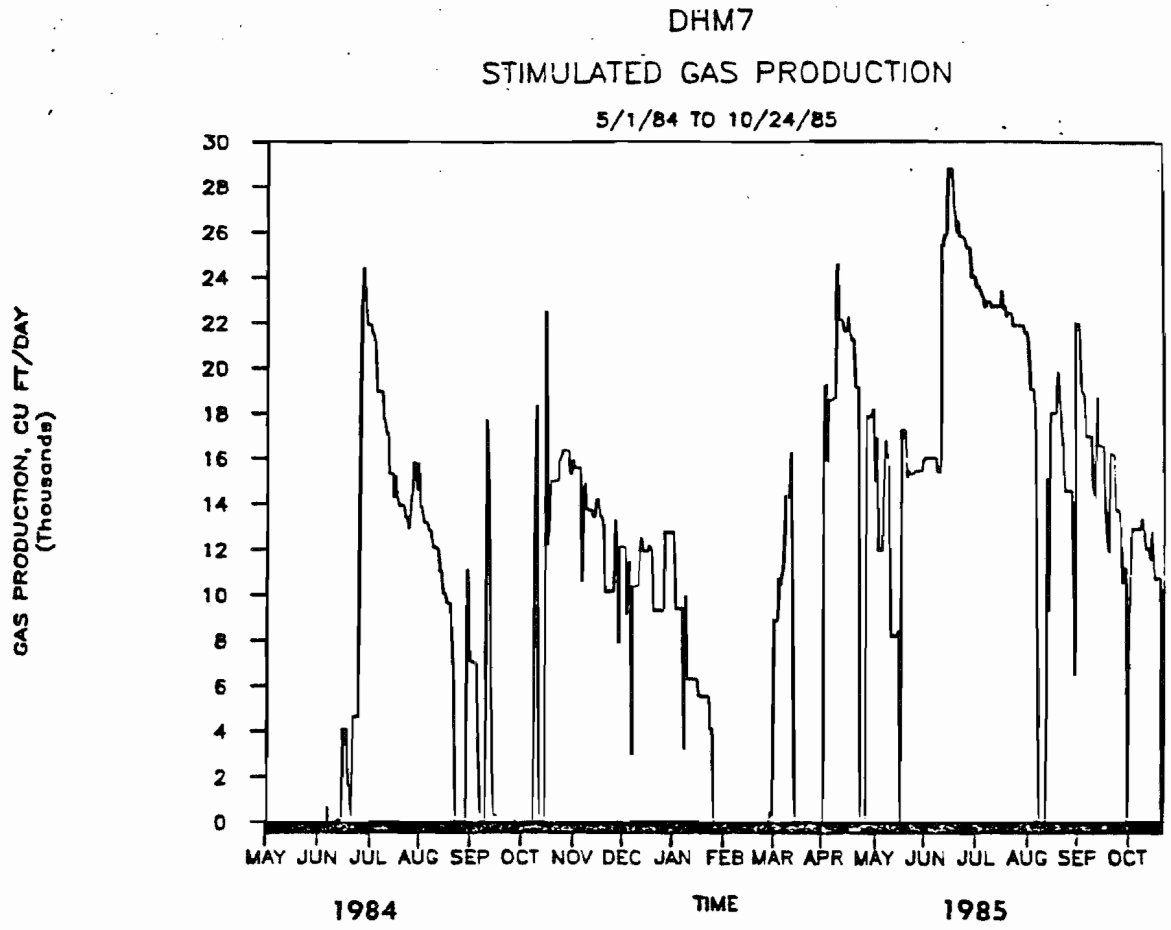
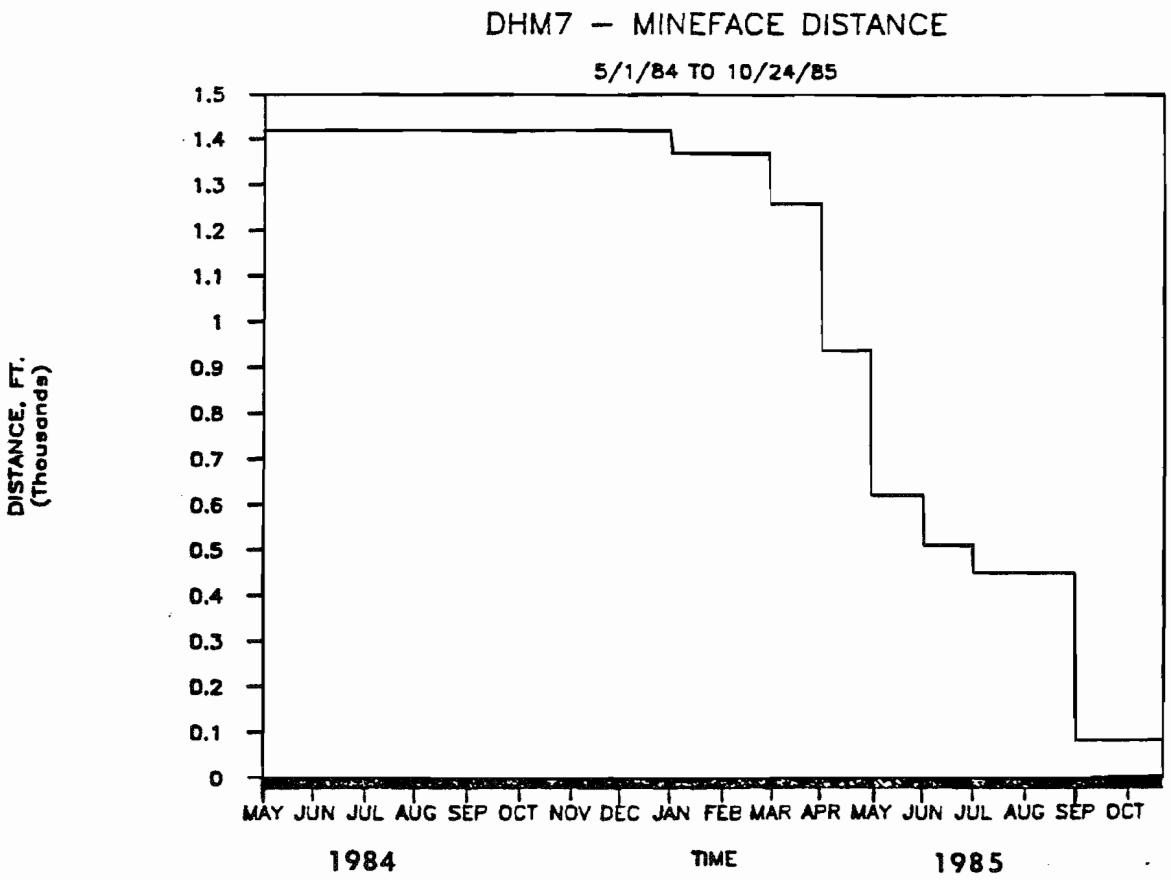


Figure 40 - Stimulated Gas Production and Mine Face Distance
Well DHM-7, Oak Grove, Alabama





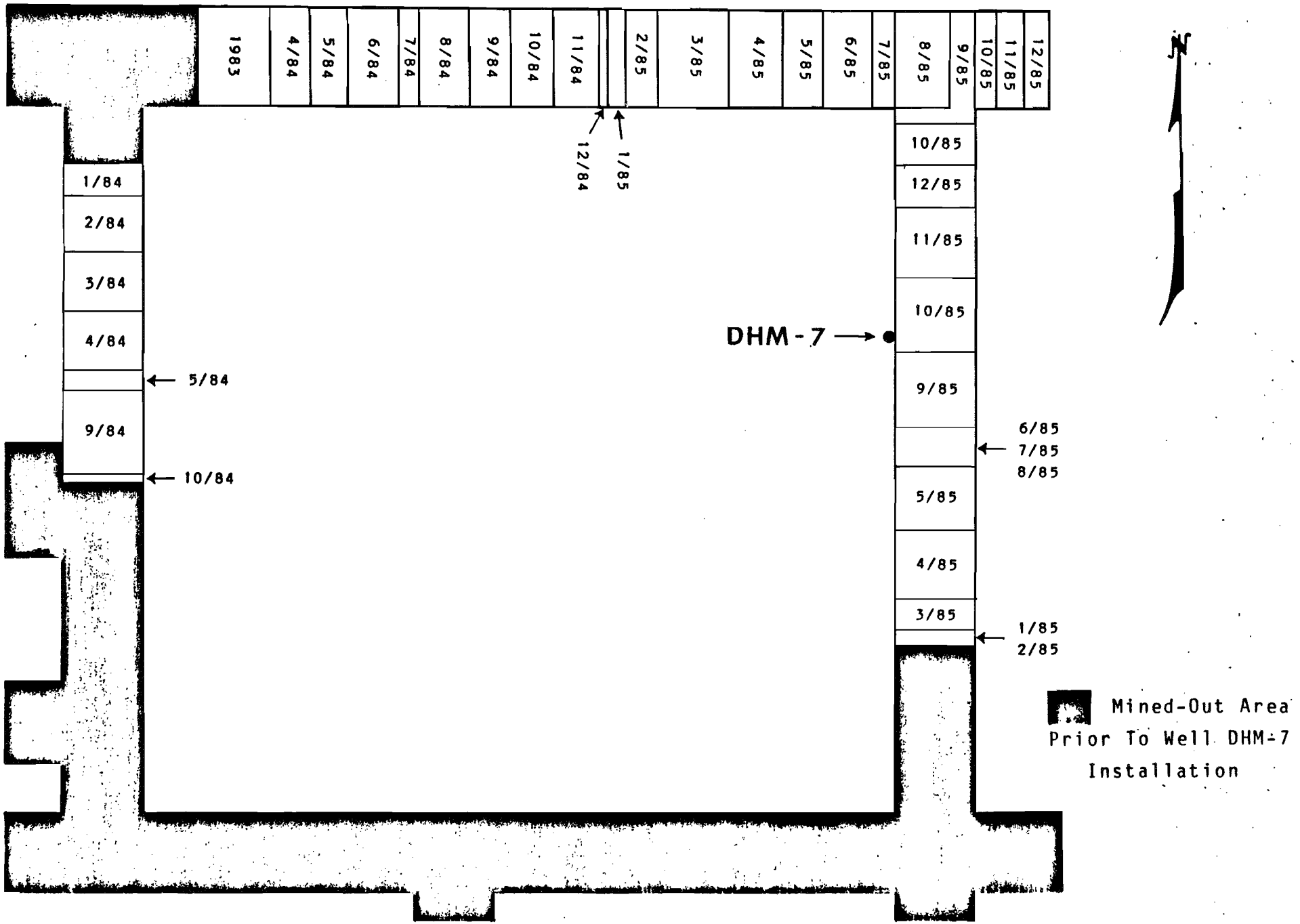


Figure 41 - Mine Face Location in Relation to Well DHM-7

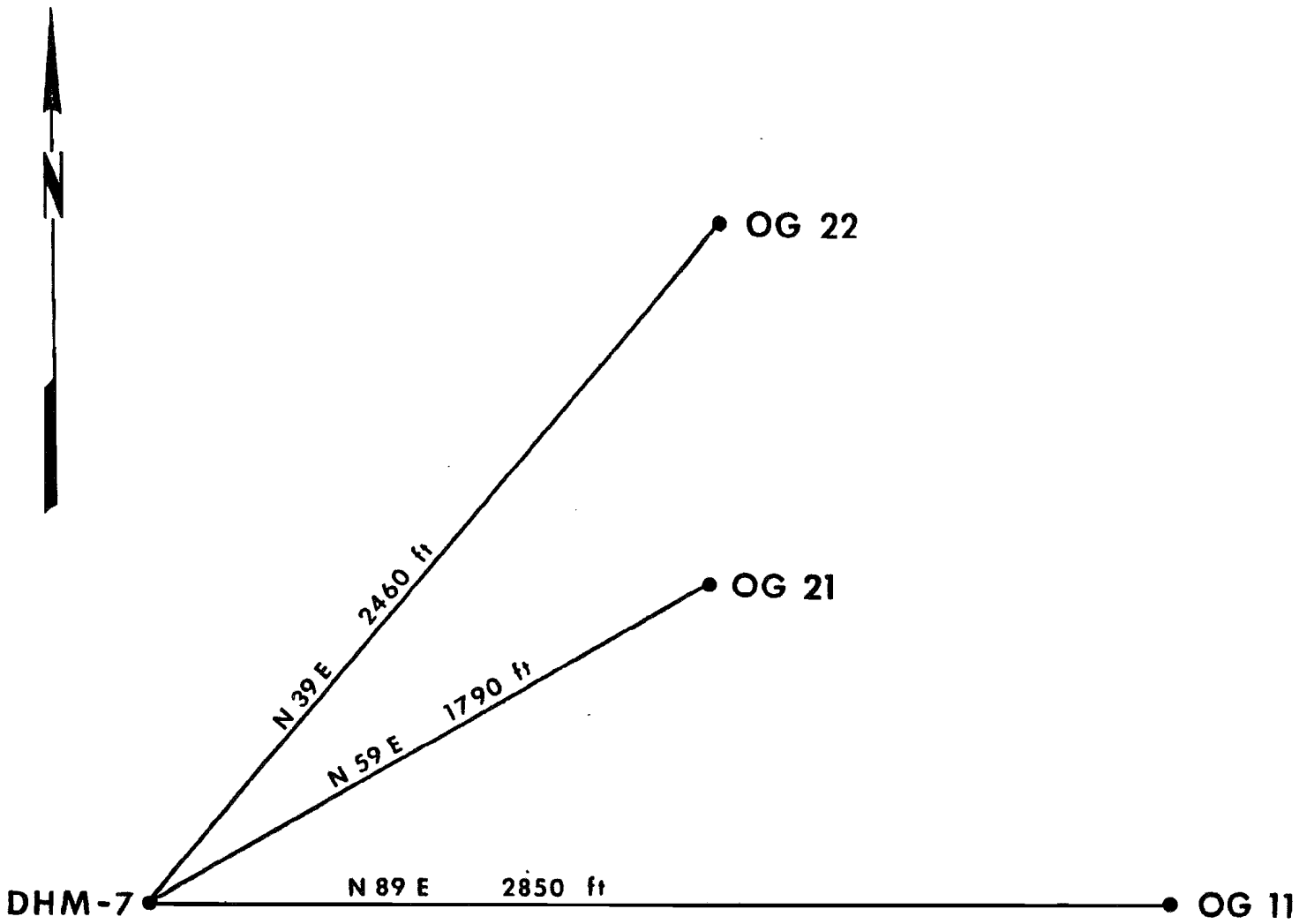
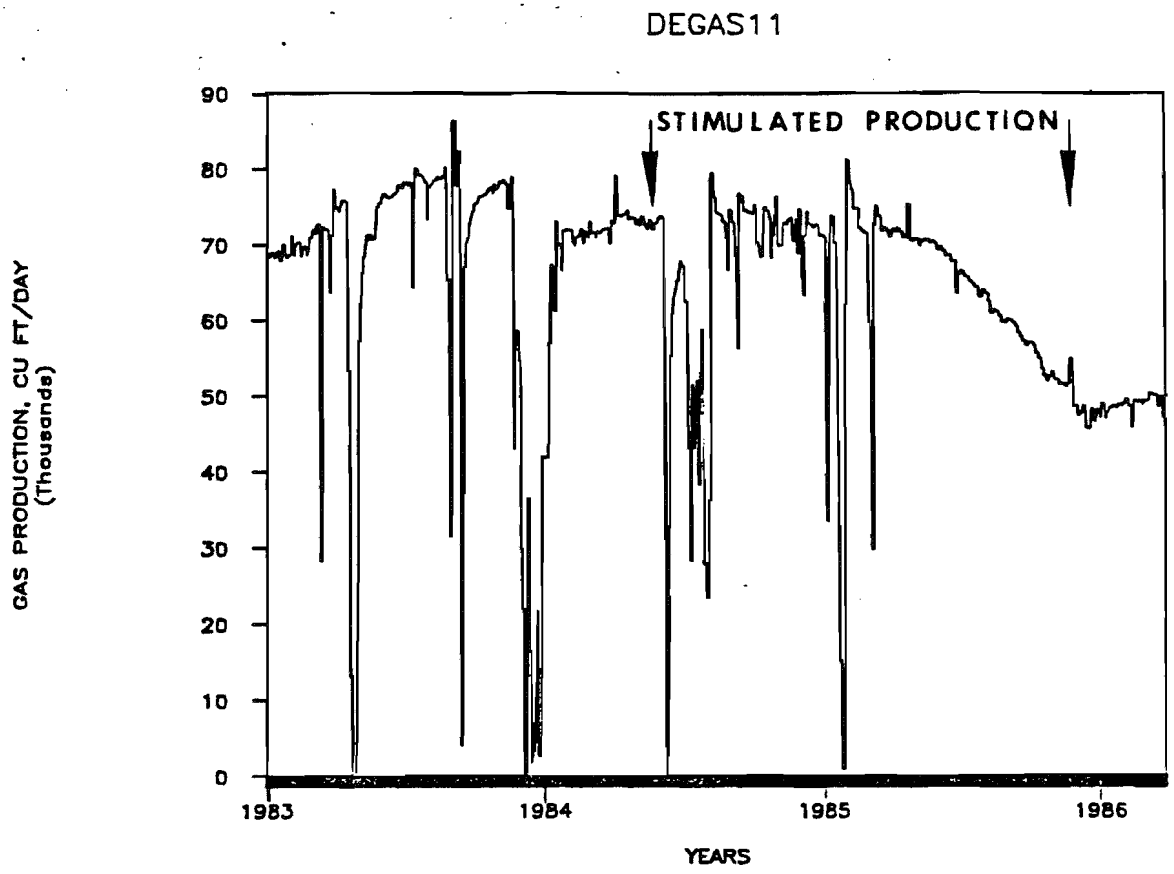


Figure 42 - Location of Adjacent Coalbed Methane Production in Relation to Well DHM-7, Oak Grove, Alabama

Figure 43 - Gas and Water Production, Oak Grove Grid Well 11
Oak Grove, Alabama



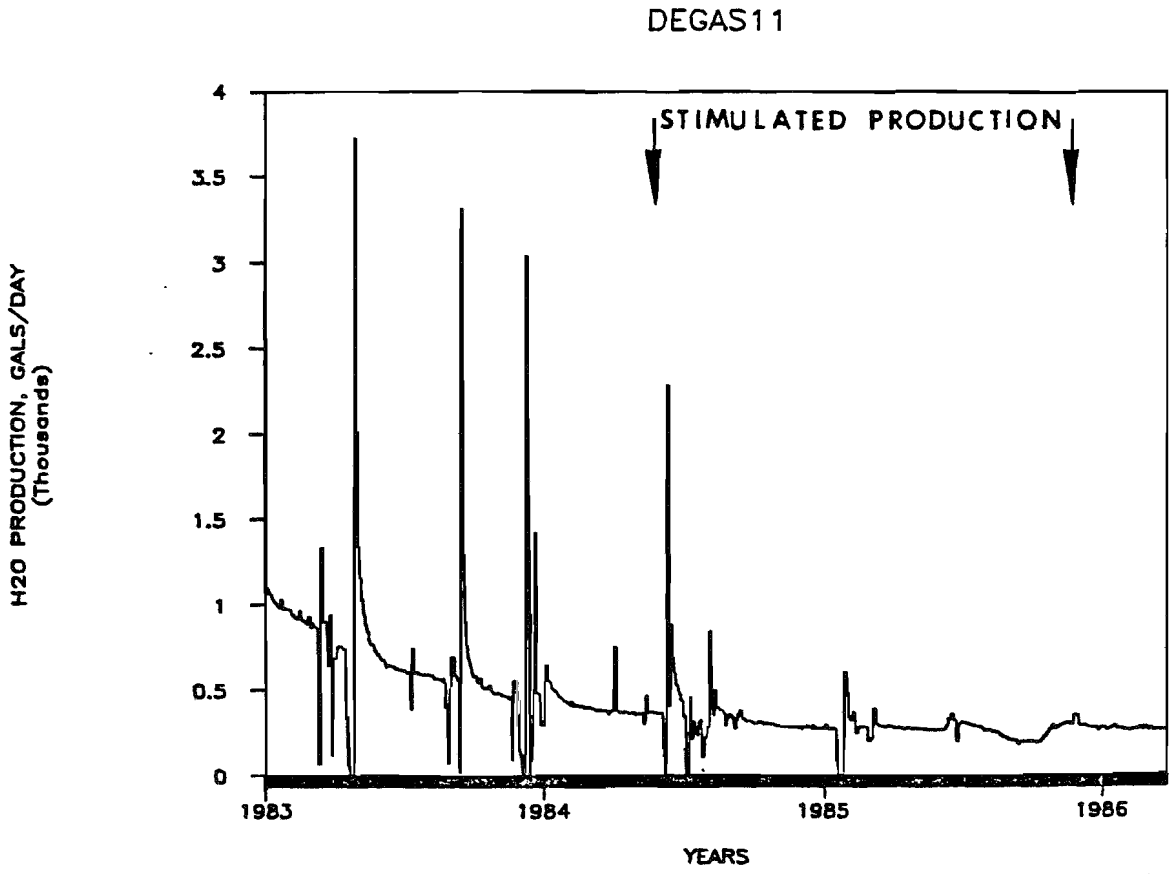
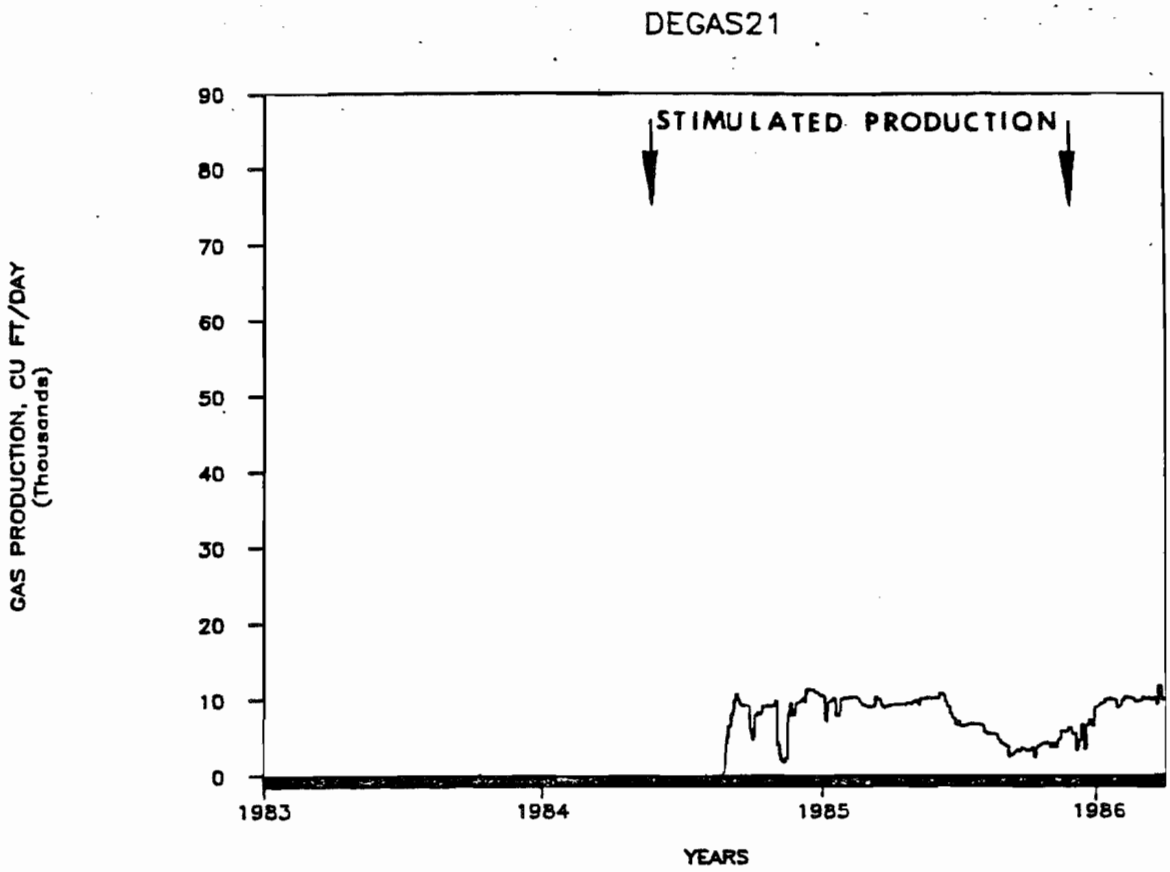


Figure 44 - Gas and Water Production, Oak Grove Grid Well 21
Oak Grove, Alabama



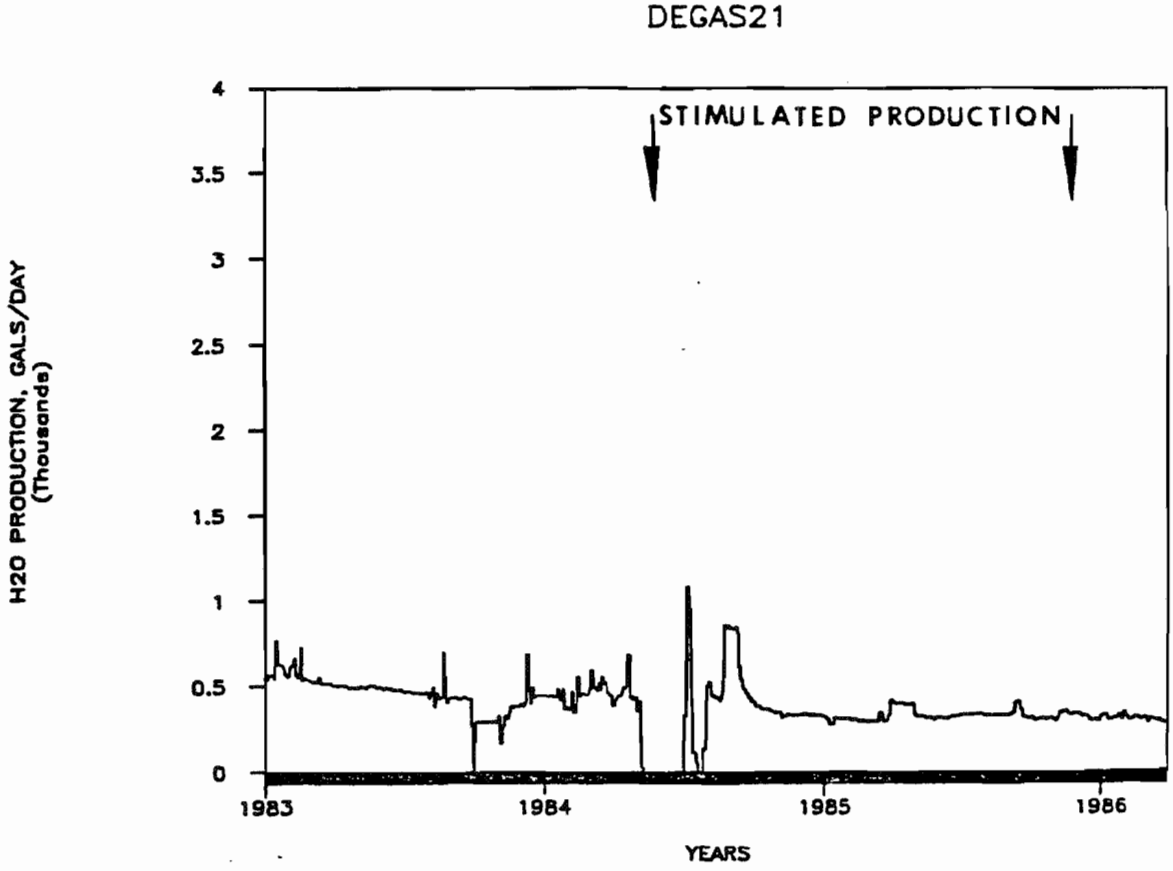
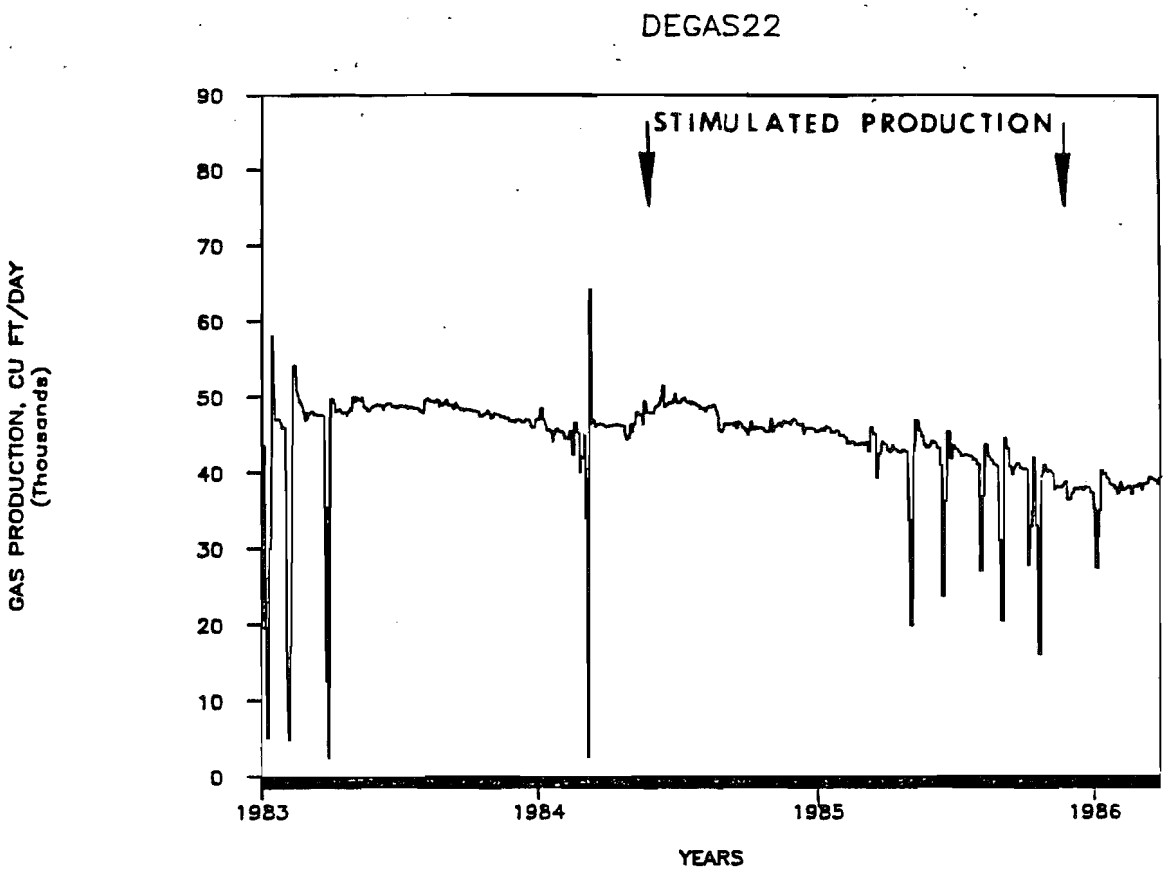


Figure 45 - Gas and Water Production, Oak Grove Grid Well 22
Oak Grove, Alabama



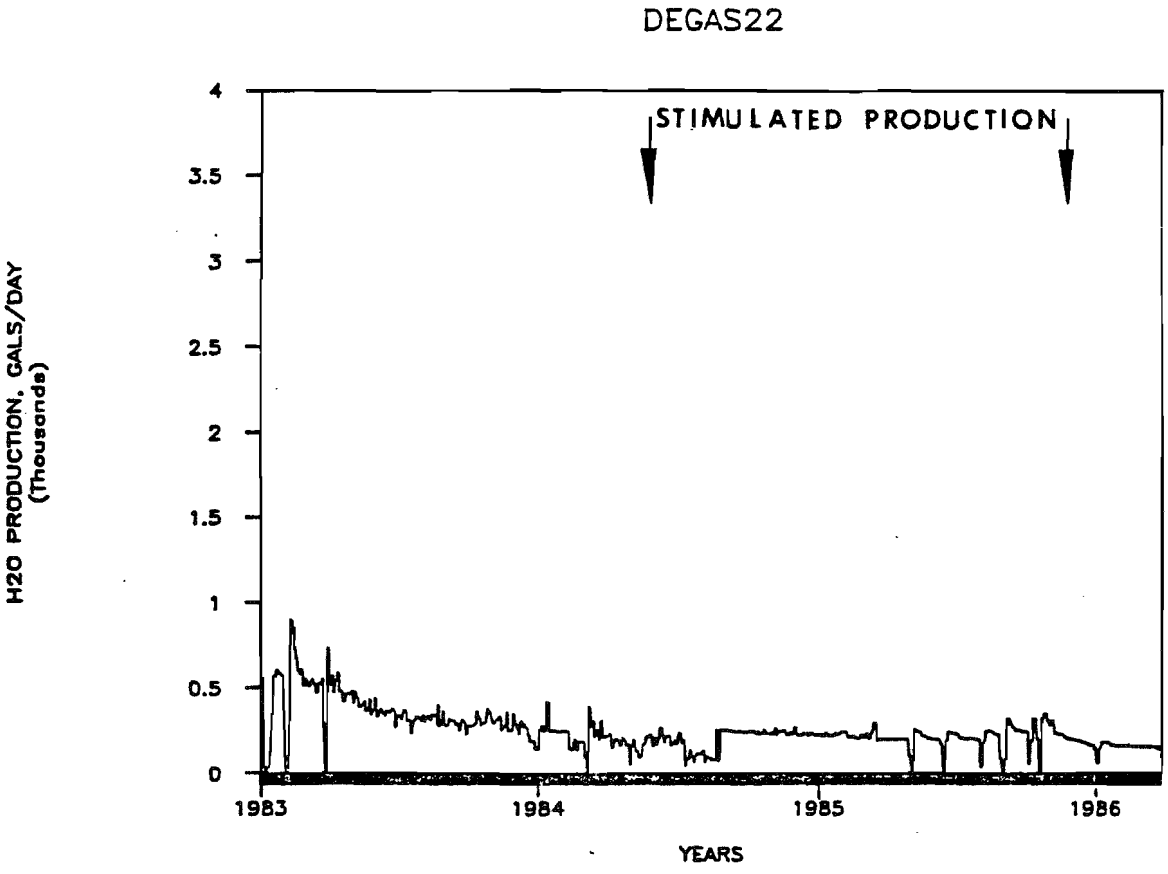
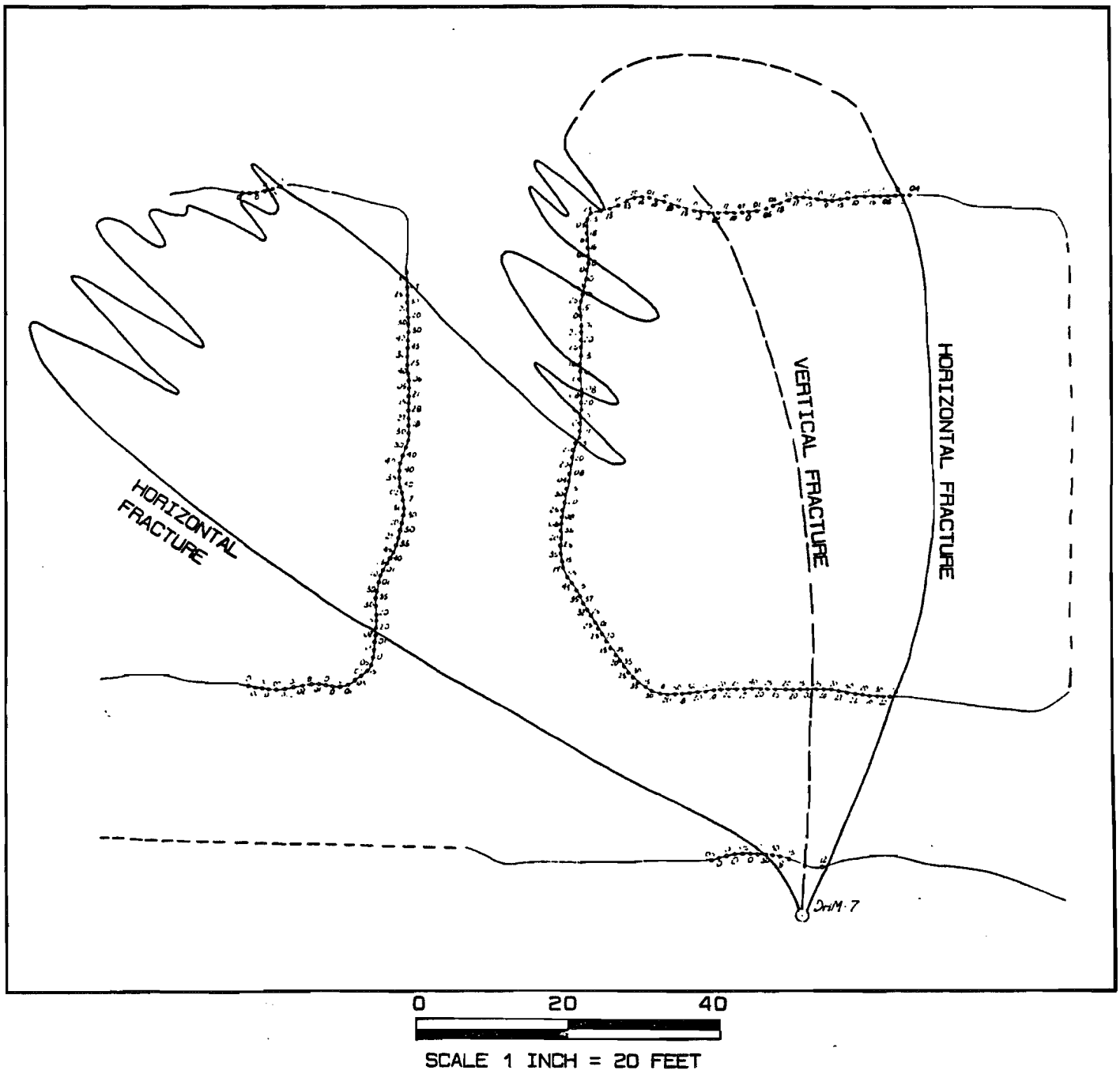


Figure 46 - Plan View of Horizontal and Vertical Fracture
Well DHM-7, Oak Grove, Alabama

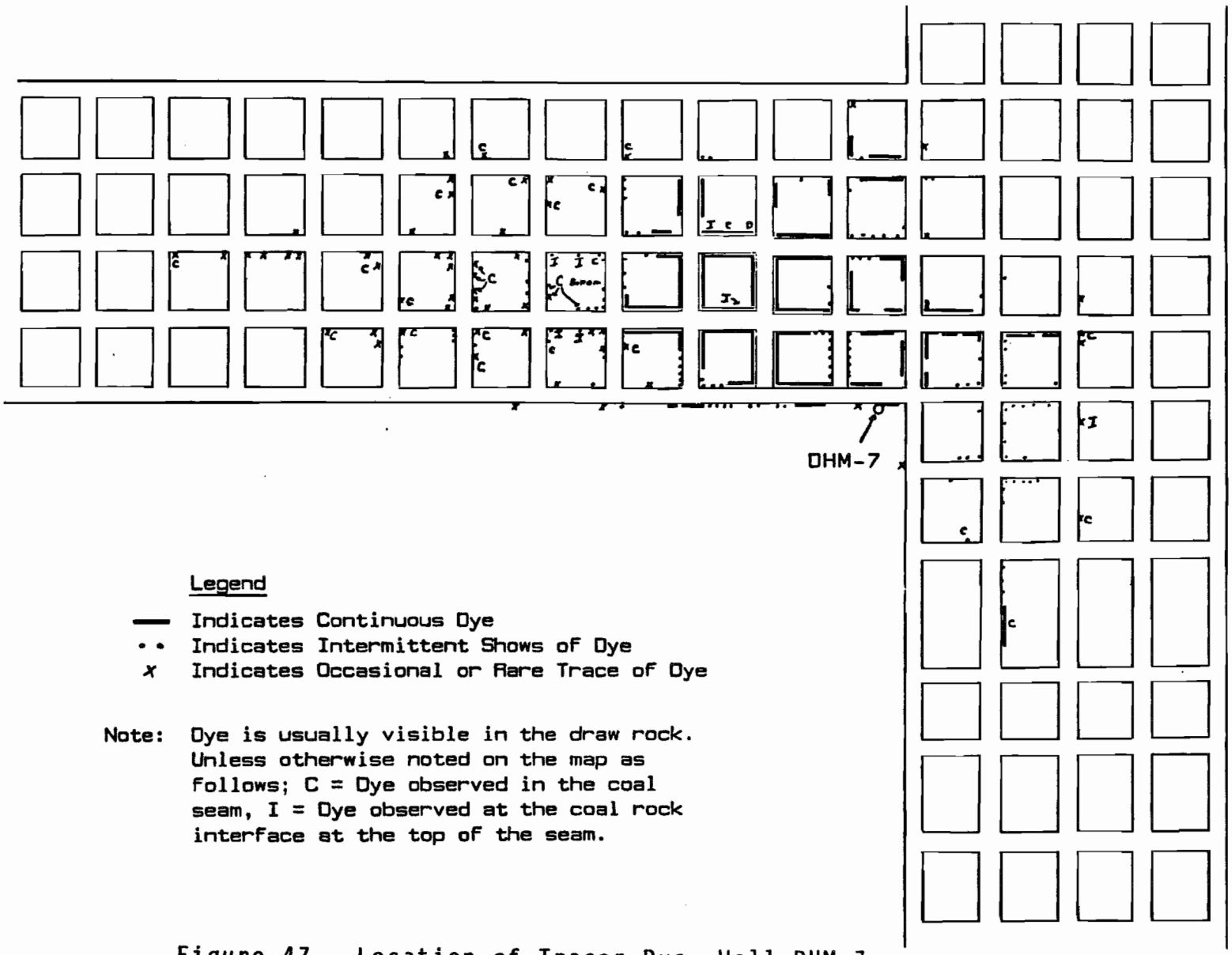
PLAN VIEW OF HORIZONTAL AND VERTICAL FRACTURE



25● Mapping station with average sand thickness for 1 foot section of horizontal fracture.

* Sand thickness reported in hundredths of inches.

LOCATION OF TRACER DYE



Legend

—— Indicates Continuous Dye
• • Indicates Intermittent Shows of Dye
x Indicates Occasional or Rare Trace of Dye

Note: Dye is usually visible in the draw rock. Unless otherwise noted on the map as follows; C = Dye observed in the coal seam, I = Dye observed at the coal rock interface at the top of the seam.

Figure 47 - Location of Tracer Dye, Well DHM-7
Oak Grove, Alabama